2007-2010 IAPSO report: Four years of Physical Oceanography in Canada

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Physical oceanography research in Canada has been extremely productive for the period of 2007-2010, with over 750 peer-reviewed journal articles by over 600 individual researchers from 111 institutions, departments, or companies from across the country. These accomplishments are recorded in the 2011 report to the International Association for the Physical Sciences of the Oceans (IAPSO) compiled by Blair Greenan and Jody Klymak with assistance from Tineke van der Baaren. This report is provided in three components (bibliography with full abstracts, alphabetical listing of the bibliography and a list of Canadian researchers and organizations). The documents are available on the CNC-SCOR web site at http://www.cmos.ca/scor/scorindexe.html. The bibliography is also available on the Mendeley website at http://www.mendeley.com/groups/1305293/canadian-iapso-2007-2010/.

The following criteria were used in the compilation of this report:

- Canadian publications are those published by researchers in Canadian institutions such as universities or government labs. It does not include publications by Canadian researchers working at institutions outside Canada.
- This survey only includes peer-reviewed journal articles (no tech reports, data reports, white papers, etc.)
- The time frame of the survey is 1 Jan 2007 to 31 Dec 2010

The report consists of a categorized bibliography summarizing abstracts from Canadian scientists conducting physical oceanography research. Topics span the breadth of the global oceans, with Canadian contributions, including observations of the oceans on all scales, laboratory studies, numerical studies, and theoretical work. The list of papers makes clear that Canadians are sought after for many international collaborations, as well as working on problems of national significance. In addition, the impact of student training on the papers is clear, with many of the 600 Canadian researchers mentioned above being students when the cited work was written.

The report is deliberately broad in its interpretation of "physical science of the oceans", and includes a number of climate papers, papers on atmospheric flows, and a significant number of papers on the chemistry of the oceans. We hope no one is offended if their work ended up on one side of the line or the other and it is certainly possible that we have omitted some publications in error. Hence, we would encourage the community to provide feedback to us.

The numbers above are an impressive body of research for a four year period, and it is worth noting where the support for these programs came from:

- First, and most noteworthy, this was the period when the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) was being actively funded. This allowed support for graduate students, post-docs, and technicians that made many of these papers possible.
- This period also encompassed the first batch of papers from the International Polar Year (2007-2008). Physical oceanographers participated in the C3O project, the Circumpolar Flaw Lead

System Study, along with significant effort put into Arctic climate and ice changes during these years. This effort was reflected in a recent special issue of Atmosphere-Oceans.
- NSERC Discovery Grants still remained an important source of funding of the University system, funding diverse programs across the discipline.
- Research in the federal government lab system was supported through departmental core A-base funding as well at targeted funding through programs such as CSA-GRIP and PERD.

Arguably, the backbone of observational physical oceanography in Canada remains the government laboratories operated by Fisheries and Oceans Canada (DFO). These labs have a mission that attempts to balance efforts in environmental monitoring with directed research. The Bedford Institute of Oceanography (BIO), St. Andrews Biological Station, Maurice Lamontagne Institute and the Northwest Atlantic Fisheries Centre have well-established long-term monitoring programs both on and off the continental shelves of the Northwest Atlantic. The Institute of Ocean Sciences (IOS) maintains the Station Papa time series, monitoring of the Strait of Georgia, and the west coast of Vancouver Island. Work regularly takes place by Arctic groups from BIO, IOS, and the Freshwater Institute Science Laboratory on the Coast Guard icebreakers. These efforts are complemented through academia with platforms such as the CCGS Amundsen, which focuses on Arctic research.

The successes of previous years point towards challenges for the future. Firstly, CFCAS is no longer being funded by the federal government. This is a major loss for physical oceanographers, as our efforts do not always fit in well with multidisciplinary programs and networks, and CFCAS was a good way to keep small independent efforts funded. Secondly, federal spending is restrained and this has and will continue to have impact on federal laboratories. Third, shiptime for government and academia will continue to be constrained by the availability of platforms.

Academia can possibly take up some of this slack, and perhaps universities are an appropriate place for basic research to be carried out. However, it is quite difficult to get adequate funding from NSERC for field-going programs without assembling something on the scale of a Network Centre of Excellence. We would argue more medium-scale funding needs to be made available, and the unique nature of seagoing research needs to be argued for vigorously if Canada is to remain internationally relevant in oceanography.

These challenges are mitigated by many advances that are being made in physical oceanography that Canadian scientists can take advantage of. Autonomous instruments are becoming cheaper and much more flexible. Canada already plays an important role in the Argo profiling float program. We are starting to gain expertise in gliders and other floats. Improvements in battery technology and data telemetry via Iridium satellites makes collecting comprehensive data sets with these instruments possible for a fraction of the cost of using a ship. Of course, in the meantime improved numerical models and laboratory experiments will continue to guide our understanding of physical oceanography.

In summary, the document we assembled is perhaps idiosyncratic in scope, but it highlights the comprehensive work being done by Canadian oceanographers. Assembling these reports is a significant effort, and we would be interested in ideas as to how to improve it in the future. In

particular, as we argue for our science to our funding agencies, it would really help to indicate what investments pay off in terms of impact on the scientific community. Future efforts will be directed towards assembling those metrics, but based on this effort we suspect Canada is getting a phenomenal return for its investment in our research, and further renewal and investment is necessary to keep the discipline alive and healthy.

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Physical Oceanography in Canada, 2007-2010: A Review for the International Association for the Physical Sciences of the Oceans

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Physical Oceanography in Canada, 2007-2010: A Review for the International Association for the Physical Sciences of the Oceans

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1 Global Ocean

1.1 Coastal Processes

Gilbert, D., N. N. Rabalais, R. J. Dí az, and J. Zhang, 2010, Evidence for greater oxygen decline rates in the co astal ocean than in the open ocean, *Biogeosciences*, **7**: 2283-2296, doi:10.5194/bg-7-2283-2010

> In the global ocean, the num ber of reported hypoxic sites (oxygen <30% saturation) is on the rise both near the coast and in the open ocean. But unfortunately, most of the papers on hypoxia only present oxygen data from one or two years, so that w e often lack a long-term perspective on whether oxygen levels at these locations are decreasing, steady or increasing. Consequently, we cannot rule out the possibility that many of the newly reported hypoxic areas were hypoxic in the past, and that the increas ing number of hypoxic areas partly reflects increased res earch and monitoring efforts. Here we ad dress this shortcoming by computing oxygen concentration trends in the global ocean from published time series and from tim e series that we calculated using a global oxygen database. Our calculations reveal that median oxygen decline rates are more severe in a 30 km band near the coast than in the open ocean (>100 km from the coast). Percentages of oxygen time series with negative oxygen trends are also greater in the coas tal ocean th an in the open ocean. Finally, a s ignificant difference between median published oxygen trends and median trends calculated

from raw oxygen data suggests the existence of a publication bias in favor of negative trends in the open ocean.

Kemp, W. M., J. M. Testa, D. J. Conley, D. Gilbert, and J. D. Hagy, 2009, Temporal responses of coastal hypoxia to nutrient loading and physical controls, *Biogeosciences*, **6**: 2985-3008, doi:10.5194/bg-6-2985-2009

The incidence and intensity of hypoxic waters in coastal aquatic ecosystems has been expanding in recent decades coincident with eutrophication of the coastal zone. Worldwide, there is strong interest in reducing the size and duration of hypoxia in coastal waters, because hypoxia causes negative effects for many organisms and ecosystem processes. Although strategies to reduce hypoxia by decreasing nutrient loading are predicated on the assumption that this action would reverse eutrophication, recent analyses of historical data from European and North American coastal systems suggest little evidence for simple linear response trajectories. We review published parallel time-series data on hypoxia and loading rates for inorganic nutrients and labile organic matter to analyze trajectories of oxygen (O_2) response to nutrient loading. We also assess existing knowledge of physical and ecological factors regulating O_2 in coastal marine waters to facilitate analysis of hypoxia responses to reductions in nutrient (and/or organic matter) inputs. Of the 24 systems identified where concurrent time series of loading and O_2 were available, half displayed relatively clear and direct recoveries following remediation. We explored in detail 5 well-studied systems that have exhibited complex, non-linear responses to variations in loading, including apparent "regime shifts". A summary of these analyses suggests that O_2 conditions improved rapidly and linearly in systems where remediation focused on organic inputs from sewage treatment plants, which were the primary drivers of hypoxia. In larger more open systems where diffuse nutrient loads are more important in fueling O_2 depletion and where climatic influences are pronounced, responses to remediation tended to follow non-linear trends that may include hysteresis and time-lags. Improved understanding of hypoxia remediation requires that future studies use comparative approaches and consider multiple regulating factors. These analyses should consider: (1) the dominant temporal scales of the hypoxia, (2) the relative contributions of inorganic and organic nutrients, (3) the influence of shifts in climatic and oceanographic processes, and (4) the roles of feedback interactions whereby O_2-sensitive biogeochemistry, trophic interactions, and habitat conditions influence the nutrient and algal dynamics that regulate O_2 levels.

Maji, R. and L. Smith, 2009, Quantitative analysis of seabed mixing and intertidal zone discharge in coastal aquifers, *Water Resour. Res.*, **45**, W11401, doi:10.1029/2008WR007532

Contaminant loading from an inland source zone to the nearshore marine environment is examined using a saturated-unsaturated simulation model which incorporates both the influence of the growth and the extinction of the seepage face in the intertidal zone and the inclusion of hydromechanical stress coupling due to tidal loading. The system analyzed represents a site where an unconfined

aquifer extends offshore with a broad intertidal zone. The volumetric discharge of groundwater in the intertidal zone dominates the discharge occurring beyond the low-tide line. For most of the cases examined, within the intertidal zone, the recirculated saline component of the discharge is greater than the freshwater component. The majority of the contaminant mass exits through the seepage face located above the instantaneous tide line. The peak contaminant loading rate occurs around the time of the falling midtide. At low tide, the contaminant loading rate is more than 2 orders of magnitude lower than the peak rates, even though groundwater discharge rates are highest as low tide is approached. Sensitivity studies indicate that the relative proportion of recirculated intertidal zone discharge to fresh intertidal zone discharge is most sensitive to the magnitude of the freshwater flux, the spatial variation of the outflow across the intertidal zone as influenced by anisotropy in hydraulic conductivity, and tidal pumping as influenced by specific storage. Dilution of contaminant concentrations due to mixing with seawater beneath the sediment-water interface is represented in terms of a dilution factor, defined relative to the onshore source concentration. For our base case, the dilution factor for the contaminant concentration averaged over one tidal cycle at the high-tide, midtide, and low-tide lines was 1.3, 3.9, and 560, respectively. The key factors determining contaminant dilution at the sediment interface are location within the intertidal zone and the vertical extent of the contaminant plume as it enters the intertidal zone.

1.2 Global Sea Level

Freeland, H. J. and D. Gilbert, 2009, Estimate of the Steric Contribution to Global Sea Level Rise from a Comparison of the WOCE One-Time Survey with 2006-2008 Argo Observations, *Atmos.-Ocean*, **47**(4): 292–298, doi:10.3137/OC312.2009

It is well known from observations by altimetric satellites (predominantly TOPEX/Poseidon and Jason-1) that global sea level is rising. What is less well known is exactly how the observed sea level rise is partitioned between a steric contribution (sea level rising because of changes in ambient temperature and salinity) and a contribution arising from the addition of new water mass to the oceans. Strictly speaking, such a separation is not possible because of the non-linearity in the equation of state for sea water, but in practice the non-linearities are sufficiently small to allow this separation as a very good first approximation. A careful comparison of the World Ocean Circulation Experiment (WOCE) one-time survey with recent observations by the Argo array indicate a steric component to sea level rise of 2.2 mm y–1 between the early 1990s and 2006 to 2008. This is a significantly larger rise rate than previously estimated and, along with recent estimates of melt rate from ice sheets, is in much closer agreement with the total rise rate as reported by altimetric satellites, 3.2 ± 0.4 mm y–1 over this period.

Oliver, E. C. J. and K. R. Thompson, 2010, Madden-Julian Oscillation and sea level: Local and remote forcing, *J. Geophys. Res.*, **115**, C01003, doi:10.1029/2009JC005337

The Madden-Julian Oscillation (MJO) is the dominant mode of atmospheric variability in the tropical atmosphere on intraseasonal time scales (i.e., weeks to

seasons). This study examines the connection between the MJO and global sea level measured by altimeters over the last 17 years. We first identify regions exhibiting a significant (both statistical and practical) relationship between sea level and the MJO. The first region consists of the equatorial Pacific and western coastal zones of North and South America. Consistent with previous studies, we identify wind-driven equatorially trapped Kelvin waves that propagate eastward along the equatorial Pacific and then transform into coastal trapped waves that propagate poleward along the western coasts of North and South America. The second region includes the shallow waters of the Gulf of Carpentaria (off Australia's north coast) and the adjacent Arafura and Timor seas. Setup by onshore winds is shown to be the dominant physical process. Finally, the northeastern Indian Ocean is shown to be a complex region involving a combination of equatorially trapped Kelvin waves, coastal trapped waves, and westward-propagating Rossby waves exhibiting characteristics of both local and remote forcing. The implications of the results for deep and coastal ocean forecasting are discussed.

1.3 Global Scale Modeling

Gertz, A., D. N. Straub, 2009, Near-Inertial Oscillations and the Damping of Midlatitude Gyres: A Modeling Study, *J. Phys. Oceanogr.*, **39**(9): 2338–2350

The classic wind-driven double-gyre problem for a homogeneous (unstratified) thin aspect ratio fluid is considered, but allowing for the flow to be depth dependent. Linear free modes for which the vertical wavenumber $k_z \neq 0$ are inertial oscillations, and they are excited with a large-scale stochastic forcing. This produces a background sea of near-inertial oscillations and their interaction with the vertically averaged flow is the focus of this study. In the absence of 3D forcing, the near-inertial motion vanishes and the barotropic quasigeostrophic system is recovered. With 3D forcing, 2D-to-3D energy transfers—coupled with a forward cascade of 3D energy and scale-selective dissipation—provide an energy dissipation mechanism for the gyres. The relative strength of this mechanism and a Rayleigh drag applied to the 2D flow depends on both the 3D forcing strength and the Rayleigh drag coefficient.

Griffiths, S. D. and W. R. Peltier, 2009, Modeling of Polar Ocean Tides at the Last Glacial Maximum: Amplification, Sensitivity, and Climatological Implications. *J. Clim.*, **22**, 2905–2924, doi:10.1175/2008JCLI2540.1

Diurnal and semidiurnal ocean tides are calculated for both the present day and the Last Glacial Maximum. A numerical model with complete global coverage and enhanced resolution at high latitudes is used including the physics of self-attraction and loading and internal tide drag. Modeled present-day tidal amplitudes are overestimated at the standard resolution, but the error decreases as the resolution increases. It is argued that such results, which can be improved in the future using higher-resolution simulations, are preferable to those obtained by artificial enhancement of dissipative processes. For simulations at the Last Glacial Maximum a new version of the ICE-5G topographic reconstruction is used along

with density stratification determined from coupled atmosphere–ocean climate simulations. The model predicts a significant amplification of tides around the Arctic and Antarctic coastlines, and these changes are interpreted in terms of Kelvin wave dynamics with the aid of an exact analytical solution for propagation around a polar continent or basin. These polar tides are shown to be highly sensitive to the assumed location of the grounding lines of coastal ice sheets, and the way in which this may contribute to an interaction between tides and climate change is discussed. Globally, the picture is one of energized semidiurnal tides at the Last Glacial Maximum, with an increase in tidal dissipation from present-day values, the dominant energy sink being the conversion to internal waves.

Haidvogel, D. B., Arango, H., Budgell, W. P., Cornuelle, B. D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W. R., Hermann, A. J., Lanerolle, L., Levin, J., McWilliams, J. C., Miller, A. J., Moore, A. M., Powell, T. M., Shchepetkin, A. F., Sherwood, C. R., Signell, R. P., Warner, J. C., Wilkin, J., 2008, Regional Ocean Forecasting in Terrain-following Coordinates: Model Formulation and Skill Assessment, *J. Comp. Phys.*, **227**: 3595–3624, doi:10.1016/j.jcp.2007.06.016

Systematic improvements in algorithmic design of regional ocean circulation models have led to significant enhancement in simulation ability across a wide range of space/time scales and marine system types. As an example, we briefly review the Regional Ocean Modeling System, a member of a general class of three-dimensional, free-surface, terrain-following numerical models. Noteworthy characteristics of the ROMS computational kernel include: consistent temporal averaging of the barotropic mode to guarantee both exact conservation and constancy preservation properties for tracers; redefined barotropic pressure-gradient terms to account for local variations in the density field; vertical interpolation performed using conservative parabolic splines; and higher-order, quasi-monotone advection algorithms. Examples of quantitative skill assessment are shown for a tidally driven estuary, an ice-covered high-latitude sea, a wind- and buoyancy-forced continental shelf, and a mid-latitude ocean basin. The combination of moderate-order spatial approximations, enhanced conservation properties, and quasi-monotone advection produces both more robust and accurate, and less diffusive, solutions than those produced in earlier terrain-following ocean models. Together with advanced methods of data assimilation and novel observing system technologies, these capabilities constitute the necessary ingredients for multi-purpose regional ocean prediction systems.

Hofmann, E., Druon, J.-N., Fennel, K., Friedrichs, M., Haidvogel, D., Lee, C., Mannino, A., McClain, C., Najjar, R., O'Reilly, J., Siewert, J., Pollard, D., Previdi, M., Seitzinger, S., Signorini, S., and Wilkin, J., 2008, Eastern U.S. Continental Shelf Carbon Budget: Integrating Models, Data Assimilation, and Analysis, *Oceanography*, **21**(1): 32–50

no abstract; first paragraph

The past two decades have seen the development of large multidisciplinary oceanographic programs that focus on understanding carbon cycling processes in coastal and oceanic environments. Synthesis and modeling activities typically followed toward the ends of these programs (e.g., Joint Global Ocean Flux

Study), usually long after the field experiments had been planned and carried out. A lesson from these programs was articulated in subsequent community planning reports (e.g., the Ocean Carbon Transport, Exchanges and Transformations Report [OCTET; http://www.msrc.sunysb.edu/octet/Workshop_Report.htm] and Ocean Carbon and Climate Change Report [OCCC; http://www.carboncyclescience.gov/documents/occc_is_2004.pdf]): future ocean carbon cycle research programs should promote close collaborations among scientists with expertise in measurement, data analysis, and numerical modeling at every stage of development— formative stages of hypothesis building, planning and execution of field programs, data analysis, numerical modeling, and synthesis.

Holloway, G., 2008, Observing global ocean topostrophy, *J. Geophys. Res.,* 113, C07054, doi:10.1029/2007JC004635

Recent publications have evaluated topostrophy, $\tau \equiv \mathbf{f} \times \mathbf{V} \cdot \nabla D$ where is $\mathbf{f}$ Coriolis, $\mathbf{V}$ is velocity, and ∇D is gradient of total depth, as a means of comparing models' circulations. Some results are striking. Comparing four global models, two with modest grid size and two with fine grids, Merryfield and Scott (2007) show that finer grid models are characterized by more positive τ, especially at greater depths and higher latitudes. Among nine Arctic Ocean models, Holloway et al. (2007) find τ in three of the models quite distinct from the other six, a result shown to depend upon subgrid eddy parameterization. From different choices of numerical method within the same model, Penduff et al. (2007) show that improved numerical representations support more positive τ. Can these model results be compared with observations? A global compilation has been prepared from 17120 current meter records, spanning 83087 current meter-months. The compilation tends to confirm modeling progress achieved by finer resolution, improved parameterizations and better representations. A new characterization of global ocean circulation emerges, with suggestive dynamical insights.

Maltrud, M. and G. Holloway, 2008, Implementing biharmonic neptune in a global eddying ocean model, *Ocean Modelling*, **21**(1-2): 22-34, doi:10.1016/j.ocemod.2007.11.003

Results are presented from a pair of global ocean circulation simulations whose horizontal resolution is fine enough to allow spontaneous formation of eddies. The only difference between the two runs is inclusion of a parameterization for the "neptune effect" [Holloway, G., 2004. From classical to statistical ocean dynamics. Surv. Geophys. 25, 203–219] in one of them, which tends to force the flow along local topographic contours. A Laplacian operator form of this force has been used for numerous studies with coarse (non-eddying) resolution models. For eddying resolutions, however, a biharmonic friction operator is commonly used to avoid strong damping at small scales. Here we extend the neptune parameterization to a biharmonic operator, and test how inclusion of neptune affects the fidelity of simulation.

Wakamatsu, T., M. G. G. Forem an, P. F. Cumm ins, J. Y. Cherniawsky, 2009, On the Influence of Random Wind Stress E rrors on the Four-Dimensional, Midlatitude Ocean Inverse Problem, *Mon. Wea. Rev.*, **137**(6): 1844–1862, doi:10.1175/2008MWR2621.1

The effects of the param eterized wind stress error cova riance function on the a priori error covariance of an ocean general circulation model (OGCM) are examined. These effects are diagnosed by co mputing the projection of the a priori model state error cov ariance matrix to sea surface height (SSH). The sensitivities of the a priori error covariance to the wind stress curl error are inferred from the a priori SSH error covariance and are show n to differ between the subpolar and subtropical gyres because of different contributions from barotropic and baroclinic ocean dynamics. The spatial st ructure of the SSH error cov ariance due to the wind stress error indi cates that the a priori m odel state error is determined indirectly by the wind stress cu rl error. The impact of this sensitiv ity on the solution of a four-dimensional inverse problem is inferred.

Stuhne, G. R. and W . R. Peltier, 2 009, An unstructured C-grid based method for 3-D global ocean d ynamics, *Ocean Modelling*, **28**(1-3): 97-105, doi:10.1016/j.ocemod.2008.11.005

In an earlier work, we describ ed how an unstructured grid num erical framework based on an energy-conserving Arakawa C-gr id discretization could be applied to ocean general circulation models (OGCMs). We discuss herein how we adapted our previously published rigid-lid, hydr ostatic, Boussinesq OGCM techniques to shallow-water and baroclinic free-su rface dynamics. The sim ulation of the global M_2 tide is proposed as a useful benchm ark for testing unstructured grid ocean models. Tidal simulations are m uch more manageable that full-fledged OGCM climate simulations, being based on si mpler physical assum ptions and parameterizations, and requiring less com putation time per test. W e demonstrate that the results of unstructured Arakawa C-grid sim ulations of the M_2 tide reproduce those of an equivalent regular grid discretization. Because unstructured grid methods carry a com putational overhead, however, their use can only be justified where reso lution must be concentr ated in localiz ed regions. The tides around Hudson's Bay are well-d escribed in a multi-scale context, and we show that strong discontinuities in m esh resolution do not appreciably distort the shallow-water tidal solution. Progressing to fully 3-D m odels, it is demonstrated that the barotropic M_2 tidal structure is consistently represented between m odels. Efforts to resolve the generation of baroclinic waves by the barotropic tide were, however, frustrated by the exis tence of a num erical mode that has been independently verified by other investigators working on similar methods. This

Merryfield, W. J., W.-S. Lee, G. J. Boer, V. V. Kharin, B. Pal, J. F. Scinocca, and G. M. Flato, 2010, The first coupled historic al forecasting project (CHFP1), *Atmos.-Ocean*, **48**(4): 263-283, doi:10.3137/AO1008.2010

A set of retrospectiv e multi-seasonal ensemble predictions based on a coupled global atmosphere-ocean model is described. These predictions, designated as the first coupled Historical Forecastin g Project or CHFP1, are produced with the climate model CGCM3.1 of the Canadian Centre for Clim ate Modelling and

Analysis using a very simple initialization procedure in which model sea surface temperatures (SSTs) are nudged toward the observed values during a multi-year period preceding the beginning of a forecast. This procedure, in addition to constraining initial SSTs to be close to observations, initializes equatorial Pacific zonal wind stress and thermocline depth with some skill. The ability of the subsequent forecasts to predict the evolution of SSTs, particularly in the equatorial Pacific, and surface air temperatures globally and in Canada is assessed. The results are compared with those of the second Historical Forecasting Project or HFP2, which uses a two-tier strategy in which model SSTs are externally specified. Skill of CHFP1 forecasts, though generally modest, exceeds those of HFP2 in some cases, despite the larger multi-model ensemble used in HFP2. CHFP1 represents an initial step in development directed toward a coupled operational seasonal prediction system for Canada.

Saenko, O. A, and W. G. Lee, 2010, Reorganization of the ocean overturning in a colder climate, *Geophys. Res. Lett.*, **37**, L04606, doi:10.1029/2010GL042417

Using a climate model, the effect of strong cooling on the ocean overturning circulation is investigated. The cooling has a profound impact. Essentially, the conversion of dense water of Northern Hemisphere origin to lighter water shifts from taking place predominantly in the Southern Ocean in the present day, relatively warm climate to the low-latitude oceans in the cold climate. The main factors contributing to this reorganization of oceanic overturning are related to the changes in oceanic stratification and wind field.

1.4 Climate Science

Matthews, H. D., and A. J. Weaver, 2010, Committed climate warming, *Nature Geoscience*, **3**, 142-143, doi:10.1038/ngeo813

The perception that future climate warming is inevitable stands at the centre of current climate-policy discussions. We argue that the notion of unavoidable warming owing to inertia in the climate system is based on an incorrect interpretation of climate science.

Rabalais, N. N., R. J. Díaz, L. A. Levin, R. E. Turner, D. Gilbert, and J. Zhang, 2010, Dynamics and distribution of natural and human-caused hypoxia, *Biogeosciences*, **7**: 585-619, doi:10.5194/bg-7-585-2010

Water masses can become undersaturated with oxygen when natural processes alone or in combination with anthropogenic processes produce enough organic carbon that is aerobically decomposed faster than the rate of oxygen re-aeration. The dominant natural processes usually involved are photosynthetic carbon production and microbial respiration. The re-supply rate is indirectly related to its isolation from the surface layer. Hypoxic water masses (<2 mg L^{-1}, or approximately 30% saturation) can form, therefore, under "natural" conditions, and are more likely to occur in marine systems when the water residence time is extended, water exchange and ventilation are minimal, stratification occurs, and where carbon production and export to the bottom layer are relatively high. Hypoxia has occurred through geological time and naturally occurs in oxygen

minimum zones, deep basins, eastern boundary upwelling systems, and fjords.

Hypoxia development and continuation in many areas of the world's coastal ocean is accelerated by human activities, especially where nutrient loading increased in the Anthropocene. This higher loading set in motion a cascading set of events related to eutrophication. The formation of hypoxic areas has been exacerbated by any combination of interactions that increase primary production and accumulation of organic carbon leading to increased respiratory demand for oxygen below a seasonal or permanent pycnocline. Nutrient loading is likely to increase further as population growth and resource intensification rises, especially with increased dependency on crops using fertilizers, burning of fossil fuels, urbanization, and waste water generation. It is likely that the occurrence and persistence of hypoxia will be even more widespread and have more impacts than presently observed.

Global climate change will further complicate the causative factors in both natural and human-caused hypoxia. The likelihood of strengthened stratification alone, from increased surface water temperature as the global climate warms, is sufficient to worsen hypoxia where it currently exists and facilitate its formation in additional waters. Increased precipitation that increases freshwater discharge and flux of nutrients will result in increased primary production in the receiving waters up to a point. The interplay of increased nutrients and stratification where they occur will aggravate and accelerate hypoxia. Changes in wind fields may expand oxygen minimum zones onto more continental shelf areas. On the other hand, not all regions will experience increased precipitation, some oceanic water temperatures may decrease as currents shift, and frequency and severity of tropical storms may increase and temporarily disrupt hypoxia more often.

The consequences of global warming and climate change are effectively uncontrollable at least in the near term. On the other hand, the consequences of eutrophication-induced hypoxia can be reversed if long-term, broad-scale, and persistent efforts to reduce substantial nutrient loads are developed and implemented. In the face of globally expanding hypoxia, there is a need for water and resource managers to act now to reduce nutrient loads to maintain, at least, the current status.

1.4.1 Attribution

Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D. J., Stone, D. A., Zhang, X. and Zwiers, F., 2010, Detection and attribution of climate change: a regional perspective, *Wiley Interdisciplinary Reviews: Climate Change*, **1**: 192–211, doi:10.1002/wcc.34

The Intergovernmental Panel on Climate Change fourth assessment report, published in 2007 came to a more confident assessment of the causes of global temperature change than previous reports and concluded that 'it is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent except Antarctica.' Since then, warming over Antarctica has also been attributed to human influence, and further evidence has accumulated

attributing a much wider range of climate changes to human activities. Such changes are broadly consistent with theoretical understanding, and climate model simulations, of how the planet is expected to respond. This paper reviews this evidence from a regional perspective to reflect a growing interest in understanding the regional effects of climate change, which can differ markedly across the globe. We set out the methodological basis for detection and attribution and discuss the spatial scales on which it is possible to make robust attribution statements. We review the evidence showing significant human-induced changes in regional temperatures, and for the effects of external forcings on changes in the hydrological cycle, the cryosphere, circulation changes, oceanic changes, and changes in extremes. We then discuss future challenges for the science of attribution. To better assess the pace of change, and to understand more about the regional changes to which societies need to adapt, we will need to refine our understanding of the effects of external forcing and internal variability.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P Gillett, S. Solomon, 2007, Detection of human influence on 20th century precipitation trends, *Nature*, **448:** 461-465, doi:10.1038/nature06025

Human influence on climate has been detected in surface air temperature, sea level pressure, free atmospheric temperature, tropopause height and ocean heat content. Human-induced changes have not, however, previously been detected in precipitation at the global scale, partly because changes in precipitation in different regions cancel each other out and thereby reduce the strength of the global average signal. Models suggest that anthropogenic forcing should have caused a small increase in global mean precipitation and a latitudinal redistribution of precipitation, increasing precipitation at high latitudes, decreasing precipitation at sub-tropical latitudes, and possibly changing the distribution of precipitation within the tropics by shifting the position of the Intertropical Convergence Zone. Here we compare observed changes in land precipitation during the twentieth century averaged over latitudinal bands with changes simulated by fourteen climate models. We show that anthropogenic forcing has had a detectable influence on observed changes in average precipitation within latitudinal bands, and that these changes cannot be explained by internal climate variability or natural forcing. We estimate that anthropogenic forcing contributed significantly to observed increases in precipitation in the Northern Hemisphere mid-latitudes, drying in the Northern Hemisphere subtropics and tropics, and moistening in the Southern Hemisphere subtropics and deep tropics. The observed changes, which are larger than estimated from model simulations, may have already had significant effects on ecosystems, agriculture and human health in regions that are sensitive to changes in precipitation, such as the Sahel.

Zwiers, F. W. and G. C. Hegerl, 2008, Climate change: attributing cause and effect, *Nature*, **453**: 296-297, doi:10.1038/453296a

No abstract; this is the first 2 paragraphs

The climate is changing, and so are aspects of the world's physical and biological systems. It is no easy matter to link cause and effect — the latest attack on the problem brings the power of meta-analysis to bear.

The article by Rosenzweig and colleagues[1] that appears on page 353 of this issue is the first to formally link observed global changes in physical and biological systems to human-induced climate change, predominantly from increasing greenhouse gases. By surveying a huge literature, Rosenzweig *et al*. demonstrate that changes in physical and biological systems are pervasive; that these impacts lie mainly in directions consistent with warming of the climate system; and that, at least partly, they are likely to be the result of climate change caused by increasing concentrations of greenhouse gases.

1.4.2 Climate Modelling

Eby, M., K. Zickfeld, A. Montenegro, D. Archer, K. J. Meissner, and A. J. Weaver, 2009, Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations, *J. Clim.*, **22**: 2501-2511, doi:10.1175/2008JCLI2554.1

Multimillennial simulations with a fully coupled climate–carbon cycle model are examined to assess the persistence of the climatic impacts of anthropogenic CO_2 emissions. It is found that the time required to absorb anthropogenic CO_2 strongly depends on the total amount of emissions; for emissions similar to known fossil fuel reserves, the time to absorb 50% of the CO_2 is more than 2000 yr. The long-term climate response appears to be independent of the rate at which CO_2 is emitted over the next few centuries. Results further suggest that the lifetime of the surface air temperature anomaly might be as much as 60% longer than the lifetime of anthropogenic CO_2 and that two-thirds of the maximum temperature anomaly will persist for longer than 10 000 yr. This suggests that the consequences of anthropogenic CO_2 emissions will persist for many millennia.

Fyke, J., A. J. Weaver, D. Pollard, M. Eby, L. Carter, and A. Mackintosh, 2010, A new coupled ice sheet-climate model: description and sensitivity to Eemian, Last Glacial Maximum, late Holocene and modern conditions. *Geoscientific Model Development Discussion*, **3**: 1223-1269, doi:10.5194/gmdd-3-1223-2010

The need to better understand long-term climate/ice sheet feedback loops is motivating efforts to couple ice sheet models into Earth System models which are capable of long-timescale simulations. In this paper we describe a coupled model, that consists of the University of Victoria Earth System Climate Model (UVic ESCM) and the Pennsylvania State University Ice model (PSUI). The climate model generates a surface mass balance (SMB) field via a sub-gridded surface energy/moisture balance model that resolves narrow ice sheet ablation zones. The ice model returns revised elevation, surface albedo and ice area fields, plus coastal fluxes of heat and moisture. An arbitrary number of ice sheets can be simulated, each on their own high-resolution grid and each capable of synchronous or asynchronous coupling with the overlying climate model. The model is designed to conserve global heat and moisture. In the process of improving model performance we developed a procedure to account for modelled surface air

temperature (SAT) biases within the energy/moisture balance surface model and improved the UVic ESCM snow surface scheme through addition of variable albedos and refreezing over the ice sheet.

Fyke, J. G., L. Carter, A. Mackintosh, A. J. Weaver, and K. J. Meissner, 2010, Surface melting over ice shelves and ice sheets as assessed from modelled surface air temperatures, J. of Clim., **23**, 1929-1936, doi:10.1175/2009JCLI3122.1

Summer surface melting plays an important role in the evolution of ice shelves and their progenitor ice sheets. To explore the magnitude of surface melt occurring over modern ice shelves and ice sheets in a climate scenario forced by anthropogenic emissions of carbon dioxide (CO_2), a coupled climate model was used to simulate the distribution of summer melt at high latitudes and project the future evolution of high-melt regions in both hemispheres. Forcing of the climate model with CO_2 emissions resulting from combustion of the present-day fossil-fuel resource base resulted in expansion of high-melt regions, as defined by the contour marking 200 positive degree-days per year, in the Northern Hemisphere and the Antarctic Peninsula and the introduction of high summer melt over the Ross, Ronne-Filchner, and Amery ice shelves as well as a large portion of the West Antarctic Ice Sheet (WAIS) and most of the Greenland Ice Sheet (GIS) by the year 2500. Capping CO_2 concentrations at present-day levels avoided significant summer melt over the large Antarctic shelves, the WAIS, and much of the GIS.

Le Clainche, Y., A. F. Vézina, M. Levasseur, R. Cropp, J. Gunson, S. Vallina, M. Vogt, C. Lancelot, I. Allen, S. Archer, L. Bopp, C. Deal, S. Elliott, M. Jin, G. Malin, V. Schoemann, R. Simò, K. Six, and J. Stefels, 2010, A first appraisal of prognostic ocean DMS models and prospects for their use in climate models, *Global Biogeochem. Cycles*, **24**, GB3021, doi:10.1029/2009GB003721

Ocean dimethylsulfide (DMS) produced by marine biota is the largest natural source of atmospheric sulfur, playing a major role in the formation and evolution of aerosols, and consequently affecting climate. Several dynamic process-based DMS models have been developed over the last decade, and work is progressing integrating them into climate models. Here we report on the first international comparison exercise of both 1D and 3D prognostic ocean DMS models. Four global 3D models were compared to global sea surface chlorophyll and DMS concentrations. Three local 1D models were compared to three different oceanic stations (BATS, DYFAMED, OSP) where available time series data offer seasonal coverage of chlorophyll and DMS variability. Two other 1D models were run at one site only. The major point of divergence among models, both within 3D and 1D models, relates to their ability to reproduce the summer peak in surface DMS concentrations usually observed at low to mid- latitudes. This significantly affects estimates of global DMS emissions predicted by the models. The inability of most models to capture this summer DMS maximum appears to be constrained by the basic structure of prognostic DMS models: dynamics of DMS and dimethylsulfoniopropionate (DMSP), the precursor of DMS, are slaved to the parent ecosystem models. Only the models which include environmental

effects on DMS fluxes independently of ecological dynamics can reproduce this summer mismatch between chlorophyll and DMS. A major conclusion of this exercise is that prognostic DMS models need to give more weight to the direct impact of environmental forcing (e.g., irradiance) on DMS dynamics to decouple them from ecological processes.

Lewis, J.P., A. J. Weaver and M. Eby, 2007, Snowball versus slushball Earth: Dynamic versus nondynamic sea ice? *J. Geophys. Res.*, **112**, C11014, doi:10.1029/2006JC004037

Modeling studies of the Neoproterozoic snowball Earth offer two variations for snowball conditions, the original "hard" snowball Earth where the ocean is completely covered by sea ice, and an alternate slushball Earth or "soft" snowball, where there is an equatorial oasis of open water. We use the University of Victoria Earth System Climate Model to show that the soft snowball result is only possible when dynamics are excluded from the sea ice component of the model. Using a purely thermodynamic sea ice component the soft snowball condition is stable, whereas with a dynamic and thermodynamic sea ice component it is not. As the behavior of dynamic sea ice largely depends on wind stress, we compare simulations using two different wind fields: a zonally averaged present-day wind field and a wind field derived by a general circulation model, the Fast Ocean Atmosphere Model, using Neoproterozoic conditions. Another consequence of using dynamic sea ice is that the sea ice does not become sufficiently thick to flow under its own weight when there is open water; this suggests that sea glacier dynamics are not important for snowball inception.

Meissner, K. J., M. Eby, A. J. Weaver, and O. A. Saenko, 2008, CO_2 threshold for millennial-scale oscillations in the climate system: implications for global warming scenarios, *Clim. Dyn.*, **30**: 161-174, doi:10.1007/s00382-007-0279-0

We present several equilibrium runs under varying atmospheric CO_2 concentrations using the University of Victoria Earth System Climate Model (UVic ESCM). The model shows two very different responses: for CO_2 concentrations of 400 ppm or lower, the system evolves into an equilibrium state. For CO_2 concentrations of 440 ppm or higher, the system starts oscillating between a state with vigorous deep water formation in the Southern Ocean and a state with no deep water formation in the Southern Ocean. The *flushing* events result in a rapid increase in atmospheric temperatures, degassing of CO_2 and therefore an increase in atmospheric CO_2 concentrations, and a reduction of sea ice cover in the Southern Ocean. They also cool the deep ocean worldwide. After the flush, the deep ocean warms slowly again and CO_2 is taken up by the ocean until the stratification becomes unstable again at high latitudes thousands of years later. The existence of a threshold in CO_2 concentration which places the UVic ESCM in either an oscillating or non-oscillating state makes our results intriguing. If the UVic ESCM captures a mechanism that is present and important in the real climate system, the consequences would comprise a rapid increase in atmospheric carbon dioxide concentrations of several tens of ppm, an increase in global surface temperature of the order of 1–2°C, local temperature changes of the order

of 6°C and a profound change in ocean stratification, deep water temperature and sea ice cover.

Min, S.-K., X. Zhang, F. W. Zwiers, P. Friederichs, and A. Hense, 2009, Signal detectability in extreme precipitation changes assessed from twentieth century climate simulations, *Clim. Dyn.*, **32**: 95–111, doi:10.1007/s00382-008-0376-8

This study assesses the detectability of external influences in changes of precipitation extremes in the twentieth century, which is explored through a perfect model analysis with an ensemble of coupled global climate model (GCM) simulations. Three indices of precipitation extremes are defined from the generalized extreme value (GEV) distribution: the 20-year return value (P_{20}), the median (P_m), and the cumulative probability density as a probability-based index (*PI*). Time variations of area-averages of these three extreme indices are analyzed over different spatial domains from the globe to continental regions. Treating all forcing simulations (ALL; natural plus anthropogenic) of the twentieth century as observations and using a preindustrial control run (CTL) to estimate the internal variability, the amplitudes of response patterns to anthropogenic (ANT), natural (NAT), greenhouse-gases (GHG), and sulfate aerosols (SUL) forcings are estimated using a Bayesian decision method. Results show that there are *decisively* detectable ANT signals in global, hemispheric, and zonal band areas. When only land is considered, the global and hemispheric detection results are unchanged, but detectable ANT signals in the zonal bands are limited to low latitudes. The ANT signals are also detectable in the P_m and *PI* but not in P_{20} at continental scales over Asia, South America, Africa, and Australia. This indicates that indices located near the center of the GEV distribution (P_m and *PI*) may give better signal-to-noise ratio than indices representing the tail of the distribution (P_{20}). GHG and NAT signals are also detectable, but less robustly for more limited extreme indices and regions. These results are largely insensitive when model data are masked to mimic the availability of the observed data. An imperfect model analysis in which fingerprints are obtained from simulations with a different GCM suggests that ANT is robustly detectable only at global and hemispheric scales, with high uncertainty in the zonal and continental results.

Montenegro, A., M. Eby, A. J. Weaver, and S.R. Jayne, 2007, Response of a climate model to tidal mixing parameterization under present day and Last Glacial Maximum conditions, *Ocean Modelling*, **19**: 125-137, doi:10.1016/j.ocemod.2007.06.009

Experiments with a climate model were conducted under present day and last glacial maximum conditions in order to examine the model's response to a vertical mixing scheme based on internal tide energy dissipation. The increase in internal tide energy flux caused by a ~120 m reduction in sea level had the expected effect on diffusivity values, which were higher under lower sea level conditions. The impact of this vertical diffusivity change on the Atlantic meridional overturning is not straightforward and no clear relationship between diffusivity and overturning is found. There exists a weak positive correlation between overturning and changes to the power consumed by vertical mixing. Most of the climatic response generated by sea level change was not related to

alterations in the internal tide energy flux but rather to the direct change in sea level itself.

Montenegro, A., V. Brovkin, M. Eby, D. Archer, and A. J. Weaver, 2007, Long term fate of anthropogenic carbon, *Geophys. Res. Lett.*, **34**, L19707, doi:10.1029/2007GL030905

Two earth-system models of intermediate complexity are used to study the long term response to an input of 5000 Pg of carbon into the atmosphere. About 75% of CO_2 emissions have an average perturbation lifetime of 1800 years and 25% have lifetimes much longer than 5000 years. In the simulations, higher levels of atmospheric CO_2 remain in the atmosphere than predicted by previous experiments and the average perturbation lifetime of atmospheric CO_2 for this level of emissions is much longer than the 300–400 years proposed by other studies. At year 6800, CO_2 concentrations between about 960 to 1440 ppmv result in global surface temperature increases between 6 and 8°C. There is also significant surface ocean acidification, with pH decreasing from 8.16 to 7.46 units between years 2000 and 2300.

Mysak, L. A., 2008, Glacial inceptions: Past and future, *Atmosphere-Ocean*, **46**: 317-341, doi:10.3137/ao.460303

The realistic simulation of northern hemisphere glacial inceptions, which occurred during the Quaternary period, has challenged scores of climate theoreticians and modellers. After reviewing the Milankovitch theory of glaciation, a number of earlier modelling studies of the last glacial inception (LGI) which have employed either high-resolution General Circulation Models (GCMs) or Earth system Models of Intermediate Complexity (EMICs) are described. The latter class of models has been developed over the past two decades in order to investigate the many interactions and feedbacks among the geophysical and biospheric components of the Earth system that take place over long time scales.

Sedlacek, J., J.-F. Lemieux, L. A. Mysak, L. B. Tremblay, and D. M. Holland, 2007, The granular sea ice model in spherical coordinates and its application to a global climate model. *J. Clim*, **20**: 5946-5961, doi:10/1175/2007JCLI1664.1

The granular sea ice model (GRAN) from Tremblay and Mysak is converted from Cartesian to spherical coordinates. In this conversion, the metric terms in the divergence of the deviatoric stress and in the strain rates are included. As an application, the GRAN is coupled to the global Earth System Climate Model from the University of Victoria. The sea ice model is validated against standard datasets. The sea ice volume and area exported through Fram Strait agree well with values obtained from in situ and satellite-derived estimates. The sea ice velocity in the interior Arctic agrees well with buoy drift data. The thermodynamic behavior of the sea ice model over a seasonal cycle at one location in the Beaufort Sea is validated against the Surface Heat Budget of the Arctic Ocean (SHEBA) datasets. The thermodynamic growth rate in the model is almost twice as large as the observed growth rate, and the melt rate is 25% lower than observed. The larger growth rate is due to thinner ice at the beginning of the SHEBA period and the absence of internal heat storage in the ice layer in the

model. The simulated lower summer melt is due to the smaller-than-observed surface melt.

Sedlacek, J. and L. A. Mysak, 2008a, A model study of the Little Ice Age and beyond: changes in ocean heat content, hydrography, and circulation, *Clim. Dyn.*, **33**(4): 461-475, doi:10.1007/s00382-008-0503-6

The Earth System Climate Model from the University of Victoria is used to investigate changes in ocean properties such as heat content, temperature, salinity, density and circulation during 1500 to 2000, the time period which includes the Little Ice Age (LIA) (1500-1850) and the industrial era (1850-2000). We force the model with two different wind-stress fields which take into account the North Atlantic Oscillation. Furthermore, temporally varying radiative forcings due to volcanic activity, insolation changes and greenhouse gas changes are also implemented. We find that changes in the upper ocean (0-300 m) heat content are mainly driven by changes in radiative forcing, except in the polar regions where the varying wind-stress induces changes in ocean heat content. In the full ocean (0-3,000 m) the wind-driven effects tend to reduce, prior to 1700, the downward trend in the ocean heat content caused by the radiative forcing. Afterwards no dynamical effect is visible. The colder ocean temperatures in the top 600 m during the LIA are caused by changes in radiative forcing, while the cooling at the bottom is wind-driven. The changes in salinity are small except in the Arctic Ocean. The reduced salinity content in the subsurface Arctic Ocean during the LIA is a result from reduced wind-driven inflow of saline water from the North Atlantic. At the surface of the Arctic Ocean the changes in salinity are caused by changes in sea-ice thickness. The changes in density are a composite picture of the temperature and salinity changes. Furthermore, changes in the meridional overturning circulation (MOC) are caused mainly by a varying wind-stress forcing; the additional buoyancy driven changes due to the radiative forcings are small. The simulated MOC is reduced during the LIA as compared to the industrial era. On the other hand, the ventilation rate in the Southern Ocean is increased during the LIA.

Sedlacek, J. and L.A. Mysak, 2008b. Sensitivity of sea ice to wind stress and radiative forcing since 1500: A model study of the Little Ice Age and beyond, *Clim. Dyn.*, **32**(6): 817-831, doi:10.1007/s00382-008-0406-6

Three different reconstructed wind-stress fields which take into account variations of the North Atlantic Oscillation, one general circulation model wind-stress field, and three radiative forcings (volcanic activity, insolation changes and greenhouse gas changes) are used with the UVic Earth System Climate Model to simulate the surface air temperature, the sea-ice cover, and the Atlantic meridional overturning circulation (AMOC) since 1500, a period which includes the Little Ice Age (LIA). The simulated Northern Hemisphere surface air temperature, used for model validation, agrees well with several temperature reconstructions. The simulated sea-ice cover in each hemisphere responds quite differently to the forcings. In the Northern Hemisphere, the simulated sea-ice area and volume during the LIA are larger than the present-day area and volume. The wind-driven changes in sea-ice

area are about twice as large as those due to thermodynamic (i.e., radiative) forcing. For the sea-ice volume, changes due to wind forcing and thermodynamics are of similar magnitude. Before 1850, the simulations suggest that volcanic activity was mainly responsible for the thermodynamically produced area and volume changes, while after 1900 the slow greenhouse gas increase was the main driver of the sea-ice changes. Changes in insolation have a small effect on the sea ice throughout the integration period. The export of the thicker sea ice during the LIA has no significant effect on the maximum strength of the AMOC. A more important process in altering the maximum strength of the AMOC and the sea-ice thickness is the wind-driven northward ocean heat transport. In the Southern Hemisphere, there are no visible long-term trends in the simulated sea-ice area or volume since 1500. The wind-driven changes are roughly four times larger than those due to radiative forcing. Prior to 1800, all the radiative forcings could have contributed to the thermodynamically driven changes in area and volume. In the 1800s the volcanic forcing was dominant, and during the first part of the 1900s both the insolation changes and the greenhouse gas forcing are responsible for thermodynamically produced changes. Finally, in the latter part of the 1900s the greenhouse gas forcing is the dominant factor in determining the sea-ice changes in the Southern Hemisphere.

Skvortsov, A., M. Eby, and A. J. Weaver, 2009, Snow cover validation and sensitivity to CO_2 in the UVic ESCM, *Atmos-Ocean.*, **47**(3): 224-237, doi:10.3137/AO929.2009

The University of Victoria's (UVic) Earth System Climate model is used to conduct equilibrium atmospheric CO_2 sensitivity experiments over the range 200–1600 ppm in order to explore changes in northern hemisphere snow cover and feedbacks on terrestrial surface air temperature (SAT). Simulations of warmer climates predict a retreat of snow cover over northern continents, in a northeasterly direction. The decline in northern hemisphere global snow mass is estimated to reach 33% at 600 ppm and 54% at 1200 ppm. In the most northerly regions, annual mean snow depth increases for simulations with CO_2 levels higher than present day. The shift in the latitude of maximum snowfall is estimated to be inversely proportional to the CO_2 concentration. The northern hemisphere net shortwave radiation changes are found to be greater over land than over the ocean, suggesting a stronger albedo feedback from changes in terrestrial snow cover than from changes in sea ice. Results also reveal high sensitivity of the snow mass balance under low CO_2 conditions. The amplification feedback (defined as the zonal SAT anomaly caused by doubling CO_2 divided by the equatorial anomaly) is greatest for scenarios with less than 300 ppm, reaching 1.9 at the pole for 250 ppm. The stronger feedback is attributed to the significant albedo changes over land areas. The simulation with 200 ppm triggers continuous accumulation of snow ('glaciation') in regions which, according to paleo-reconstructions, were covered by ice during the last glacial cycle (the Canadian Arctic, Scandinavia, and the Taymir Peninsula).

Weaver, A. J., K. Zickfeld, A. Montenegro and M. Eby, 2007, Long term climate implications of 2050 emission reduction targets, *Geophys. Res. Lett.*, **34**, L19703, doi:10.1029/2007GL031018

A coupled atmosphere-ocean-carbon cycle model is used to examine the long term climate implications of various 2050 greenhouse gas emission reduction targets. All emission targets considered with less than 60% global reduction by 2050 break the 2.0°C threshold warming this century, a number that some have argued represents an upper bound on manageable climate warming. Even when emissions are stabilized at 90% below present levels at 2050, this 2.0°C threshold is eventually broken. Our results suggest that if a 2.0°C warming is to be avoided, direct CO_2 capture from the air, together with subsequent sequestration, would eventually have to be introduced in addition to sustained 90% global carbon emissions reductions by 2050.

1.4.3 Modes of Climate Variability: eg. El Nino-Southern Oscillation (ENSO)

Cheng, Y., Y. Tang, X. Zhou, P. Jackson, and D. Chen, 2009, Further analysis of singular vector and ENSO predictability in the Lamont model—Part I: singular vector and the control factors, *Clim. Dyn.*, **35**(5): 807-826, doi:10.1007/s00382-009-0595-7

In this study, singular vector analysis was performed for the period from 1856 to 2003 using the latest Zebiak–Cane model version LDEO5. The singular vector, representing the optimal growth pattern of initial perturbations/errors, was obtained by perturbing the constructed tangent linear model of the Zebiak–Cane model. Variations in the singular vector and singular value, as a function of initial time, season, ENSO states, and optimal period, were investigated. Emphasis was placed on exploring relative roles of linear and nonlinear processes in the optimal perturbation growth of ENSO, and deriving statistically robust conclusions using long-term singular vector analysis. It was found that the first singular vector is dominated by a west–east dipole spanning most of the equatorial Pacific, with one center located in the east and the other in the central Pacific. Singular vectors are less sensitive to initial conditions, i.e., independence of seasons and decades; while singular values exhibit a strong sensitivity to initial conditions. The dynamical diagnosis shows that the total linear and nonlinear heating terms play opposite roles in controlling the optimal perturbation growth, and that the linear optimal perturbation is more than twice as large as the nonlinear one. The total linear heating causes a warming effect and controls two positive perturbation growth regions: one in the central Pacific and the other in the eastern Pacific; whereas the total linearized nonlinear advection brings a cooling effect controlling the negative perturbation growth in the central Pacific.

Cheng, Y., Y. Tang, P. Jackson, D. Chen, and Z. Deng, 2010, Ensemble Construction and Verification of the Probabilistic ENSO Prediction in the LDEO5 Model, *J. Clim.*, **23**,(20): 5476–5497, doi:10.1175/2010JCLI3453.1

El Niño–Southern Oscillation (ENSO) retrospective ensemble-based probabilistic predictions were performed for the period of 1856–2003 using the Lamont-Doherty Earth Observatory, version 5 (LDEO5), model. To obtain more reliable

and skillful ENSO probabilistic predictions, first, four ensemble construction strategies were investigated: (i) the optimal initial perturbation with singular vector of sea surface temperature anomaly (SSTA), (ii) the realistic high-frequency anomalous winds, (iii) the stochastic optimal pattern of anomalous winds, and (iv) a combination of the first and the third strategy. Second, verifications were conducted to examine the reliability and resolution of the probabilistic forecasts provided by the four methods. Results suggest that reliability of ENSO probabilistic forecast is more sensitive to the choice of ensemble construction strategy than the resolution, and a reliable and skillful ENSO probabilistic prediction system may not necessarily have the best deterministic prediction skills. Among these ensemble construction methods, the fourth strategy produces the most reliable and skillful ENSO probabilistic prediction, benefiting from the joint contributions of the stochastic optimal winds and the singular vector of SSTA. In particular, the stochastic optimal winds play an important role in improving the ENSO probabilistic predictability for the LDEO5 model.

Cheng, Y., Y. Tang, X. Zhou, P. Jackson, and D. Chen, 2010, Further analysis of singular vector and ENSO predictability in the Lamont model—Part I: singular vector and the control factors, **35**(5): 807-826, doi:10.1007/s00382-009-0595-7

In this study, singular vector analysis was performed for the period from 1856 to 2003 using the latest Zebiak–Cane model version LDEO5. The singular vector, representing the optimal growth pattern of initial perturbations/errors, was obtained by perturbing the constructed tangent linear model of the Zebiak–Cane model. Variations in the singular vector and singular value, as a function of initial time, season, ENSO states, and optimal period, were investigated. Emphasis was placed on exploring relative roles of linear and nonlinear processes in the optimal perturbation growth of ENSO, and deriving statistically robust conclusions using long-term singular vector analysis. It was found that the first singular vector is dominated by a west–east dipole spanning most of the equatorial Pacific, with one center located in the east and the other in the central Pacific. Singular vectors are less sensitive to initial conditions, i.e., independence of seasons and decades; while singular values exhibit a strong sensitivity to initial conditions. The dynamical diagnosis shows that the total linear and nonlinear heating terms play opposite roles in controlling the optimal perturbation growth, and that the linear optimal perturbation is more than twice as large as the nonlinear one. The total linear heating causes a warming effect and controls two positive perturbation growth regions: one in the central Pacific and the other in the eastern Pacific; whereas the total linearized nonlinear advection brings a cooling effect controlling the negative perturbation growth in the central Pacific.

d'Orgeville, M. and W. R. Peltier, 2007, On the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation: Might they be related?, *Geophys. Res. Lett.*, **34**, L23705, doi:10.1029/2007GL031584

The nature of the Pacific Decadal Oscillation (PDO) is investigated based upon analyses of sea surface temperature observations over the last century. The PDO

is suggested to be comprised of a 20 year quasi-periodic oscillation and a lower frequency component with a characteristic timescale of 60 years. The 20 year quasi-periodic oscillation is clearly identified as a phase locked signal at the eastern boundary of the Pacific basin, which could be interpreted as the signature of an ocean basin mode. We demonstrate that the 60 year component of the PDO is strongly time-lag correlated with the Atlantic Multidecadal Oscillation (AMO). On this timescale the AMO is shown to lead the PDO by approximately 13 years or to lag the PDO by 17 years. This relation suggests that the AMO and the 60 year component of the PDO are signatures of the same oscillation cycle.

Fyfe, J. C., N. P. Gillett, and D. W. J. Thompson, 2010, Comparing variability and trends in observed and modelled global-mean surface temperature, *Geophys. Res. Lett.*, **37**, L16802, doi:10.1029/2010GL044255

The observed evolution of the global-mean surface temperature over the twentieth century reflects the combined influences of natural variations and anthropogenic forcing, and it is a primary goal of climate models to represent both. In this study we isolate, compare, and remove the following natural signals in observations and in climate models: dynamically induced atmospheric variability, the El Niño-Southern Oscillation, and explosive volcanic eruptions. We make clear the significant model-to-model variability in estimates of the variance in global-mean temperature associated with these natural signals, especially associated with the El Niño-Southern Oscillation and explosive volcanic eruptions. When these natural signals are removed from time series of global-mean temperature, the statistical uncertainty in linear trends from 1950 to 2000 drops on average by about half. Hence, the results make much clearer than before where some model estimates of global warming significantly deviate from observations and where others do not.

Lin, H., G. Brunet, and J. S. Fontecilla, 2010, Impact of the Madden-Julian Oscillation on the intraseasonal forecast skill of the North Atlantic Oscillation, *Geophys. Res. Lett.*, **37**, L19803, doi:10.1029/2010GL044315

Using the output of the intraseasonal hindcast experiment conducted with the GEM global atmospheric model during 24 extended winters, the association between the forecast skill of the NAO and the amplitude and phase of the MJO in the initial condition is investigated. It is found that with a lead time up to about one month the NAO forecast skill is significantly influenced by the existence of the MJO signal in the initial condition. A strong MJO leads to a better NAO forecast skill than a weak MJO. An initial state with an MJO phase corresponding to a dipole tropical convection anomaly in the eastern Indian Ocean and western Pacific favors a more skillful NAO forecast than an MJO phase with a single tropical convection anomaly near 120°E. These results indicate that it is possible to increase the skill of the NAO and the extratropical surface air temperature intraseasonal forecast with an improved tropical initialization, a better prediction of the tropical MJO and a better representation of the tropical-extratropical interaction in dynamical models.

Tang, Y., H. Lin, J. Derome, and M. K. Tippett, 2007, A predictability measure applied to seasonal predictions of the Arctic Oscillation, *J. Clim.*, **20:** 4733-4750, doi:10.1175/JCLI4276.1

In this study, ensemble seasonal predictions of the Arctic Oscillation (AO) were conducted for 51 winters (1948–98) using a simple global atmospheric general circulation model. A means of estimating a priori the predictive skill of the AO ensemble predictions was developed based on the relative entropy (*R*) of information theory, which is a measure of the difference between the forecast and climatology probability density functions (PDFs). Several important issues related to the AO predictability, such as the dominant precursors of forecast skill and the degree of confidence that can be placed in an individual forecast, were addressed. It was found that *R* is a useful measure of the confidence that can be placed on dynamical predictions of the AO. When *R* is large, the prediction is likely to have a high confidence level whereas when *R* is small, the prediction skill is more variable. A small *R* is often accompanied by a relatively weak AO index. The value of *R* is dominated by the predicted ensemble mean. The relationship identified here, between model skills and the *R* of an ensemble prediction, offers a practical means of estimating the confidence level of a seasonal forecast of the AO using the dynamical model. Through an analysis of the global sea surface temperature (SST) forcing, it was found that the winter AO-related *R* is correlated significantly with the amplitude of the SST anomalies over the tropical central Pacific and the North Pacific during the previous October. A large value of *R* is usually associated with strong SST anomalies in the two regions, whereas a poor prediction with a small *R* indicates that SST anomalies are likely weak in these two regions and the observed AO anomaly in the specific winter is likely caused by atmospheric internal dynamics.

Tang, Y., Z. Deng, X. Zhou, Y. Cheng, and D. Chen, 2008, Interdecadal Variation of ENSO Predictability in Multiple Models, *J. Clim.*, **21**(18): 4811–4833, doi:10.1175/2008JCLI2193.1

In this study, El Niño–Southern Oscillation (ENSO) retrospective forecasts were performed for the 120 yr from 1881 to 2000 using three realistic models that assimilate the historic dataset of sea surface temperature (SST). By examining these retrospective forecasts and corresponding observations, as well as the oceanic analyses from which forecasts were initialized, several important issues related to ENSO predictability have been explored, including its interdecadal variability and the dominant factors that control the interdecadal variability.

The prediction skill of the three models showed a very consistent interdecadal variation, with high skill in the late nineteenth century and in the middle–late twentieth century, and low skill during the period from 1900 to 1960. The interdecadal variation in ENSO predictability is in good agreement with that in the signal of interannual variability and in the degree of asymmetry of ENSO system. A good relationship was also identified between the degree of asymmetry and the signal of interannual variability, and the former is highly related to the latter. Generally, the high predictability is attained when ENSO signal streng th

and the degree of asymmetry are enhanced, and vice versa. The atmospheric noise generally degrades overall prediction skill, especially for the skill of mean square error, but is able to favor some individual prediction cases. The possible reasons why these factors control ENSO predictability were also discussed.

Tang, Y., H. Lin, and A. M. Moore, 2008, Measuring the potential predictability of ensemble climate predictions, *J. Geophys. Res.*, **113**, D04108, doi:10.1029/2007JD008804

In this study, ensemble predictions of the El Niño Southern Oscillation (ENSO) and the Arctic Oscillation (AO) were conducted using two coupled models and two atmospheric circulation models, respectively, as well as various ensemble schemes. Several measures of potential predictability including ensemble mean square (EM^2), ensemble spread and the ratio of signal-to-noise were explored in terms of their ability of estimating a priori the predictive skill of the ENSO and AO ensemble predictions. The emphasis was put on examining the relationship between the measures of predictability that do not use observations and the model prediction skill of correlation and mean square error (MSE) that make use of observations. The relationship identified here offers a practical means of estimating the potential predictability and the confidence level of an individual prediction. It was found that the EM^2 is a better indicator of the actual skill of ensemble ENSO and AO prediction than the ratio of signal-to-noise. When correlation-based metrics are used, the prediction skill is likely to be a linear function of EM^2, i.e., the larger the EM^2 the higher skill the prediction; whereas when *MSE*-based metrics are used, a "triangular relationship" is suggested between them, namely, that when EM^2 is large, the prediction is likely to be reliable whereas when EM^2 is small the prediction skill is highly variable. In contrast with ensemble weather prediction (NWP), the ensemble spread is not a good predictor in quantifying climate prediction skill in the models used in this study because the forced response may be much larger than the noise in the climate timescales compared to the NWP. A statistical framework was proposed to explain why EM^2 is a good indicator of actual prediction skill in the ensemble climate predictions.

Tang, Y. and Z. Deng, 2010b, Low-dimensional nonlinearity of ENSO and its impact on predictability, *Physica D: Nonlinear Phenomena*, **239**(5): 258-268, doi:10.1016/j.physd.2009.11.006

Using a hybrid coupled model, we perform a bred vector (BV) analysis and retrospective ENSO (El Niño and the Southern Oscillation) forecast for the period from 1881 to 2000. The BV local dimension and BV-skewness inherent to the intensity of nonlinearity are analyzed. Emphasis is placed on exploring the nature of the low-dimensional nonlinearity of the ENSO system and the relationship between BV-skewness and model prediction skills. The results show that ENSO is a low-dimensional nonlinear system, and the BV-skewness is a good measure of its predictability at the decadal/interdecadal time scales. As the low-dimensional nonlinearity of ENSO is weakened, high predictability is attained, and vice versa.

The low-dimensional nonlinearity of ENSO is also investigated and verified using observations.

Another finding in this study is the relationship between the error growth rate (BV-rate) and actual prediction skill. While there is a good positive correlation between them in some decades, the BV-rate demonstrates a strong inverse correlation with the prediction skill in other decades. The BV-rate components contributed by the nonlinear process play a dominant role in quantifying ENSO predictability. The possible mechanism for the link between BV-rate, BV-skewness and ENSO predictability is discussed.

Vettoretti, G., M. D'Orgeville, W. R. Peltier, and M. Stastna, 2009, Polar climate instability and climate teleconnections from the Arctic to the midlatitudes and tropics, *J. Clim.*, **22**: 3513-3539, doi:10.1175/2009JCLI2481.1

It is generally accepted that the ocean thermohaline circulation plays a key role in polar climate stability and rapid climate change. Recently reported analyses of the impact of anomalous freshwater outflows from the North American continent onto either the North Atlantic or Arctic Oceans demonstrate that, in either case, a clear reduction in the Atlantic meridional overturning circulation, accompanied by an increase in sea ice extent, is predicted. The results also reconcile proxy-inferred Younger Dryas Greenland temperature variations. The aim of the present work is to provide a detailed investigation of the pathways along which the signal associated with overturning circulation anomalies propagates into both the midlatitudes and the tropics and the effect such teleconnections have on the tropical ocean–atmosphere system. The authors consider both the impact of substantial slowing of the overturning circulation due to freshwater forcing of the North Atlantic as well as its recovery after the anomalous forcing has ceased. The changes in tropical climate variability are shown to manifest themselves in shifts of both the typical time scale and intensity of ENSO events in the model. Evidence is presented for mechanisms that involve both atmospheric and oceanic pathways through which such Northern Hemisphere high-latitude events are communicated into both the midlatitudes and the tropics and thereafter transformed into changes in the nature of tropical variability.

Wu, A., W. W. Hsieh, G. J. Boer, and F. W. Zwiers, 2007, Changes in the Arctic Oscillation under increased atmospheric greenhouse gases, *Geophys. Res. Lett.*, **34**, L12701, doi:10.1029/2007GL029344

The Arctic Oscillation (AO) under increased atmospheric concentration of greenhouse gases (GHG) was studied by comparing an ensemble of simulations from 13 coupled general circulation models with GHG at the pre-industrial level and at the late 20th century level, for November to March. The change in the linear AO pattern as GHG increased reveals positive sea level pressure (SLP) anomalies centered over the Gulf of Alaska, and weaker negative SLP anomalies over eastern Canada and North Atlantic – a pattern resembling the nonlinear AO pattern arising from a quadratic relation to the AO index. This quadratic AO pattern itself has positive SLP anomalies receding from Europe but strengthening

over the Gulf of Alaska and surrounding areas as GHG increased. This study points to the importance of the nonlinear structure in determining how the linear oscillatory pattern changes when there is a change in the mean climate.

Yu, B., A. Shabbar, and F. W. Zwiers, 2007, The enhanced PNA-like climate response to Pacific interannual and decadal variability, *J. Clim.*, **20**: 5285-5300, doi:10.1175/2007JCLI1480.1

This study provides further evidence of the impacts of tropical Pacific interannual [El Niño–Southern Oscillation (ENSO)] and Northern Pacific decadal–interdecadal [North Pacific index (NPI)] variability on the Pacific–North American (PNA) sector. Both the tropospheric circulation and the North American temperature suggest an enhanced PNA-like climate response and impacts on North America when ENSO and NPI variability are out of phase. In association with this variability, large stationary wave activity fluxes appear in the mid- to high latitudes originating from the North Pacific and flowing downstream toward North America. Atmospheric heating anomalies associated with ENSO variability are confined to the Tropics, and generally have the same sign throughout the troposphere with maximum anomalies at 400 hPa. The heating anomalies that correspond to the NPI variability exhibit a center over the midlatitude North Pacific in which the heating changes sign with height, along with tropical anomalies of comparable magnitudes. Atmospheric heating anomalies of the same sign appear in both the tropical Pacific and the North Pacific with the out-of-phase combination of ENSO and NPI. Both sources of variability provide energy transports toward North America and tend to favor the occurrence of stationary wave anomalies.

Yu, B. and F. W. Zwiers, 2007, The impact of combined ENSO and PDO on the PNA climate: a 1000-yr climate modeling study, *Clim. Dyn.*, **29**: 837-851, doi:10.1007/s00382-007-0267-4

This study analyzes the atmospheric response to the combined Pacific interannual ENSO and decadal–interdecadal PDO variability, with a focus on the Pacific-North American (PNA) sector, using a 1,000-year long integration of the Canadian Center for Climate Modelling and Analysis (CCCma) coupled climate model. Both the tropospheric circulation and the North American temperature suggest an enhanced PNA-like climate response and impacts on North America when ENSO and PDO variability are in phase. The anomalies of the centers of action for the PNA-like pattern are significantly different from zero and the anomaly pattern is field significant. In association with the stationary wave anomalies, large stationary wave activity fluxes appear in the mid-high latitudes originating from the North Pacific and flowing downstream toward North America. There are significant Rossby wave source anomalies in the extratropical North Pacific and in the subtropical North Pacific. In addition, the axis of the Pacific storm track shifts southward with the positive PNA. Atmospheric heating anomalies associated with ENSO variability are confined primarily to the tropics. There is an anomalous heating center over the northeast Pacific, together with anomalies with the same polarity in the tropical Pacific, for the PDO variability.

The in-phase combination of ENSO and PDO would in turn provide anomalous atmospheric energy transports towards North America from both the Tropical Pacific and the North Pacific, which tends to favor the occurrence of stationary wave anomalies and would lead to a PNA-like wave anomaly structure. The modeling results also confirm our analysis based on the observational record in the twentieth century.

Zhang, X., J. Wang, F. W. Zwiers, and P. Ya Groisman, 2010, The influence of large scale climate variability on winter maximum daily precipitation over North America, *J. Clim.*, **23**: 2902- 2915, doi:10.1175/2010JCLI3249.1

The generalized extreme value (GEV) distribution is fitted to winter season daily maximum precipitation over North America, with indices representing El Niño–Southern Oscillation (ENSO), the Pacific decadal oscillation (PDO), and the North Atlantic Oscillation (NAO) as predictors. It was found that ENSO and PDO have spatially consistent and statistically significant influences on extreme precipitation, while the influence of NAO is regional and is not field significant. The spatial pattern of extreme precipitation response to large-scale climate variability is similar to that of total precipitation but somewhat weaker in terms of statistical significance. An El Niño condition or high phase of PDO corresponds to a substantially increased likelihood of extreme precipitation over a vast region of southern North America but a decreased likelihood of extreme precipitation in the north, especially in the Great Plains and Canadian prairies and the Great Lakes/Ohio River valley.

Zhou, X., Y. Tang, and Z. Deng, 2007, The impact of atmospheric nonlinearities on the fastest growth of ENSO prediction error, *Clim. Dyn.*, **30**(5): 519-531, doi:10.1007/s00382-008-0392-5

In this paper we explore the impact of atmospheric nonlinearities on the optimal growth of initial condition error of El Niño and the Southern Oscillation (ENSO) prediction using singular vector (SV) analysis. This is performed by comparing and analyzing SVs of two hybrid coupled models (HCMs), one composed of an intermediate complexity dynamical ocean model coupled with a linear statistical atmospheric model, and the other one with the same ocean model coupled with a nonlinear statistical atmosphere. Tangent linear and adjoint models for both HCMs are developed. SVs are computed under the initial conditions of seasonal background and actual ENSO cycle simulated by the ocean model forced with the real wind data of 1980–1999. The optimization periods of 3, 6 and 9 months are individually considered. The results show that the first SVs in both HCMs are very similar to each other, characterized by a central east-west dipole pattern spanning over the entire tropical Pacific. The spatial patterns of the leading SV in both HCMs are not sensitive to optimization periods and initial time. However, the first singular value, indicating the optimal growth rate of prediction error, displays considerable differences between the two HCMs, indicating a significant impact of atmospheric nonlinearities on the optimal growth of ENSO prediction error. These differences are greater with increasing optimization time, suggesting

that the impact of atmospheric nonlinearities on the optimal growth of prediction error becomes larger for a longer period of prediction.

Zhou, X., Y. Tang, Y. Cheng, and Z. Deng, 2009, Improved ENSO Prediction by Singular Vector Analysis in a Hybrid Coupled Model. *J. Atmos. Oceanic Technol.*, **26**, 626–634, doi:10.1175/2008JTECHO599.1

In this study, a method based on singular vector analysis is proposed to improve El Niño–Southern Oscillation (ENSO) predictions. Its essential idea is that the initial errors are projected onto their optimal growth patterns, which are propagated by the tangent linear model (TLM) of the original prediction model. The forecast errors at a given lead time of predictions are obtained, and then removed from the raw predictions. This method is applied to a realistic ENSO prediction model for improving prediction skill for the period from 1980 to 1999. This correction method considerably improves the ENSO prediction skill, compared with the original predictions without the correction.

Zhou, X., Y. Tang, and Z. Deng, 2009, Assimilation of historical SST data for long-term ENSO retrospective forecasts, *Ocean Modeling*, **30**(2-3): 143-154, doi:10.1016/j.ocemod.2009.06.015

In this study, the assimilation of historic SST (sea surface temperature) data was performed for long-term ENSO hindcasts. The emphasis was placed on the design of background error covariance (BEC) that dominates the transfer of SST information to the subsurface. Four different data-assimilation schemes, based on Optimal Interpolation (OI) algorithm, were proposed, and compared in terms of ENSO simulation and prediction skills for the period from 1876 to 2000.

It was found that the data-assimilation scheme that has a three-dimensional BEC constructed from model simulations forced by observed wind stress can effectively correct the second-layer temperature in the SST assimilation and lead to the best ENSO prediction skill. Further analysis for the long-term hindcasts shows that the prediction skills have a striking decadal/interdecadal variability similar to that found in other models. These results provide a fundamental basis for the further study of ENSO predictability.

1.4.4 Sea Level

Abeysirigunawardena, D. S. and I. J. Walker 2008, Sea Level Responses to Climatic Variability and Change in Northern British Columbia, *Atmos.-Ocean*, **46**(3): 277–296, doi:10.3137/ao.460301

Sea level responses to climatic variability (CV) and change (CC) signals at multiple temporal scales (interdecadal to monthly) are statistically examined using long-term water level records from Prince Rupert (PR) on the north coast of British Columbia. Analysis of observed sea level data from PR, the longest available record in the region, indicates an annual average mean sea level (MSL) trend of +1.4±0.6 mm yr-1 for the period (1939–2003), as opposed to the longer term trend of 1±0.4 mm yr-1 (1909–2003). This suggests a possible acceleration in MSL trends during the latter half of the twentieth century. According to the

results of this study, the causes behind this acceleration can be attributed not only to the effects of global warming but also to cyclic climate variability patterns such as the strong positive Pacific Decadal Oscillation (PDO) phase that has been present since the mid-1970s. The linear regression model based on highest sea levels (MAXSL) of each calendar year showed a trend exceeding twice that (3.4 mm yr-1) of MSL. Previous work shows that the influence of vertical crustal motions on relative sea level are negligible at PR. Relations between sea levels and known CV indices (e.g., the Multivariate ENSO Index (MEI), PDO, Northern Oscillation Index (NOI), and Aleutian Low Pressure Index (ALPI)) are explored to identify potential controls of CV phenomena (e.g., the El Niño Southern Oscillation (ENSO), PDO) on regional MSL and MAXSL. Linear and non-linear statistical methods including correlation analyses, multiple regression, Cumulative Sum (CumSum) analysis, and Superposed Epoch Analysis (SEA) are used. Results suggest that ENSO forcing (as shown by the MEI and NOI indices) exerts significant influence on winter sea level fluctuations, while the PDO dominates summer sea level variability. The observational evidence at PR also shows that, during the period 1939–2003, these cyclic shorter temporal scale sea level fluctuations in response to CV were significantly greater than the longer term sea-level rise trend by as much as an order of magnitude and with trends over twice that of MSL. Such extreme sea level fluctuations related to CV events should be the immediate priority for the development of coastal adaptation strategies, as they are superimposed on long-term MSL trends, resulting in greater hazard than longer term MSL rise trends alone.

Berthier, E., E. Schiefer, G. K. C. Clarke, B. Menounos, and F. Rémy, 2010, Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery, *Nature Geoscience*, doi:10.1038/NGEO737

Over the past 50 years, retreating glaciers and ice caps contributed 0.5 mm yr^{-1} to sea-level rise, and one third of this contribution is believed to come from ice masses bordering the Gulf of Alaska. However, these estimates of ice loss in Alaska are based on measurements of a limited number of glaciers that are extrapolated to constrain ice wastage in the many thousands of others. Uncertainties in these estimates arise, for example, from the complex pattern of decadal elevation changes at the scale of individual glaciers and mountain ranges. Here we combine a comprehensive glacier inventory with elevation changes derived from sequential digital elevation models. We find that between 1962 and 2006, Alaskan glaciers lost 41.9±8.6 km^3 yr^{-1} of water, and contributed 0.12±0.02 mm yr^{-1} to sea-level rise, 34% less than estimated earlier. Reasons for our lower values include the higher spatial resolution of our glacier inventory as well as the reduction of ice thinning underneath debris and at the glacier margins, which were not resolved in earlier work. We suggest that estimates of mass loss from glaciers and ice caps in other mountain regions could be subject to similar revisions.

Gower, J. F. R., 2010, Comment on "Response of the global ocean to Greenland and Antarctic ice melting" by D. Stammer, *J. Geophys. Res.*, **115**, C10009, doi:10.1029/2010JC006097

no abstract; introduction

[1] Stammer [2008] comes to the conclusion that sea level rise from melting Greenland ice will have little effect on sea levels in the Pacific and other distant areas for over 50 years. This result has important ramifications and has been reported in the press. He derives a similar result for melting of Antarctica. However, these are conclusions that the paper is unable to support. A retraction needs to be printed.

[2] Stammer's [2008] study is on the redistribution of water properties (including sea level) in the oceans of the world in response to injection of fresh water near Greenland and Antarctica. Stammer's Figure 1 shows locations and amounts of fresh water entering the oceans in a graphical, semiquantitative form. Stammer's Figures 2–11 show maps and plots of the response of the global ocean after time steps of up to 50 years. Stammer's Figure 6 shows that in 50 years, sea level will have increased in the Baffin Bay/Labrador Sea area by about 30 mm, but in the rest of the Atlantic by less than 10 mm, and in the Pacific by only 1.5 to 2 mm. Similarly, Stammer's Figure 10 shows sea level rise after 50 years due to melting of Antarctica, of 10 cm close to Antarctica, but less than 0.5 mm for areas north of 60°S.

[3] Stammer's [2008] paragraph 47 in section 5 states, "The corollary of our findings is that melt water dumped into the North Atlantic from Greenland will reside first of all in the Atlantic and will only slowly propagate into the other basins. In particular, it will take a significant length of time until the Pacific Ocean will "feel" this extra volume, for example, in form of sea level rise. This is an important result since it implies that melting of Greenland's ice cap is much less of a threat to tropical islands in the Pacific than it is for the coasts of North America and Europe."

Peltier, W. R., 2009, Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment, *Quat. Sci. Rev.*, **28**(17-18): 1658-1674, doi:10.1016/j.quascirev.2009.04.004

The budget of global sea level rise includes contributions from several distinct factors, including thermosteric effects, the wasting of small ice sheets and glaciers, and the loss of mass by the great polar ice sheets and by the continents due to desiccation. Since the former contribution may be estimated on the basis of both hydrographic survey data and more recently using Argo float data, the second may be estimated on the basis of mass balance measurements on existing ice-fields, and the latter on the basis of modern GRACE-based time dependent gravity field measurements, the inputs to the globally averaged rate of sea level rise may be directly constrained. Since GRACE also provides a measurement of the rate at which mass is being added to the oceans, we are now in a position to ask whether this rate of mass addition to the oceans matches the rate at which mass is being removed from the continents. As demonstrated herein, the mass component of the budget of global sea level is closed within the observational

errors. When the mass-derived contribution is added to the thermosteric contribution it is furthermore shown that the inference of the net rate of global sea level rise by the altimetric satellites Topex/Poseidon and Jason 1 is also reconcilable over the GRACE era. It is noted those individual terms in the budget, especially the contribution from small ice sheets and glaciers, remains insufficiently accurate. It is demonstrated that the lingering influence of the Late Quaternary ice-age upon sea level is profound and that closure of the budget requires an accurate model of its impact.

1.4.5 Carbon Cycle and Climate Change

Boer, G. J. and V. Arora, 2009, Temperature and concentration feedbacks in the carbon cycle, *Geophys. Res. Lett.*, **36**, L02704, doi:10.1029/2008GL036220

Feedback processes in the carbon budget are investigated in a manner that parallels the treatment of feedback processes in the energy budget. The analysis is applied to simulations with the CCCma earth system model CanESM1 using a range of emission scenarios. For the atmosphere there is a positive "carbon-temperature" feedback which acts to increase CO_2 flux to the atmosphere as temperatures warm. There is also a negative "carbon-concentration" feedback which acts to remove CO_2 from the atmosphere via enhanced uptake of CO_2 by the land and ocean as CO_2 concentration increases. While the positive feedback associated with temperature change is reasonably linear and consistent as temperature increases, the feedback associated with CO_2 concentration is not. The negative carbon-concentration feedback weakens with increasing CO_2 concentration thereby enhancing atmospheric CO_2 and accelerating global warming. The behaviour of the inferred carbon-concentration feedback is different for different emission scenarios implying a dependence on state variables other than CO_2 concentration. The carbon-concentration feedback behaviour inferred for a particular scenario may not, therefore, be used to infer system behaviour for other scenarios.

Boer, G. J. and V. Arora, 2010, Geographic Aspects of Temperature and Concentration Feedbacks in the Carbon Budget. *J. Clim.*, **23(3):** 775–784, doi:10.1175/2009JCLI3161.1

The geographical distribution of feedback processes in the carbon budget is investigated in a manner that parallels that for climate feedback/sensitivity in the energy budget. Simulations for a range of emission scenarios, made with the Canadian Centre for Climate Modelling and Analysis (CCCma) earth system model (CanESM1), are the basis of the analysis. Anthropogenic CO_2 emissions are concentrated in the Northern Hemisphere and provide the forcing for changes to the atmospheric carbon budget. Transports redistribute the emitted CO_2 globally where local feedback processes act to enhance (positive feedback) or suppress (negative feedback) local CO_2 amounts in response to changes in CO_2 concentration and temperature.

An increased uptake of CO_2 by the land and ocean acts to counteract increased atmospheric CO_2 concentrations so that "carbon–concentration" feedbacks are broadly negative over the twenty-first century. Largest values are found over land

and particularly in tropical regions where CO_2 acts to fertilize plant growth. Extratropical land also takes up CO_2 but here the effect is limited by cooler temperatures. Oceans play a lesser negative feedback role with comparatively weak uptake associated with an increase in the atmosphere–ocean CO_2 gradient rather than with oceanic biological activity.

The effect of CO_2-induced temperature increase is, by contrast, to increase atmospheric CO_2 on average and so represents an overall positive "carbon–temperature" feedback. Although the average is positive, local regions of both positive and negative carbon–temperature feedback are seen over land as a consequence of the competition between changes in biological productivity and respiration. Positive carbon–temperature feedback is found over most tropical land while mid–high-latitude land exhibits negative feedback. There are also regions of positive and negative oceanic carbon–temperature feedback in the eastern tropical Pacific.

The geographical patterns of carbon–concentration and carbon–temperature feedbacks are comparatively robust across the range of emission scenarios used, although their magnitudes are somewhat less robust and scale nonlinearly as a consequence of the large CO_2 concentration changes engendered by the scenarios. The feedback patterns deduced nevertheless serve to illustrate the localized carbon feedback processes in the climate system.

Christian, J. R., V. K. Arora, G. J. Boer, C. L. Curry, K. Zahariev, K. L. Denman, G. M. Flato, W. G. Lee, W. J. Merryfield, N. T. Roulet, and J. F. Scinocca, 2010, The global carbon cycle in the Canadian Earth System Model (CanESM1): Preindustrial control simulation, *J. Geophys. Res.*, **115**, G03014, doi:10.1029/2008JG000920

The preindustrial carbon cycle is described for the Canadian Centre for Climate Modelling and Analysis Earth system model (CanESM1). The interhemispheric gradient of surface atmospheric CO_2 concentration (xCO_2) is reversed from the present day, with higher concentrations in the Southern Hemisphere, and southward interhemispheric transport by the ocean, estimated at 0.38 Pg C yr^{-1}. The seasonal cycles of xCO_2 and surface CO_2 exchange are dominated by Northern Hemisphere terrestrial processes; the ocean contribution to CO_2 flux is in phase with the larger terrestrial flux in the tropics and out of phase in the extratropics. Ocean processes dominate the relatively small Southern Hemisphere variability. Interannual variability of land carbon exchange is much larger than ocean exchange; both are comparable to results from previously published models with possibly larger variability in the terrestrial flux. Terrestrial net primary production (NPP) is determined largely by water availability at low latitudes, with temperature becoming more important at high latitudes. Temperature and moisture affect both NPP and heterotrophic respiration such that respiration effects tend to dampen the effect of fluctuations in NPP on CO_2 exchange. Ocean CO_2 flux variability is controlled by a variety of physical and biological processes with greater control by physical processes in the tropics and a larger biological contribution in the extratropics. Ocean CO_2 flux is more strongly correlated with

tropical sea surface temperature (SST) than terrestrial, but the variance associated with tropical SST is larger on land, in absolute terms, because of the much greater total variance of the land carbon flux. A novel hypothesis is advanced to explain how biological drawdown can cause recently upwelled water to be a net sink rather than source for atmospheric CO_2. This process occurs over large areas of extratropical ocean and forms a natural sink for atmospheric CO_2 that is potentially sensitive to both ocean acidification and anthropogenic perturbations of the aeolian iron flux.

Matthews, H. D. and D. W. Keith, 2007, Carbon-cycle feedbacks increase the likelihood of a warmer future, *Geophys. Res. Lett.*, **34**, L09702, doi:10.1029/2006GL028685

Positive carbon-cycle feedbacks have the potential to reduce natural carbon uptake and accelerate future climate change. In this paper, we introduce a novel approach to incorporating carbon-cycle feedbacks into probabilistic assessments of future warming. Using a coupled climate-carbon model, we show that including carbon-cycle feedbacks leads to large increases in extreme warming probabilities. For example, for a scenario of CO_2 stabilization at 550 ppm, the probability of exceeding 2°C warming at 2100 increased by a factor of between 1.7 and 3, while the probability of exceeding 3°C warming increased from a few percent to as much as 22%. CO_2 fertilization was found to exert little influence on the amount of future warming, since increased carbon uptake was partially offset by fertilization-induced surface albedo changes. The effect of positive carbon-cycle feedbacks on the likelihood of extreme future warming must be incorporated into climate policy-related decision making.

Matthews, H. D., L. Cao, and K. Caldeira, 2009, Sensitivity of ocean acidification to geoengineered climate stabilization, *Geophys. Res. Lett.*, **36**, L10706, doi:10.1029/2009GL037488

Climate engineering has been proposed as a possible response to anthropogenic climate change. While climate engineering may be able to stabilize temperatures, it is generally assumed that this will not prevent continued ocean acidification. However, due to the strong coupling between climate and the carbon cycle, climate engineering could indirectly affect ocean chemistry. We used a global Earth-system model to investigate how climate engineering may affect surface ocean pH and the degree of aragonite saturation. Climate engineering could significantly re-distribute carbon emissions among atmosphere, land and ocean reservoirs. This could slow pH decreases somewhat relative to the non-engineered case, but would not affect the level of aragonite saturation due to opposing responses of pH and aragonite saturation to temperature change. However, these effects are dependent on enhanced carbon accumulation in the land biosphere; without this, climate engineering has little effect on pH, and leads to accelerated declines in aragonite saturation.

Schmittner, A., A. Oschlies, H. Damon Matthews, and E. D. Galbraith, 2008, Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated

for a business-as-usual CO_2 emission scenario until year 4000 AD, *Glob. Biogeochem. Cycles*, **22**, GB1013, doi:10.1029/2007GB002953

A new model of global climate, ocean circulation, ecosystems, and biogeochemical cycling, including a fully coupled carbon cycle, is presented and evaluated. The model is consistent with multiple observational data sets from the past 50 years as well as with the observed warming of global surface air and sea temperatures during the last 150 years. It is applied to a simulation of the coming two millennia following a business-as-usual scenario of anthropogenic CO_2 emissions (SRES A2 until year 2100 and subsequent linear decrease to zero until year 2300, corresponding to a total release of 5100 GtC). Atmospheric CO_2 increases to a peak of more than 2000 ppmv near year 2300 (that is an airborne fraction of 72% of the emissions) followed by a gradual decline to ~1700 ppmv at year 4000 (airborne fraction of 56%). Forty-four percent of the additional atmospheric CO_2 at year 4000 is due to positive carbon cycle–climate feedbacks. Global surface air warms by ~10°C, sea ice melts back to 10% of its current area, and the circulation of the abyssal ocean collapses. Subsurface oxygen concentrations decrease, tripling the volume of suboxic water and quadrupling the global water column denitrification. We estimate 60 ppb increase in atmospheric N_2O concentrations owing to doubling of its oceanic production, leading to a weak positive feedback and contributing about 0.24°C warming at year 4000. Global ocean primary production almost doubles by year 4000. Planktonic biomass increases at high latitudes and in the subtropics whereas it decreases at midlatitudes and in the tropics. In our model, which does not account for possible direct impacts of acidification on ocean biology, production of calcium carbonate in the surface ocean doubles, further increasing surface ocean and atmospheric pCO_2. This represents a new positive feedback mechanism and leads to a strengthening of the positive interaction between climate change and the carbon cycle on a multicentennial to millennial timescale. Changes in ocean biology become important for the ocean carbon uptake after year 2600, and at year 4000 they account for 320 ppmv or 22% of the atmospheric CO_2 increase since the preindustrial era.

Zickfeld, K., J. C. Fyfe, O. A. Saenko, M. Eby and A. J. Weaver, 2007, Response of the global carbon cycle to human-induced changes in Southern Hemisphere winds. *Geophys. Res. Lett.*, **34**, L12712, doi:10.1029/2006GL028797

An Earth System model is used to explore the response of the oceanic and terrestrial carbon sinks to strengthening and poleward shifting of the extratropical Southern Hemisphere winds, which is a robust feature of climate models' response to greenhouse gas forcing through the 20th and 21st centuries. We find that under time-varying CO_2 emissions poleward intensifying Southern Hemisphere winds act on average to slightly enhance the efficacy of both the oceanic and terrestrial carbon sinks, thus providing a small negative feedback on the atmospheric CO_2 concentration. Regionally, the effects of the changing winds on oceanic and terrestrial carbon uptake are more pronounced and partly of opposite sign. We further show that the magnitude and sign of global oceanic CO_2

uptake is also controlled by changes in mesoscale eddy activity, which has been suggested to increase in response to intensifying Southern Hemisphere winds.

1.5 Carbon Cycle and Ecosystems

Christian, J. R., 2007, Advection in plankton models with variable elemental ratios, *Ocean Dyn.*, **57**(1): 63-71, doi:10.1007/s10236-006-0097-7

As ocean biogeochemical models evolve to permit the elemental composition of plankton populations and dissolved organic matter to vary, each element is normally assigned a separate state variable, which is advected and mixed independently of the others. In a population of cells with varying elemental quotas, the proper currency of the advection operator is subpopulations of similar cells. The spatial gradient in total C, N, or P summed over the spectrum of such subpopulations is identical to that calculated for the population means, so treating the various elements as independent should generally be a valid approximation. However, errors can arise in high-order advection schemes with nonlinear corrector terms, which are not additive across the subpopulations. Some numerical examples indicate that these errors are relatively small [$O(10^{-3}$-$10^{-4})$] but can be as high as $O(10^{-2})$ in certain cases. As grid resolution varies, the error scales approximately to the Courant number.

Galbraith, E. D., S. Jaccard, T. F. Pedersen, D. M. Sigman, G. H. Haug, M. Cook, J. R. Southon, and R. Francois, 2007, Carbon dioxide release from the North Pacific abyss during the last deglaciation, *Nature*, **449**: 890-894, doi:10.1038/nature06227

Atmospheric carbon dioxide concentrations were significantly lower during glacial periods than during intervening interglacial periods, but the mechanisms responsible for this difference remain uncertain. Many recent explanations call on greater carbon storage in a poorly ventilated deep ocean during glacial periods, but direct evidence regarding the ventilation and respired carbon content of the glacial deep ocean is sparse and often equivocal. Here we present sedimentary geochemical records from sites spanning the deep subarctic Pacific that—together with previously published results—show that a poorly ventilated water mass containing a high concentration of respired carbon dioxide occupied the North Pacific abyss during the Last Glacial Maximum. Despite an inferred increase in deep Southern Ocean ventilation during the first step of the deglaciation (18,000–15,000 years ago), we find no evidence for improved ventilation in the abyssal subarctic Pacific until a rapid transition ~14,600 years ago: this change was accompanied by an acceleration of export production from the surface waters above but only a small increase in atmospheric carbon dioxide concentration. We speculate that these changes were mechanistically linked to a roughly coeval increase in deep water formation in the North Atlantic, which flushed respired carbon dioxide from northern abyssal waters, but also increased the supply of nutrients to the upper ocean, leading to greater carbon dioxide sequestration at mid-depths and stalling the rise of atmospheric carbon dioxide concentrations. Our findings are qualitatively consistent with hypotheses invoking a deglacial flushing of respired carbon dioxide from an isolated, deep ocean reservoir, but suggest that the reservoir may have been released in stages, as vigorous deep

water ventilation switched between North Atlantic and Southern Ocean source regions.

Hamme, R. C. and R. F. Keeling, 2008, Ocean ventilation as a driver of interannual variability in atmospheric potential oxygen, *Tellus B*, **60**(5): 706-717, doi:10.1111/j.1600-0889.2008.00376.x

We present observations of interannual variability on 2-5 yr timescales in atmospheric potential oxygen (APO $\approx O_2 + CO_2$) from the Scripps Institution of Oceanography global flask sampling network. Interannual variations in the tracer APO are expected to arise from air-sea fluxes alone, because APO is insensitive to exchanges with the terrestrial biosphere. These interannual variations are shown to be regionally coherent and robust to analytical artefacts. We focus on explaining a feature dominant in records from the Northern Hemisphere stations, marked by increasing APO in the late 1990s, followed by an abrupt drawdown in 2000-2001. The timing of the drawdown matches a renewal of deep convection in the North Atlantic, followed the next year by a severe winter in the western North Pacific that may have allowed ventilation of denser isopycnals than usual. We find a weak correlation between changes in the interhemispheric APO difference and El Niño indices, and the observations show no strong features of the 1997-98 El Niño. Comparisons with estimates of variations in ocean productivity and ocean heat content demonstrate that these processes are secondary influences at these timescales. We conclude that the evidence points to variability in ocean ventilation as the main driver of interannual variability in APO.

Juranek, L. W., R. C. Hamme, J. Kaiser, R. Wanninkhof, and P. D. Quay, 2010, Evidence of O_2 consumption in underway seawater lines: Implications for air-sea O_2 and CO_2 fluxes, *Geophys. Res. Lett.*, **37**, L01601, doi:10.1029/2009GL040423

We observed O_2 deficits of 0.5 to 2.0% (1 to 4 μmol/kg) in the underway seawater lines of three different ships. Deficits in O_2/Ar and isotopic enrichments in dissolved O_2 observed in underway seawater lines indicate a respiratory removal process. A 1% respiratory bias in underway lines would lead to a 2.5–5 μatm (2.5–5 μbar) enhancement in surface water pCO_2. If an underway pCO_2 bias of this magnitude affected all measurements, the global oceanic carbon uptake based on pCO_2 climatologies would be 0.5–0.8 Pg/yr higher than the present estimate of 1.6 Pg/yr. Treatment of underway lines with bleach for several hours and thorough flushing appeared to minimize O_2 loss. Given the increasing interest in underway seawater measurements for the determination of surface CO_2 and O_2 fluxes, respiration in underway seawater lines must be identified and eliminated on all observing ships to ensure unbiased data.

Peltier, W. R., Y. Liu, and J. W. Crowley, 2007, Snowball Earth prevention by dissolved organic carbon remineralization, *Nature*, **450**, 813-818, doi:10.1038/nature06354

The 'snowball Earth' hypothesis posits the occurrence of a sequence of glaciations in the Earth's history sufficiently deep that photosynthetic activity was essentially arrested. Because the time interval during which these events are believed to have occurred immediately preceded the Cambrian explosion of life,

the issue as to whether such snowball states actually developed has important implications for our understanding of evolutionary biology. Here we couple an explicit model of the Neoproterozoic carbon cycle to a model of the physical climate system. We show that the drawdown of atmospheric oxygen into the ocean, as surface temperatures decline, operates so as to increase the rate of remineralization of a massive pool of dissolved organic carbon. This leads directly to an increase of atmospheric carbon dioxide, enhanced greenhouse warming of the surface of the Earth, and the prevention of a snowball state.

Pena, M. A., S. Katsev, T. Oguz, and D. Gilbert, 2010, Modeling dissolved oxygen dynamics and hypoxia, *Biogeosciences*, **7**(3): 933-957, doi:10.5194/bg-7-933-2010

Hypoxia conditions are increasing throughout the world, influencing biogeochemical cycles of elements and marine life. Hypoxia results from complex interactions between physical and biogeochemical processes, which can not be understood by observations alone. Models are invaluable tools at studying system dynamics, generalizing discrete observations and predicting future states. They are also useful as management tools for evaluating site-specific responses to management scenarios. Here we review oxygen dynamics models that have significantly contributed to a better understanding of the effects of natural processes and human perturbations on the development of hypoxia, factors controlling the extent and temporal variability of coastal hypoxia, and the effects of oxygen depletion on biogeochemical cycles. Because hypoxia occurs in a variety of environments and can be persistent, periodic or episodic, models differ significantly in their complexity and temporal and spatial resolution. We discuss the progress in developing hypoxia models for benthic and pelagic systems that range from simple box models to three dimensional circulation models. Applications of these models in five major hypoxia regions are presented. In the last decades, substantial progress has been made towards the parameterization of biogeochemical processes in both hypoxic water columns and sediments. In coastal regions, semi-empirical models have been used more frequently than mechanistic models to study nutrient enrichment and hypoxia relationships. Recent advances in three-dimensional coupled physical-ecological-biogeochemical models have allowed a better representation of physical-biological interactions in these systems. We discuss the remaining gaps in process descriptions and suggest directions for improvement. Better process representations in models will help us answer several important questions, such as those about the causes of the observed worldwide increase in hypoxic conditions, and future changes in the intensity and spread of coastal hypoxia. At the same time, quantitative model intercomparison studies suggest that the predictive ability of our models may be adversely affected by their increasing complexity, unless the models are properly constrained by observations.

Zahariev, K., J. R. Christian, and K. L. Denman, 2008, Preindustrial, historical, and fertilization simulations using a global ocean carbon model with new parameterizations of iron limitation, calcification, and N2 fixation, *Prog. Oceanogr.y*, **77**(1): 56-82, doi:10.1016/j.pocean.2008.01.007

The Canadian Model of Ocean Carbon (CMOC) has been developed as part of a global coupled climate carbon model. In a stand-alone integration to preindustrial equilibrium, the model ecosystem and global ocean carbon cycle are in general agreement with estimates based on observations. CMOC reproduces global mean estimates and spatial distributions of various indicators of the strength of the biological pump; the spatial distribution of the air–sea exchange of CO_2 is consistent with present-day estimates. Agreement with the observed distribution of alkalinity is good, consistent with recent estimates of the mean rain ratio that are lower than historic estimates, and with calcification occurring primarily in the lower latitudes. With anthropogenic emissions and climate forcing from a 1850–2000 climate model simulation, anthropogenic CO_2 accumulates at a similar rate and with a similar spatial distribution as estimated from observations. A hypothetical scenario for complete elimination of iron limitation generates maximal rates of uptake of atmospheric CO_2 of less than 1 PgC y^{-1}, or about 11% of 2004 industrial emissions. Even a 'perfect' future of sustained fertilization would have a minor impact on atmospheric CO_2 growth. In the long term, the onset of fertilization causes the ocean to take up an additional 77 PgC after several thousand years, compared with about 84 PgC thought to have occurred during the transition into the last glacial maximum due to iron fertilization associated with increased dust deposition.

Zhang, J., D. Gilbert, A. J. Gooday, L. Levin, S. W. A. Naqvi, J. J. Middelburg., M. Scranton, W. Ekau, A. Peña, B. Dewitte, T. Oguz, P. M. S. Monteiro, E. Urban, MN. N. Rabalais, V. Ittekkot, W. M. Kemp, O. Ulloa, R. Elmgren, E. Escobar-Briones, and A. K. Van der Plas, 2010, Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development, *Biogeosciences*, **7**: 1443-1467, doi:10.5194/bg-7-1443-2010

Hypoxia has become a world-wide phenomenon in the global coastal ocean and causes a deterioration of the structure and function of ecosystems. Based on the collective contributions of members of SCOR Working Group #128, the present study provides an overview of the major aspects of coastal hypoxia in different biogeochemical provinces, including estuaries, coastal waters, upwelling areas, fjords and semi-enclosed basins, with various external forcings, ecosystem responses, feedbacks and potential impact on the sustainability of the fishery and economics. The obvious external forcings include freshwater runoff and other factors contributing to stratification, organic matter and nutrient loadings, as well as exchange between coastal and open ocean water masses. Their different interactions set up mechanisms that drive the system towards hypoxia. Coastal systems also vary in their relative susceptibility to hypoxia depending on their physical and geographic settings. It is understood that coastal hypoxia has a profound impact on the sustainability of ecosystems, which can be seen, for example, by the change in the food-web structure and system function; other influences include compression and loss of habitat, as well as changes in organism life cycles and reproduction. In most cases, the ecosystem responds to the low dissolved oxygen in non-linear ways with pronounced feedbacks to other compartments of the Earth System, including those that affect human society. Our

knowledge and previous experiences illustrate that there is a need to develop new observational tools and models to support integrated research of biogeochemical dynamics and ecosystem behavior that will improve confidence in remediation management strategies for coastal hypoxia.

1.6 Heat Transport

Greatbatch, R. J. and X. Zhai, 2007, The Generalized heat function, *Geophys. Res. Lett.*, **34**, L21601, doi:10.1029/2007GL031427

A generalized heat function is defined for diagnosing the pathways by which heat is carried by the ocean. In contrast to previous work, our generalized heat function varies along an isentrope only in the presence of mixing. The generalized heat function is diagnosed using the Levitus global ocean data set, net northward heat transport based on the data set of Grist and Josey, and different specifications for mixing in the ocean. The separation between the heat flux carried by the shallow wind driven cells and the deep overturning circulation is clearly revealed, with up to 0.4 PW being associated with the spreading of North Atlantic Deep Water. The importance of eddy-induced mixing near the surface of the Southern Ocean is evident.

1.7 Abyssal Flows

Swaters, G. E., 2009, Mixed bottom-friction-Kelvin-Helmholtz destabilization of source-driven abyssal overflows in the ocean, *J. Fluid Mech.*, **626**: 33-67, doi:10.1017/S0022112008005673

Source-driven ocean currents that flow over topographic sills are important initiation sites for the abyssal component of the thermohaline circulation. These overflows exhibit vigorous space and time variability over many scales as they progress from a predominately gravity-driven downslope flow to a geostrophic along-slope current. Observations show that in the immediate vicinity of a sill, grounded abyssal ocean overflows can possess current speeds greater than the local long internal gravity wave speed with bottom friction and downslope gravitational acceleration dominating the flow evolution. It is shown that these dynamics lead to the mixed frictionally induced and Kelvin–Helmholtz instability of grounded abyssal overflows. Within the overflow, the linearized instabilities correspond to bottom-intensified baroclinic roll waves, and in the overlying water column amplifying internal gravity waves are generated. The stability characteristics are described as functions of the bottom drag coefficient and slope, Froude, bulk Richardson and Reynolds numbers associated with the overflow and the fractional thickness of the abyssal current compared to the mean depth of the overlying water column. The marginal stability boundary and the boundary separating the parameter regimes in which the most unstable mode has a finite or infinite wavenumber are determined. When it exists, the high-wavenumber cutoff is obtained. Conditions for the possible development of an ultraviolet catastrophe are determined. In the infinite-Reynolds-number limit, an exact solution is obtained which fully includes the effects of mean depth variations in the overlying water column associated with a sloping bottom. For parameter values

characteristic of the Denmark Strait overflow, the most unstable mode has a wavelength of about 19 km, a geostationary period of about 14 hours, an e-folding amplification time of about 2 hours and a downslope phase speed of about 74 cm s^{-1}.

Swaters, G. E., 2009, Ekman destabilization of inertially-stable baroclinic abyssal flow on a sloping bottom, *Phys. Fluids*, **21**(8), 086601, doi:10.1063/1.3211274

Baroclinic abyssal currents on a sloping bottom, which are nonlinearly stable in the sense of Liapunov in the absence of dissipation, are shown to be destabilized by the presence of a bottom Ekman boundary layer for any positive value of the Ekman number. When the abyssal flow is baroclinically unstable, the dissipation acts to reduce the inviscid growth rates except near the marginal stability boundary where it acts to increase the inviscid growth rates. It is shown that when the abyssal flow is baroclinically stable, the Ekman destabilization corresponds to the kinematic wave phase velocity lying outside the range of the inertial topographic Rossby phase velocities. The transition mechanism described here might provide a dynamical bridge between the nonrotational roll-wave instability that can occur in supercritical abyssal overflows and frictionally induced destabilization in subinertial geostrophically balanced baroclinic abyssal currents. In addition, the theory presented here suggests a dissipation-induced destabilization mechanism for coastal downwelling fronts whose cross-slope potential vorticity gradient does not satisfy the necessary condition for baroclinic instability.

1.8 IPCC 4th Assessment Report

Kharin, V. V., F. W. Zwiers, X. Zhang, and G. C. Hegerl, 2007: Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations, *J. Clim.*, **20**: 1419-1444, http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4066.1

Temperature and precipitation extremes and their potential future changes are evaluated in an ensemble of global coupled climate models participating in the Intergovernmental Panel on Climate Change (IPCC) diagnostic exercise for the Fourth Assessment Report (AR4). Climate extremes are expressed in terms of 20-yr return values of annual extremes of near-surface temperature and 24-h precipitation amounts. The simulated changes in extremes are documented for years 2046–65 and 2081–2100 relative to 1981–2000 in experiments with the Special Report on Emissions Scenarios (SRES) B1, A1B, and A2 emission scenarios. Overall, the climate models simulate present-day warm extremes reasonably well on the global scale, as compared to estimates from reanalyses. The model discrepancies in simulating cold extremes are generally larger than those for warm extremes, especially in sea ice–covered areas. Simulated present-day precipitation extremes are plausible in the extratropics, but uncertainties in extreme precipitation in the Tropics are very large, both in the models and the available observationally based datasets. Changes in warm extremes generally follow changes in the mean summertime temperature. Cold extremes warm faster than warm extremes by about 30%–40%, globally averaged. The excessive warming of cold extremes is generally confined to regions where snow and sea

ice retreat with global warming. With the exception of northern polar latitudes, relative changes in the intensity of precipitation extremes generally exceed relative changes in annual mean precipitation, particularly in tropical and subtropical regions. Consistent with the increased intensity of precipitation extremes, waiting times for late-twentieth-century extreme precipitation events are reduced almost everywhere, with the exception of a few subtropical regions. The multimodel multiscenario consensus on the projected change in the globally averaged 20-yr return values of annual extremes of 24-h precipitation amounts is that there will be an increase of about 6% with each kelvin of global warming, with the bulk of models simulating values in the range of 4%–10% K_1. The very large intermodel disagreements in the Tropics suggest that some physical processes associated with extreme precipitation are not well represented in models. This reduces confidence in the projected changes in extreme precipitation.

1.9 Other Global Studies

Avis, C., A. Montenegro and A. J. Weaver, 2007, The discovery of Western Oceania: A new perspective, J. Coastal and Island Archaeology, **2**: 197-209, doi:10.1080/15564890701518557

Settling the islands of Oceania required that thousands of kilometers of open ocean be crossed in stone-age vessels. This feat must surely rank among the most impressive achievements of mankind, but exactly how it occurred is unclear, since nothing definite is known about the navigation skills or vessels used at this time. Here we use a computer simulation to study the potential role of drift voyages and exploration by sailing downwind in the discovery of new island groups in the region of the Lapita expansion in western Oceania. Contradicting an important early simulation, our results show that both drift and downwind sailing voyages can account for all the major crossings in the Lapita region extending from Near Oceania to Samoa. Tonga and Samoa, at the eastern limits of this area, can only be reached under anomalous wind and current conditions, demonstrating the importance of considering interannual variability in assessing exploration and settlement theories.

Cherniawsky, J. Y. and G. J. Sutherland, 2008, Large-scale errors in ERS altimeter data, *Marine Geodesy,* **31**(1):2-16, doi:10.1080/01490410701812212

A method is described for mapping time-uncorrelated large-scale errors in satellite altimeter sea surface heights. Standard deviations of differences between pairs of successive measurements at track crossovers are computed, and the functional dependence of these deviations on absolute time difference is used to estimate the errors of individual measurements. This is first applied to all of ERS-1,2 altimeter data in the Pacific Ocean, yielding average errors of 3.2 cm in the deep ocean (>1 km) and 4.7 cm in the shallow seas (<1 km). The procedure is repeated for variable latitude bands, each with a full range of possible time differences, yielding a meridional profile of computed errors, ranging from 2.6 cm near the Antarctic continent (67-60S) and South Subtropical regions (25-5S) to 3.5 cm in the Antarctic Circumpolar Current (60-45S) and the Northern

Hemisphere Subtropical and Subpolar Gyres. Finally, coarse-resolution maps of these errors are produced by subdividing the Pacific Ocean into latitude-longitude bins, each large enough to contain a sufficient number of samples for the functional fits. The larger errors are in Northwest and Subtropical Pacific, especially in South China Sea (4.3 to 4.5 cm) and off northern Australia (5.4 cm), while the smaller errors (2.5 to 3 cm) are in Northeast Pacific, central Tropical Pacific and near Antarctica in Southeast Pacific Ocean. These are lower bounds on altimeter errors, as they do not include contributions from time-correlated errors. We find that the computed error fields are not correlated with sea level standard deviations, thus disproving the notion that altimeter error variance can be scaled with the variance of sea surface height data.

Cossu, R., and M. G. Wells, 2010, Coriolis forces influence the secondary circulation of gravity currents flowing in large-scale sinuous submarine channel systems, *Geophys. Res. Lett.*, **37**, L17603, doi:10.1029/2010GL044296

A combination of centrifugal and Coriolis forces drive the secondary circulation of turbidity currents in sinuous channels, and hence determine where erosion and deposition of sediment occur. Using laboratory experiments we show that when centrifugal forces dominate, the density interface shows a superelevation at the outside of a channel bend. However when Coriolis forces dominate, the interface is always deflected to the right (in the Northern Hemisphere) for both left and right turning bends. The relative importance of either centrifugal or Coriolis forces can be described in terms of a Rossby number defined as $Ro = U/fR$, where U is the mean downstream velocity, f the Coriolis parameter and R the radius of curvature of the channel bend. Channels with larger bends at high latitudes have $|Ro| < 1$ and are dominated by Coriolis forces, whereas smaller, tighter bends at low latitudes have $|Ro| \gg 1$ and are dominated by centrifugal forces.

Cossu, R., M. G. Wells, and A. K. Wåhlin, 2010, Influence of the Coriolis force on the velocity structure of gravity currents in straight submarine channel systems, *J. Geophys. Res.*, **115**, C11016, doi:10.1029/2010JC006208

Large-scale turbidity currents in submarine channels often show a significant asymmetry in the heights of their levee banks. In the Northern Hemisphere, there are many observations of the right-hand channel levee being noticeably higher than the left-hand levee, a phenomenon that is usually attributed to the effect of Coriolis forces upon turbidity currents. This article presents results from an analog model that documents the influence of Coriolis forces on the dynamics of gravity currents flowing in straight submarine channels. The observations of the transverse velocity structure, downstream velocity, and interface slope show good agreement with a theory that incorporates Ekman boundary layer dynamics. Coriolis forces will be important for most large-scale turbidity currents and need to be explicitly modeled when the Rossby number of these flows (defined as $Ro = |U/Wf|$, where U is the mean downstream velocity, W is the channel width, and f is the Coriolis parameter defined as $f = 2\Omega \sin(\theta)$, with Ω being the Earth's rotation rate and θ being the latitude) is less than order 1. When $Ro \ll 1$, the flow is substantially slower than a nonrotating flow with the same density contrast. The

secondary flow field consists of frictionally induced Ekman transports across the channel in the benthic and interfacial boundary layers and a return flow in the interior. The cross-channel velocities are of the order of 10% of the along-channel velocities. The sediment transport associated with such transverse flow patterns should influence the evolution of submarine channel levee systems.

Cullen, J. J. and P. W. Boyd, 2008, Predicting and verifying the intended and unintended consequences of large-scale ocean fertilization, *Mar. Ecol. Prog. Ser.*, **364**: 295-301, doi:10.3354/meps07551

Ocean iron fertilization (OIF) is being considered as a strategy for mitigating rising atmospheric CO_2 concentrations. One model for implementation is the sale of carbon offsets. Modeling studies predict that OIF has the potential to produce a material difference in the rise of atmospheric CO_2 over the next several decades, but this could only be attained by alteration of the ecosystems and biogeochemical cycles of much of the world's oceans. The efficacy of OIF on this scale has not been proven. However, the consequences of successful implementation must be considered now, for 2 important reasons: (1) to determine if the environmental effects would be predictable and verifiable, and if so, acceptable; and (2) to establish whether the basis for valuing carbon offsets—an accurate audit of net reductions in cumulative greenhouse gas potential over 100 yr—can be met. Potential side-effects of widespread OIF that must be considered include a reduced supply of macronutrients to surface waters downstream of fertilized regions, increased emissions of the potent greenhouse gases nitrous oxide and methane, and changes in the extent or frequency of coastal hypoxia. Given the uncertainties inherent in ocean models, predictions of environmental effects must be backed up by measurements. Thus, to go forward with confidence that the effects of rising CO_2 could indeed be mitigated through OIF over the next century, and to establish the foundations for auditing carbon offsets, it must be explicitly demonstrated that methods exist to predict and detect downstream effects of OIF against the background of both climate variability and global warming. We propose that until the side-effects of widespread OIF can be shown to be verifiable—and there is good reason to believe that they cannot—OIF should not be considered a viable technology for climate mitigation.

deYoung, B., M. Barange, G. Beaugrand, R. Harris, R. I. Perry, M. Scheffer, and F. Werner, 2008, Regime shifts in marine ecosystems: detection, prediction and management, *Trends in Ecology and Evolution*, 23: 402-209, doi:10.1016/j.tree.2008.03.008

Regime shifts are abrupt changes between contrasting, persistent states of any complex system. The potential for their prediction in the ocean and possible management depends upon the characteristics of the regime shifts: their drivers (from anthropogenic to natural), scale (from the local to the basin) and potential for management action (from adaptation to mitigation). We present a conceptual framework that will enhance our ability to detect, predict and manage regime shifts in the ocean, illustrating our approach with three well-documented examples: the North Pacific, the North Sea and Caribbean coral reefs. We

conclude that the ability to adapt to, or manage, regime shifts depends upon their uniqueness, our understanding of their causes and linkages among ecosystem components and our observational capabilities.

Nadeau, L.-P. and D. N. Straub, 2009, Basin and Channel Contributions to a Model Antarctic Circumpolar Current, *J. Phys. Oceanogr.*, **39**(4): 986–1002

The idea that basinlike dynamics may play a major role in determining the Antarctic Circumpolar Current (ACC) transport is revisited. A simple analytic model is developed to describe the relationship between the wind stress and transport. At very low-wind stress, a nonzero minimum is predicted. This is followed by two distinct dynamical regimes for stronger forcing: 1) a Stommel regime in which transport increases linearly with forcing strength; and 2) a saturation regime in which the transport levels off. The baroclinic structure of the Sverdrup flux into the Drake Passage latitude band is central to the analytic model, and the geometry of characteristics, or geostrophic contours, is key to predicting the transition between the two regimes. A robustness analysis is performed using an eddy-permitting quasigeostrophic model in idealized geometries. Many simulations were carried out in large domains across a range of forcing strengths. The simulations agree qualitatively with the analytic model, with two main discrepancies being related to zonal jet structures and to a western boundary inertial recirculation. Eddy fluxes associated with zonal jets modify the baroclinic structure and lower the saturation transport value. Inertial effects increase the transport, although this effect is mainly limited to smaller domains.

1.10 Atmosphere-Ocean

Bakalian, F., H. Ritchie, K. Thompson, and W. Merryfield, 2010, Exploring Atmosphere–Ocean Coupling Using Principal Component and Redundancy Analysis, *J. Clim.*, **23**(18): 4926–4943, doi:10.1175/2010JCLI3388.1

Principal component analysis (PCA), which is designed to look at internal modes of variability, has often been applied beyond its intended design to study coupled modes of variability in combined datasets, also referred to as combined PCA. There are statistical techniques better suited for this purpose such as singular value decomposition (SVD) and canonical correlation analysis (CCA). In this paper, a different technique is examined that has not often been applied in climate science, that is, redundancy analysis (RA). Similar to multivariate regression, RA seeks to maximize the variance accounted for in one random vector that is linearly regressed against another random vector. RA can be used for forecasting and prediction studies of the climate system. This technique has the added advantage that the time-lagged redundancy index offers a robust method of identifying lead–lag relations among climate variables. In this study, combined PCA and RA of global sea surface temperatures (SSTs) and sea level pressures (SLPs) are carried out for the National Centers for Environmental Prediction (NCEP) reanalysis data and a simulation of the Canadian Centre for Climate Modeling and Analysis (CCCma) climate model. A simplified state-space model is also constructed to aid in the diagnosis and interpretation of the results. The relative advantages and disadvantages of combined PCA and RA are discussed. Overall, RA tends to

provide a clearer and more consistent picture of the underlying physical processes than combined PCA.

Brochu, R. and R. Laprise, 2007, Surface Water and Energy Budgets over the Mississippi and Columbia River Basins as Simulated by Two Generations of the Canadian Regional Climate Model, *Atmos.-Ocean*, **45**(1): 19–35, doi:10.3137/ao.v450102

This paper aims to compare and evaluate the surface energy and water budgets of simulations with the operational version of the Canadian Regional Climate Model (CRCM op) and the developmental version (CRCM dev). The CRCM op and CRCM dev differ in their use of second- and third-generation physical parameterizations packages of the Canadian General Circulation Model (CGCM) II and III, respectively. The improvements to the physics of CGCM III include the use of the Canadian Land Surface Scheme (CLASS), a three-layer soil model with explicit treatment of snow and canopy layers; it replaces the so-called Bucket hydrological scheme and one-layer force-restore surface energy budget in the CGCM II.

The common experimental configuration for this comparison is taken from the Project to Intercompare Regional Climate Simulations (PIRCS-1c) over the continental United States between 1987 and 1994. The analysis focuses on two major river basins with substantial differences in atmospheric forcings, vegetation and topography: the Mississippi and the Columbia river basins. The evaluation is made using observation-based data for monthly means of screen temperature, diurnal temperature range, precipitation, run-off estimated from streamflow, and snow depth. Some surface fluxes are also compared with the reanalyses from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium-range Weather Forecasts (ECMWF).

Results show that CRCM dev constitutes an improvement over CRCM op, particularly for summer evapotranspiration, precipitation and diurnal temperature range; a remaining cold bias in screen temperature, however, is associated with an excessive amount of snow in winter and a high run-off peak in spring. CRCM op underestimates the snow cover at the expense of the frozen water in the soil.

Harvey, L. D. D., 2008, Mitigating the atmospheric CO_2 increase and ocean acidification by adding limestone powder to upwelling regions, *J. Geophys. Res.*, **113**, C04028, doi:10.1029/2007JC004373

The feasibility of enhancing the absorption of CO_2 from the atmosphere by adding calcium carbonate ($CaCO_3$) powder to the ocean and of partially reversing the acidification of the ocean and the decrease in calcite supersaturation resulting from the absorption of anthropogenic CO_2 is investigated. $CaCO_3$ could be added to the surface layer in regions where the depth of the boundary between supersaturated and unsaturated water is relatively shallow (250–500 m) and where the upwelling velocity is large (30–300 m a^{-1}). The $CaCO_3$ would dissolve within a few 100 m depth below the saturation horizon, and the dissolution products

would enter the mixed layer within a few years to decades, facilitating further absorption of CO_2 from the atmosphere. This absorption of CO_2 would largely offset the increase in mixed layer pH and carbonate supersaturation resulting from the upwelling of dissolved limestone powder. However, if done on a large scale, the reduction in atmospheric CO_2 due to absorption of CO_2 by the ocean would reduce the amount of CO_2 that needs to be absorbed by the mixed layer, thereby allowing a larger net increase in pH and in supersaturation in the regions receiving $CaCO_3$. At the same time, the reduction in atmospheric pCO_2 would cause outgassing of CO_2 from ocean regions not subject to addition of $CaCO_3$, thereby increasing the pH and supersaturation in these regions as well. Geographically optimal application of 4 billion t of $CaCO_3$ a^{-1} (0.48 Gt C a^{-1}) could induce absorption of atmospheric CO_2 at a rate of 600 Mt CO_2 a^{-1} after 50 years, 900 Mt CO_2 a^{-1} after 100 years, and 1050 Mt CO_2 a^{-1} after 200 years.

Karpechko, A. Y., N. P. Gillett, L. J. Gray, and M. Dall'Amico, 2010, Influence of ozone recovery and greenhouse gas increases on Southern Hemisphere circulation, *J. Geophys. Res.*, **115**, D22117, doi:10.1029/2010JD014423

Stratospheric ozone depletion has significantly influenced the tropospheric circulation and climate of the Southern Hemisphere (SH) over recent decades, the largest trends being detected in summer. These circulation changes include acceleration of the extratropical tropospheric westerly jet on its poleward side and lowered Antarctic sea level pressure. It is therefore expected that ozone changes will continue to influence climate during the 21st century when ozone recovery is expected. Here we use two contrasting future ozone projections from two chemistry-climate models (CCMs) to force 21st century simulations of the HadGEM1 coupled atmosphere-ocean model, along with A1B greenhouse gas (GHG) concentrations, and study the simulated response in the SH circulation. According to several studies, HadGEM1 simulates present tropospheric climate better than the majority of other available models. When forced by the larger ozone recovery trends, HadGEM1 simulates significant deceleration of the tropospheric jet on its poleward side in the upper troposphere in summer, but the trends in the lower troposphere are not significant. In the simulations with the smaller ozone recovery trends the zonal mean zonal wind trends are not significant throughout the troposphere. The response of the SH circulation to GHG concentration increases in HadGEM1 includes an increase in poleward eddy heat flux in the stratosphere and positive sea level pressure trends in southeastern Pacific. The HadGEM1-simulated zonal wind trends are considerably smaller than the trends simulated by the CCMs, both in the stratosphere and in the troposphere, despite the fact that the zonal mean ozone trends are the same between these simulations.

Monahan, A. H., 2008, Probability distribution of sea surface wind stresses, *Geophys. Res. Lett.*, **35**, L05704, doi:10.1029/2007GL032268

The probability density function (pdf) of sea surface wind stresses is considered. Observed sea surface wind stresses are highly non-Gaussian, with characteristic relationships between moments. A consideration of empirical models of sea

surface wind stress pdfs built from models of sea surface vector winds demonstrates that non-Gaussian structure in the vector winds must be accounted for to accurately characterise the observed relationships between wind stress moments. An idealised stochastic boundary layer model is shown to provide a good qualitative characterisation of these pdfs.

Saenko, O. A, 2009b, On the climatic impact of wind stress, *J. Phys. Oceanogr.*, **39**: 89-106, doi:10.1175/2008JPO3981.1

A climate model is used to study the climatic impact of the stress exerted on the ocean by the atmosphere. When this stress is set to zero everywhere, the climate becomes much colder, with global-mean near-surface air temperature dropping from 14.8° to 6.1°C. The largest temperature decrease occurs in high latitudes, where sea ice advances equatorward to 40° of latitude. Many of these changes are induced by the changes in the oceanic circulation. In particular, with momentum flux set to zero, the meridional transport of buoyancy in the ocean, including that fraction often associated with the buoyancy-driven circulation, essentially vanishes and, hence, so does much of the surface heat flux. Vertical transport of buoyancy in the ocean is also strongly affected. In addition, the model suggests that the flux of momentum to the ocean has a profound indirect influence on the transport of latent heat. However, the total radiative flux entering the planet at low and midlatitudes does not change much. Instead, the net energy transport across 40°S increases, whereas that across 40°N decreases. The poleward energy transport in the atmosphere increases at midlatitudes in both hemispheres, whereas the oceanic heat transport decreases most strongly in the Northern Hemisphere. The climate becomes colder in both hemispheres, which is not easy to infer from the meridional transport of energy either by the climate system as a whole or by its individual components. Furthermore, the model suggests that it is the wind stress driving the midlatitude oceans-that is, where the oceanic heat transport accounts for only a very tiny fraction of the total poleward energy transport by the climate system, which is of more importance for maintaining the mean position of sea ice edge and, hence, much of the global climate.

Sigmond, M., J. C. Fyfe, and J. F. Scinocca, 2010, Does the ocean impact the atmospheric response to stratospheric ozone depletion? *Geophys. Res. Lett.*, **37**, L12706, doi:10.1029/2010GL043773

The impact of atmosphere-ocean interactions on the atmospheric response to stratospheric ozone depletion is investigated using a global climate model with a fully resolved stratosphere, troposphere, and with and without an interactive ocean component. We find that while atmosphere-ocean interactions have an impact on internally generated atmospheric fluctuations near the surface they have no discernable influence on the externally forced atmospheric response to stratospheric ozone depletion. This implies that an interactive ocean component in global climate models may not be crucial for obtaining reliable projections of future atmospheric change following the anticipated recovery of stratospheric ozone.

Yu, B., G. J. Boer, F. W. Zwiers, and W. J. Merryfield, 2009, Covariability of SST and surface heat fluxes in reanalyses and CMIP3 climate models, *Clim. Dyn.*, **36**(3-4): 589-605, doi:10.1007/s00382-009-0669-6

The generation and dissipation of SST anomalies is mediated by the covariability of SST and surface heat fluxes. The connection between the variability of heat flux (including its radiative and turbulent components) and that of SST is investigated using the NCEP-NCAR and ERA-40 reanalyses and the CMIP3 multi-model collection of climate simulations. The covariance patterns of SST and heat flux are broadly similar in the two reanalyses. The upward heat fluxes are positively correlated with the SST anomalies in the tropics, the northern Pacific mid-latitudes, and over the Gulf Stream, and negatively correlated in the northern subtropics and the SPCZ region. Common covariance features are seen in all climate models in the tropics and the subtropics, while covariances differ considerably among models at northern mid-latitudes, where weak values of the ensemble mean are seen. Lagged covariances are broadly similar in the two reanalyses and among the models, implying that heat flux feedback is also similar. The heat flux feedback parameter is determined from the lagged cross-covariances together with the auto-covariance of SST. Feedback is generally negative and is dominated by the turbulent component. The strongest feedback is found at mid-latitudes in both hemispheres, with the largest values occurring in the western and central portions of the oceans with extensions to higher latitudes. The latter are also areas with large inter-model differences. The heat flux feedback strengthens in winter and fall and weakens in spring and summer. The magnitudes of the annual and seasonal feedback parameters are slightly weaker in most models compared to the reanalysis-based estimates. The mean model feedback parameter has the best pattern correlation and the smallest mean square difference compared to the reanalysis-based values, although spatial variances are weak. Model resolution shows no relationship with the heat flux feedback parameters obtained from model results. The SST-heat flux covariance is decomposed into components associated with surface heat flux feedback and atmospheric forcing processes. Heat flux feedback dominates over the atmospheric forcing and heat flux damps SST anomalies on average at northern Pacific mid-latitudes and southern Atlantic mid-latitudes; while the reverse occurs in the SPCZ and northern Atlantic mid-latitudes.

Zhang, W. and W. Perrie, 2008, The influence of air-sea roughness, sea spray and storm translation speed on waves, *J. Phys. Oceanogr.*, **38**(4): 817–839, doi:10.1175/2007JPO3724.1

A coupled atmosphere–wave–sea spray model system is used to evaluate the impact of sea spray and wave drag on storm-generated waves, their height variations, and directional wave spectra in relation to the storm location and translation speed. Results suggest that the *decrease* or *increase* of significant wave height due to spray and wave drag is most significant in high-wind regions to the right of the storm track. These processes are modulations on the maximum-wave region and tend to occur several hours after the peak wind events, depending on the storm translation velocity. The translation speed of the storm is

important. The directional variation between local winds and wind-generated waves within rapidly moving storms that outrun the waves is notably different from that of trapped waves, when the dominant waves' group velocity approximates the storm translation speed. While wave drag and spray can increase or reduce the magnitudes of wind and significant wave height, their nondirectional formulations allow them to have little apparent effect on the directional wave spectra.

1.11 Tidal/Shelf Dynamics

Arbic, B. K. and C. Garrett, 2009, A coupled oscillator model of shelf and ocean tides. *Cont. Shelf Res.*, **30**(6): 564-574, doi:10.1016/j.csr.2009.07.008

The resonances of tides in the coupled open ocean and shelf are modeled by a mechanical analogue consisting of a damped driven larger mass and spring (the open-ocean) connected to a damped smaller mass and spring (the shelf). When both masses are near resonance, the addition of even a very small mass can significantly affect the oscillations of the larger mass. The influence of the shelf is largest if the shelf is resonant with weak friction. In particular, an increase of friction on a near-resonant shelf can, perhaps surprisingly, lead to an increase in ocean tides. On the other hand, a shelf with large friction has little effect on ocean tides. Comparison of the model predictions with results from numerical models of tides during the ice ages, when lower sea levels led to a much reduced areal extent of shelves, suggests that the predicted larger tidal dissipation then is related to the ocean basins being close to resonance. New numerical simulations with a forward global tide model are used to test expectations from the mechanical analogue. Setting friction to unrealistically large values in Hudson Strait yields larger North Atlantic M_2 amplitudes, very similar to those seen in a simulation with the Hudson Strait blocked off. Thus, as anticipated, a shelf with very large friction is nearly equivalent in its effect on the open ocean to the removal of the shelf altogether. Setting friction in shallow waters throughout the globe to unrealistically large values yields even larger open ocean tidal amplitudes, similar to those found in simulations of ice-age tides. It thus appears that larger modeled tides during the ice ages can be a consequence of enhanced friction in shallower water on the shelf in glacial times as well as a reduced shelf area then. Single oscillator and coupled oscillator models for global tides show that the maximum extractable power for human use is a fraction of the present dissipation rate, which is itself a fraction of global human power consumption.

Arbic B. K., R. Karsten, and C. Garrett, 2009, On tidal resonance in the global ocean and the back-effect of coastal tides upon open-ocean tides, *Atmo.-Ocean*, http://www.informaworld.com/smpp/title~db=all~content=t927698294~tab=issueslist~branches=47 - v47**47**(4): 239–266, doi:10.3137/OC311.2009

The resonance of semi-diurnal tidal elevations is investigated with a forward numerical forced damped global tide model and an analytical model of forced-damped tides in a deep ocean basin coupled to a shelf. The analytical model contains the classical half-wavelength and quarter-wavelength resonances in the deep ocean and shelf, respectively, as well as a forcing-scale dependence which

depends on the ratio of the phase speed of open-ocean gravity waves to that of the astronomical forcing. In the analytical model, when the deep ocean and shelf resonate separately at the same frequency, the resonance in the coupled system shifts to frequencies slightly higher and lower than the original frequency, such that a 'double bump' is seen in plots of elevation amplitude versus frequency. The addition of a shelf to a resonant open ocean tends to reduce open-ocean tides, especially when the shelf is also near resonance. The magnitude of this 'back-effect' is controlled by shelf friction. A weakly damped resonant shelf has a larger back-effect on the open-ocean tide than does a strongly damped shelf. Numerical simulations largely bear out the analytical model predictions, at least qualitatively. Idealized simulations show that continents enhance tides by enabling the half-wavelength resonance. Simulations with realistic geometry and topography but varying longitudinal structure in the astronomical forcing display an influence of the forcing scale on tidal amplitudes somewhat similar to that seen in the analytical model. A frequency sweep in the semi-diurnal band in experiments with realistic geometry and topography reveals weakly resonant peaks in the amplitudes of several shelf regions and in the globally averaged open-ocean amplitudes. Finally, the back-effect of the shelf upon the open ocean is seen in simulations in which locations of resonant coastal tides are blocked out and open-ocean tidal elevations are significantly altered (increased, generally) as a result.

Balmforth, N. J. and T. Peacock, 2009, Tidal Conversion by Supercritical Topography, *J. Phys. Oceanogr.*, **39**(8): 1965–1974

Calculations are presented of the rate of energy conversion of the barotropic tide into internal gravity waves above topography on the ocean floor. The ocean is treated as infinitely deep, and the topography consists of periodic obstructions; a Green function method is used to construct the scattered wavefield. The calculations extend the previous results of Balmforth et al. for subcritical topography (wherein waves propagate along rays whose slopes exceed that of the topography everywhere), by allowing the obstacles to be arbitrarily steep or supercritical (so waves propagate at shallower angles than the topographic slopes and are scattered both up and down). A complicated pattern is found for the dependence of energy conversion on ϵ, the ratio of maximum topographic slope to wave slope, and the ratio of obstacle amplitude and separation. This results from a sequence of constructive and destructive interferences between scattered waves that has implications for computing tidal conversion rates for the global ocean.

Bianchin, M., L. Smith, and R. Beckie, 2010, Quantifying hyporheic exchange in a tidal river using temperature time series, *Water Resour. Res.*, **46**, W07507, doi:10.1029/2009WR008365

An investigation into groundwater-surface water interaction (GSWI) beneath a large tidally influenced river was conducted to determine the effect of tides on the development of a hyporheic zone (HZ) and to quantify mixing of river water and groundwater. Temperature measurements, coupled with independent hydraulic head measurements, were used to detect groundwater flow within the riverbed. GWSI under tidal forcing produced a 1 m deep HZ. Time-averaged riverbed

temperature profiles displayed a distinct compressed convex pattern: clear evidence of net groundwater discharge. However, the instantaneous time series data indicate that riverbed temperatures were affected by tidal forcing to a depth of 1 m. Heat transport modeling revealed that instantaneous velocities within the shallow sediments of the riverbed are rather high, creating a zone of vigorous exchange during either a flooding or ebbing tide. Furthermore, the magnitude of the tidal pressure gradient was found to be significantly greater than the pressure gradient expected across 0.8 m high dunes, evidence that bed-form-driven exchange under these conditions, and this scale of observation, did not contribute to the development of the HZ. Conditions for exchange induced by shear and current bed form are favorable during ebbing tidal conditions only; flow paths are therefore limited in depth. Exchange flow paths in an estuary setting are complex; they are limited in duration and space and dominated by tidal pumping.

Blanchfield, J., C. Garrett, P. Wild, and A. Rowe, 2008, The extractable power from a channel linking a bay to the open ocean, *J. Power and Energy*, **222**, 289-297, doi:10.1243/09576509JPE524

Interest in the power potential of tidal streams is growing worldwide. While the latest assessment for Canadian coastlines estimates a resource of approximately 42 GW, these results are based on the average kinetic energy flux through the channel. It has been shown, however, that this method cannot be used to obtain the maximum extractable power for electricity generation. This work presents an updated theory for the extractable power from a tidal stream in a channel linking a bay to the open ocean. The maximum average extractable power from a channel linking a bay to the open ocean may be estimated, within approximately 15 per cent, as $0.22\rho\, gaQ_0$, where a is the amplitude of the dominant tidal constituent in the open ocean and Q_0 is the maximum volumetric flowrate in the undisturbed state.

Cherniawsky, J. Y., M. G. G. Foreman, S. K. Kang, R. Scharroo, and A. J. Eert, 2010, 18.6-year lunar nodal tides from altimeter data, *Cont. Shelf Res.*, **30**(6): 575-587, doi:10.1016/j.csr.2009.10.002

Harmonic analyses of 16-year long time series of collocated TOPEX, Poseidon and Jason-1 altimeter data were carried out in the Pacific and western Atlantic Oceans and their marginal seas. These time series are sufficiently long to adequately separate the 18.6-year nodal satellites Q_{1n}, O_{1n}, K_{1n}, M_{2n} and K_{2n} from their parent constituents Q_1, O_1, K_1, M_2 and K_2. Editing criteria were used to eliminate results in areas where these satellites are weak (i.e., smaller than their formal error estimates), or where they are strongly affected by aliased low-frequency signals (e.g. in the Kuroshio, in the Gulfstream and in their extension regions). As expected from tidal theory, the phases of the altimetry-derived nodal satellites agree reasonably well with the phases of their parents. However, due to their relatively small amplitudes and the remaining influence from low-frequency aliased signals, the altimeter observed amplitude ratios between the nodal satellites and their parent constituents tend to exceed the values predicted by the theory.

Examination of diurnal and semidiurnal nodal amplitudes in select coastal areas and marginal seas around the Pacific and the western Atlantic Ocean allowed the assignment of a *nodal character* to regions, which were each classified as *nodal diurnal*, *nodal semidiurnal*, or *nodal mixed*, based on the nodal amplitudes in each band. While the areas with predominant diurnal tides are all *nodal diurnal*, the small nodal ratio of 0.037 for M_{2n} resulted in some regions with strong M_2 tides being classified as *nodal diurnal* or *nodal mixed*. The amplitude ratio between K_{2n} and K_2 is 0.30, making the K_{2n} amplitudes sometimes comparable to those of M_{2n}. However, this effect was not sufficient to make all the areas with dominant M_2 to be dominant *nodal semidiurnal*.

The observed amplitudes of the 18.6-year nodal constituent M_n are relatively small, 1.5–3.5 cm. These values significantly exceed its theoretical amplitudes, which are less than 1 cm almost everywhere. The analysed signals at M_n frequency are therefore of mostly non-tidal origin, part of the broad-band decadal ocean variability.

Cummins, P. F., and L. Armi, 2010, Upstream Internal Jumps in Stratified Sill Flow: Observations of Formation, Evolution, and Release, *J. Phys. Oceanogr.*, **40**(6): 1419–1426, doi:10.1175/2010JPO4435.1

The time-dependent response of upstream undular bores and internal hydraulic jumps from initial formation to eventual release is documented. Two events, characterized by qualitatively different responses, are discussed. In the first case, an undular bore develops upstream of the sill crest. This disturbance remains upstream through the ebb tidal flow but is transformed to a hydraulic jump as its amplitude increases. Toward the end of ebb tide, it is released and subsequently disperses into a group of solitary-like waves. During the second event, an upstream jump also develops at an early stage of the tide. However, it is subsequently swept downstream by the tidal flow such that the upstream region then appears featureless. Approaching slack tide, as an exchange flow becomes established, a large bore or gravity current is emitted. The different responses seen in these two events are interpreted in terms of the Froude number associated with the near-surface stratification.

Garrett, C. and P. Cummins, 2007, The efficiency of a turbine in a tidal channel, *J. Fluid. Mech.*, **588**: 243-251, doi:10.1017/S0022112007007781

There is an upper bound to the amount of power that can be generated by turbines in tidal channels as too many turbines merely block the flow. One condition for achievement of the upper bound is that the turbines are deployed uniformly across the channel, with all the flow through them, but this may interfere with other uses of the channel. An isolated turbine is more effective in a channel than in an unbounded flow, but the current downstream is non-uniform between the wake of the turbines and the free stream. Hence some energy is lost when these streams merge, as may occur in a long channel. We show here, for ideal turbine models, that the fractional power loss increases from 1/3 to 2/3 as the fraction of the

channel cross-section spanned by the turbines increases from 0 to close to 1. In another scenario, possibly appropriate for a short channel, the speed of the free stream outside the turbine wake is controlled by separation at the channel exit. In this case, the maximum power obtainable is slightly less than proportional to the fraction of the channel cross-section occupied by turbines.

Garrett, C. and P. Cummins, 2008, Limits to tidal current power, *Renewable Energy*, **33**: 2485-2490, doi:10.1016/j.renene.2008.02.009

Estimating the extractable power of tidal currents in channels is a practical question that has received attention recently. Analysis has clearly shown that the power potential is not given by the flux of kinetic energy, as has been commonly assumed. A general formula for the maximum available power is reviewed, along with assessments of the reduction if only partial fences are used, as would be required for navigational and ecological reasons. In typical situations, the maximum power obtainable may be achieved with a surprisingly small number of turbines, especially if allowance is made for the flow reduction caused by drag on the supporting structures of turbines which reduces the maximum power available. Finally, the flow through tidal turbines is compared with the cooling water demands of nuclear reactors generating the same power.

Lamb, K. G., 2007, Tidally generated near-resonant internal wave triads at a shelf break, *Geophys. Res. Lett.*, **34**, L18607, doi:10.1029/2007GL030825

Numerical simulations of internal wave generation by tidal flow over a shelf break using a linear background stratification show the presence of near-resonant internal wave triads with spatially modulated amplitudes propagating away from the shelf break. The near-resonant triad is comprised of mode-one and -three waves of tidal frequency, which are directly forced by the tide-topography interaction, and a second harmonic, mode-two wave generated by the nonlinear interaction of these waves. A theory for these near-resonant triads is presented and compared with the numerical simulations.

Li, M., S. Radhakrishnan, U. Piomelli, and W. R. Geyer, 2010, Large-eddy simulation of the tidal-cycle variations of an estuarine boundary layer, *J. Geophys. Res.*, **115**, C08003, doi:10.1029/2009JC005702

The estuarine boundary layer affected by a horizontal density gradient exhibits temporal evolution over a tidal cycle, in a manner similar to the diurnal cycle of the ocean surface mixed layer. A large eddy simulation (LES) model is developed to investigate the physics controlling the growth of the boundary layer during the flood tide and restratification during the ebb tide. Turbulent kinetic energy, momentum and salt fluxes, bottom stress, and energy dissipation rates calculated from the LES model all show a strong flood-ebb asymmetry. Analysis of the turbulent kinetic energy (TKE) budget shows a primary balance between shear production and dissipation in the well-mixed boundary layer over the tidal cycle. However, TKE transport term is found to be important across the edge of the boundary layer during the flood tide so turbulent energy generated in the bottom boundary layer can be transferred to the stratified pycnocline region. Tidal

straining leads to a small and weakly convective region inside the boundary layer during the flood tide but the strain-induced buoyancy flux does not make a significant contribution to the turbulence generation. Additional LES runs are conducted by switching off the baroclinic pressure gradient term in the momentum equation and the tidal straining term in the salinity equation to show that the baroclinic pressure gradient is the main mechanism responsible for generating the flood-ebb mixing asymmetry.

Peacock, T., P. Echeverri, and N. J. Balmforth, 2008, An Experimental Investigation of Internal Tide Generation by Two-Dimensional Topography, *J. Phys. Oceanogr.*, **38**(1): 235–242

Experimental results of internal tide generation by two-dimensional topography are presented. The synthetic Schlieren technique is used to study the wave fields generated by a Gaussian bump and a knife edge. The data compare well to theoretical predictions, supporting the use of these models to predict tidal conversion rates. In the experiments, viscosity plays an important role in smoothing the wave fields, which heals the singularities that can appear in inviscid theory and suppresses secondary instabilities of the experimental wave field.

2 The Arctic

2.1 International Polar Year (IPY)

Barber, D. G., M. G. Asplin, Y. Gratton, J. V. Lukovich, R. J. Galley, R. L. Raddatz, and D. Leitch, 2010, The International polar year (IPY) circumpolar flaw lead (CFL) system study: Overview and the physical system, *Atmos.-Ocean*, **48**(4): 225-243, doi:10.3137/OC317.2010

The Circumpolar Flaw Lead (CFL) system study is a Canadian-led International Polar Year (IPY) initiative with over 350 participants from 27 countries. The study is multidisciplinary in nature, integrating physical sciences, biological sciences and Inuvialuit traditional knowledge. The CFL study is designed to investigate the importance of changing climate processes in the flaw lead system of the northern hemisphere on the physical, biogeochemical and biological components of the Arctic marine system. The circumpolar flaw lead is a perennial characteristic of the Arctic throughout the winter season and forms when the mobile multi-year (MY) pack ice moves away from coastal fast ice, creating recurrent and interconnected polynyas in the Norwegian, Icelandic, North American and Siberian sectors of the Arctic. The CFL study was 293 days in duration and involved the overwintering of the Canadian research icebreaker CCGS Amundsen in the Cape Bathurst flaw lead throughout the annual sea-ice cycle of 2007-2008.

In this paper we provide an introduction to the CFL project and then use preliminary data from the field season to describe the physical flaw lead system, as observed during the CFL overwintering project. Preliminary data show that

ocean circulation is affected by eddy propagation into Amundsen Gulf (AG). Upwelling features arising along the ice edge and along abrupt topography are also detected and identified as important processes that bring nutrient rich waters up to the euphotic zone. Analysis of sea-ice relative vorticity and sea-ice area by ice type in the AG during the CFL study illustrates increased variability in ice vorticity in late autumn 2007 and an increase in new and young ice areas in the AG during winter. Analysis of atmospheric data show that a strong northeast-southwest pressure gradient present over the AG in autumn may be a synoptic-scale atmospheric response to sensible and latent heat fluxes arising from areas of open water persisting into late November 2007. The median atmospheric boundary layer temperature profile over the Cape Bathurst flaw lead during the winter season was stable but much less so when compared to Russian ice is land stations.

Carmack, E., F. McLaughlin, S. Vagle, and H. Melling, 2008, Canada's Three Oceans (C3O): A Canadian contribution to the International Polar Year, *PICES Press.* **16**(2): 22-25, ISSN 1195-2512

no abstract

Introduction: The purpose of climate monitoring is to collect relevant, inter-comparable data over sustained periods of time so as to allow quantification of change within a system for decision-making purposes. This is the motivation of the "Canada's Three Oceans" (C3O) project, a Canadian contribution to the International Polar Year (IPY: 2007– 2009). C3O aims to (1) build an integrated, consilient view of the physical, chemical and biological oceanic structure of subarctic and arctic waters around Canada; and (2) use this information to establish a sound scientific basis for a long-term arctic and subarctic ocean monitoring strategy. By this strategy C3O will address change within ocean domains, identify gateways and barriers, and investigate the causal mechanisms, consequences and stability of frontal boundaries separating juxtaposed ocean domains. C3O will thus establish a 'climate change fence' around all of Canada's three oceans that will allow scientists and policy-makers alike to have the data and understanding upon which to practice good governance, and to deal with emerging issues such as warming, species invasion, hypoxia and acidification.

Carmack, E. C., F. A. McLaughlin, S. Vagle, H. Melling, and W. J. Williams, 2010, Structures and property distributions in the three oceans surrounding Canada in 2007: A basis for a long-term ocean climate monitoring strategy, *Atmos.-Ocean*, **48**(4): 211-224, doi:10.3137/OC324

The panarctic region is tightly connected to subarctic regions by through-flowing Atlantic and Pacific water masses and, as such, local changes in ice cover, ocean properties and ecosystem dynamics cannot be fully understood separately from large-scale oceanographic structures and advective processes. The Canadian International Polar Year (IPY) project Canada's Three Oceans (C3O) and the related Joint Ocean Ice Study (JOIS) have collected oceanographic data along a transit extending around northern North America to establish an initial, large-scale baseline against which present and future changes can be gauged. Special

focus was given to the shelf and the basin regions of the Canada Basin and the Canadian Arctic Archipelago. We use the first results from physical and geochemical data obtained during the summer of 2007 to discuss linkages between the Arctic and Subarctic domains and trace the cascade of key processes that affect contemporary ocean structure. A review of the literature, combined with these observations, is used to identify early signs of ongoing change throughout the three oceans surrounding northern North America including ocean warming and freshening, sea-ice melting, increased hypoxia, reduced pH and altered biogeography.

Pućko, M., G. A. Stern, D. G. Barber, R. W. Macdonald, and B. Rosenberg, 2010, The international polar year (IPY) circumpolar flaw lead (CFL) system study: The importance of brine processes for α- and ϒ-hexachlorocyclohexane (HCH) accumulation or rejection in sea ice, *Atmos.-Ocean*. **48**(4): 244-262, doi:10.3137/OC318.2010

We present evidence that both geophysical and thermodynamic conditions in sea ice are important in understanding pathways of accumulation or rejection of hexachlorocyclohexanes (HCHs). α- and γ-HCH concentrations and α-HCH enantiomer fractions have been measured in various ice classes and ages from the Canadian High Arctic. Mean α-HCH concentrations reached 0.642 ± 0.046 ng L-1 in new and young ice (<30 cm), 0.261 ±0.015 ng L-1 in the first-year ice (30-200 cm) and 0.208 ±0.045 in the old ice (>200 cm). Mean γ-HCH concentrations were 0.066 ± 0.006 ng L-1 in new and young ice, 0.040 ±0.002 ng L-1 in the first-year ice and 0.040 ±0.007 ng L-1 in the old ice. In general, α-HCH concentrations and vertical distributions were highly dependent on the initial entrapment of brine and the subsequent desalination process. γ-HCH levels and distribution in sea ice were not as clearly related to ice formation processes. During the year, first-year ice progressed from freezing (accumulation) to melting (ablation). Relations between the geophysical state of the sea ice and the vertical distribution of HCHs are described as ice passes through these thermodynamic states. In melting ice, which corresponded to the algal bloom period, the influence of biological processes within the bottom part of the ice on HCH concentrations and α-HCH enantiomer fraction is discussed using both univariate and multivariate approaches.

2.2 Modelling

Häkkinen, S., F. Dupont, M. Karcher, F. Kauker, D. Worthen, and J. Zhang, 2007, Model simulation of Greenland Sea upper-ocean variability, *J. Geophys. Res.*, **112**, C06S90, doi:10.1029/2006JC003687

Observations indicate that the occurrence of dense upper-ocean water masses coincides with periods of intense deep-water formation in the Greenland Sea. This paper focuses on the upper-ocean hydrography of the area and its simulation in models. We analyze properties that reside below the summer mixed layer at 200 m and carry the winter mixing signal. The analysis employs numerical simulations from four different models, all of which are forced as specified by the Arctic Ocean Model Intercomparison Project (AOMIP). The models exhibit varying degrees of success in simulating upper-ocean properties observed in the Greenland Sea, including very dense, saline water masses in the 1950s, 1960s,

and 1970s. Two of the models predict the importance of salinity in determining the maximum density in the upper waters of the central gyre. The circulation pattern of Atlantic Water was captured well by two high-resolution models as measured by temperature-salinity-density relationships. The simulated temporal variability of Atlantic Water properties was less satisfactory, particularly in the case of salinity.

Holloway, G., F. Dupont, E. Golobeva, S. Hakkinen, E. Hunke, M. Jin, M. Karcher, F. Kauker, M. Maltrud, M. A. Morales Maqueda, W. Maslowski, G. Platov, D. Stark, M. Steele, T. Suzuki, J. Y. Wang, D. Wortheen, and J. Zhang, 2007, Water properties and circulation in Arctic Ocean models, *J. Geophys. Res.*, **112**, C04S06, doi:10.1029/2006JC003643

As a part of the Arctic Ocean Model Intercomparison Project, results from 10 Arctic ocean/ice models are intercompared over the period 1970 through 1999. Models' monthly mean outputs are laterally integrated over two subdomains (Amerasian and Eurasian basins), then examined as functions of depth and time. Differences in such fields as averaged temperature and salinity arise from models' differences in parameterizations and numerical methods and from different domain sizes, with anomalies that develop at lower latitudes carried into the Arctic. A systematic deficiency is seen as AOMIP models tend to produce thermally stratified upper layers rather than the "cold halocline", suggesting missing physics perhaps related to vertical mixing or to shelf-basin exchanges. Flow fields pose a challenge for intercomparison. We introduce topostrophy, the vertical component of $\mathbf{V}\times\nabla D$ where $\mathbf{V}$ is monthly mean velocity and ∇D is the gradient of total depth, characterizing the tendency to follow topographic slopes. Positive topostrophy expresses a tendency for cyclonic "rim currents". Systematic differences of models' circulations are found to depend strongly upon assumed roles of unresolved eddies.

Holloway, G. and Z. Wang, 2009, Representing eddy stresses in an Arctic (global) model, *J. Geophys. Res.*, **114**, C06020, doi:10.1029/2008JC005169

Experiences with a number of ocean models have shown Arctic Ocean circulation to be quite dependent upon assumptions about eddy stresses. A key difference is between assuming that subgrid eddies act as friction and assuming that eddies act to generate entropy, propelling mean flows (sometimes called "neptune"). Fisheries and Oceans Canada is developing global ocean and sea ice modeling after Nucleus for European Modeling of the Ocean (NEMO). We have modified NEMO to include neptune as an alternative to friction. Consistent with previous modeling studies, our results show marked impacts. Neptune supports narrow cyclonic midwater and deepwater currents around the peripheries of Arctic basins. Neptune also induces two-way flows through channels in the Canadian Archipelago and limits the width of the ice tongue exiting at Fram Strait.

Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H. W. Schenke, and P. Johnson, 2008, An improved bathymetric portrayal of the Arctic Ocean:

Implications for ocean modeling and geological, geophysical and oceanographic analyses, *Geophys. Res. Lett.*, **35**, L07602, doi:10.1029/2008GL033520

A digital representation of ocean floor topography is essential for a broad variety of geological, geophysical and oceanographic analyses and modeling. In this paper we present a new version of the International Bathymetric Chart of the Arctic Ocean (IBCAO) in the form of a digital grid on a Polar Stereographic projection with grid cell spacing of 2 × 2 km. The new IBCAO, which has been derived from an accumulated database of available bathymetric data including the recent years of multibeam mapping, significantly improves our portrayal of the Arctic Ocean seafloor.

2.3 Climate Change

Barber, D. G., J. V. Lukovich, J. Keogak, S. Baryluk, L. Fortier, and G. H. R. Henry, 2008, The Changing Climate of the Arctic, *Arctic*, **61**: 7-26

The first and strongest signs of global-scale climate change exist in the high latitudes of the planet. Evidence is now accumulating that the Arctic is warming, and responses are being observed across physical, biological, and social systems. The impact of climate change on oceanographic, sea-ice, and atmospheric processes is demonstrated in observational studies that highlight changes in temperature and salinity, which influence global oceanic circulation, also known as thermohaline circulation, as well as a continued decline in sea-ice extent and thickness, which influences communication between oceanic and atmospheric processes. Perspectives from Inuvialuit community representatives who have witnessed the effects of climate change underline the rapidity with which such changes have occurred in the North. An analysis of potential future impacts of climate change on marine and terrestrial ecosystems underscores the need for the establishment of effective adaptation strategies in the Arctic. Initiatives that link scientific knowledge and research with traditional knowledge are recommended to aid Canada's northern communities in developing such strategies.

Holland, M. M., B. Tremblay, D. Bailey, and C. M. Bitz, 2008, The Role of Natural Versus Forced Changes in Future Rapid Summer Arctic Ice, *Geophysical Monograph Series*, **180**:133-150, doi:10.1029/180GM10

Climate model simulations from the Community Climate System Model, version 3 (CCSM3) suggest that Arctic sea ice could undergo rapid September ice retreat in the 21st century. A previous study indicated that this results from a thinning of sea ice to more vulnerable conditions, a "kick" in the form of pulse-like increases in ocean heat transport and positive feedbacks that accelerate the retreat. Here we further examine the factors affecting these events, including the role of natural versus forced change and the possibility of threshold-like behavior in the simulated sea ice cover. We find little indication that a critical sea ice state is reached that then leads to rapid ice loss. Instead, our results suggest that the rapid ice loss events result from anthropogenic change reinforced by growing intrinsic variability. The natural variability in summer ice extent increases in the 21st century because of the thinning ice cover. As the ice thins, large regions can easily melt out, resulting in considerable ice extent variations. The important role

of natural variability in the simulated rapid ice loss is such that we find little capability for predicting these events based on a knowledge of prior ice and ocean conditions. This is supported by results from sensitivity simulations initialized several years prior to an event, which exhibit little predictive skill.

Holloway, G. and A. Proshutinsky, 2007, The role of tides in Arctic ocean/ice climate, *J. Geophys. Res.*, **112,** C04S06, doi:10.1029/2006JC003643

A three-dimensional coupled ocean/ice model, intended for long-term Arctic climate studies, is extended to include tidal effects. From saved output of an Arctic tides model, we introduce parameterizations for (1) enhanced ocean mixing associated with tides and (2) the role of tides fracturing and mobilizing sea ice. Results show tides enhancing loss of heat from Atlantic waters. The impact of tides on sea ice is more subtle as thinning due to enhanced ocean heat flux competes with net ice growth during rapid openings and closings of tidal leads. Present model results are compared with an ensemble of nine models under the Arctic Ocean Model Intercomparison Project (AOMIP). Among results from AOMIP is a tendency for models to accumulate excessive Arctic Ocean heat throughout the intercomparison period 1950 to 2000 which is contrary to observations. Tidally induced ventilation of ocean heat reduces this discrepancy.

Min, S.-K., X. Zhang, and F. Zwiers, 2008, Human-induced Arctic moistening, *Science*, **320**(5875): 518-520, doi:10.1126/science.1153468

The Arctic and northern subpolar regions are critical for climate change. Ice-albedo feedback amplifies warming in the Arctic, and fluctuations of regional fresh water inflow to the Arctic Ocean modulate the deep ocean circulation and thus exert a strong global influence. By comparing observations to simulations from 22 coupled climate models, we find influence from anthropogenic greenhouse gases and sulfate aerosols in the space-time pattern of precipitation change over high-latitude land areas north of 55°N during the second half of the 20th century. The human-induced Arctic moistening is consistent with observed increases in Arctic river discharge and freshening of Arctic water masses. This result provides new evidence that human activity has contributed to Arctic hydrological change.

2.4 Beaufort Sea / Beaufort Gyre

Asplin, M. G., J. V. Lukovich, and D. G. Barber, 2009, Atmospheric forcing of the Beaufort Sea ice gyre: Surface pressure climatology and sea ice motion, *J. Geophys. Res.*, **114**, C00A06, doi:10.1029/2008JC005127

The Beaufort Gyre (BG) typically rotates anticyclonically and exerts an important control on Arctic Sea ice dynamics. Previous studies have shown reversals in the BG to rotate cyclonically during summer months and, in recent decades, throughout the annual cycle. In this investigation, we explore the synoptic climatology of atmospheric forcing and its relationship to sea ice motion and BG reversals. A catalog of daily synoptic weather types is generated for the Beaufort Sea Region covering the period 1979 to 2006 using NCEP/NCAR reanalysis

mean sea level pressure data, principle components, and k-means cluster analyses. Mean synoptic type frequency, persistence, and duration values are calculated for each synoptic type and contrasted between the summer and winter seasons. Daily synoptic types are linked to changes in sea ice vorticity by using correlation analysis on lagged sea ice vorticity data. Lag correlations are found between synoptic types and sea ice vorticity smoothed over a 12-week running mean and show that cyclonic types, which promote southerly or easterly atmospheric circulation over the southern Beaufort Sea, commonly precede summer reversals. Furthermore, significant seasonal within-type variability in sea ice vorticity is detected within the synoptic types illustrating the importance of seasonal variability on these processes.

Darnis, G., D. G. Barber, and L. Fortier, 2007, Sea Ice and the Onshore-Offshore Gradient in pre-winter Zooplankton Assemblages in Early Fall in South-Eastern Beaufort Sea, *J. Mar. Sys.*, **74**: 994-1011, doi:10.1016/j.jmarsys.2007.09.003

Zooplankton communities were studied in southeastern Beaufort Sea (Arctic Ocean) in September–October 2002. Cluster analysis and non-metric multidimensional scaling revealed three distinct mesozooplankton assemblages. A neritic assemblage occurred on the Mackenzie Shelf and in Franklin Bay, while distinct off-shelf assemblages prevailed in the Cape Bathurst Polynya and on the Beaufort Slope respectively. Over 95% of the mesozooplankton was comprised of eight copepod taxa. *Pseudocalanus* spp. contributed predominantly to the discrimination of the three assemblages and was the only significant indicator of the Shelf assemblage. *Oithona similis*, *Oncaea borealis*, *Metridia longa* and *Calanus hyperboreus* were indicators of the Polynya assemblage. *Cyclopina* sp. and *Microcalanus pygmaeus* were indicative of the overall off-shelf community (Polynya and Slope assemblages). The importance of omnivores and carnivores increased from the shelf to the polynya and the slope. Station depth and duration of reduced ice conditions during summer (< 50% ice concentration) underpinned the distribution of the assemblages ($r^2 = 0.71$ and 0.45 respectively). The abundance of *Pseudocalanus* spp. was independent of depth and increased with the duration of reduced ice conditions ($r_s = 0.438$). The abundance of *Cyclopina* sp., *M. pygmaeus* and other indicators of the offshore assemblages followed the opposite trend ($r_s = -0.467$ and -0.5 respectively). Under continued climate warming, a reduction of the ice cover will affect the biogeography of mesozooplankton on and around the Mackenzie Shelf, to the potential advantage of *Pseudocalanus* spp. and other calanoid herbivores.

Guay, C. K. H., F. A. McLaughlin, and M. Yamamoto-Kawai, 2009, Differentiating fluvial components of upper Canada Basin waters on the basis of measurements of dissolved barium combined with other physical and chemical tracers, *J. Geophys. Res.*, **114**, C00A09, doi:10.1029/2008JC005099

The utility of dissolved barium (Ba) as a quasi-conservative tracer of Arctic water masses has been demonstrated previously. Here we report distributions of salinity, temperature, and Ba in the upper 200 m of the Canada Basin and adjacent areas observed during cruises conducted in 2003–2004 as part of the Joint Western

Arctic Climate Study and Beaufort Gyre Exploration Project. A salinity–oxygen isotope mass balance is used to calculate the relative contributions from sea ice melt, meteoric, and saline end-members, and Ba measurements are incorporated to resolve the meteoric fraction into separate contributions from North American and Eurasian sources of runoff. Large fractions of Eurasian runoff (as high as 15.5%) were observed in the surface layer throughout the Canada Basin, but significant amounts of North American runoff in the surface layer were only observed at the southernmost station occupied in the Canada Basin in 2004, nearest to the mouth of the Mackenzie River. Smaller contributions from both Eurasian and North American runoff were evident in the summer and winter Pacific-derived water masses that comprise the underlying upper halocline layer in the Canada Basin. Significant amounts of Eurasian and North American runoff were observed throughout the water column at a station occupied in Amundsen Gulf in 2004. This suggests the export of runoff from both sources through the passages of the Canadian Arctic Archipelago.

Kulikov, E. A., A. B. Rabinovich, and E. C. Carmack, 2010, Variability of baroclinic tidal currents on the Mackenzie Shelf, the Southeastern Beaufort Sea, *Cont. Shelf Res.*, **30**(6): 656-667, doi:10.1016/j.csr.2009.11.006

Semidiurnal tidal currents on the outer shelf of the Mackenzie Shelf in the Beaufort Sea were found to be strongly influenced by the locally generated baroclinic tide. Two primary factors are involved in this process: (1) the sharp shelf break along the northeastern Mackenzie Shelf, promoting the generation of vigorous internal tidal waves; and (2) the proximity to critical latitudes for M_2 and N_2 motions locking these waves and preventing them from leaving the source region. As a result, internal tides are resonantly trapped between the shelf and critical latitudes. The physical properties and temporal variations of tidal motions were examined using current meter measurements obtained from 1987–1988 at four sites (SS1, SS2, SS3, and SS4) offshore of the shelf break at depths of ~200 m. Each mooring had Aanderaa RCM4s positioned at ~35 m below the surface and ~50 m above the bottom. Complex demodulation was used to compute the envelopes (amplitude modulation) of these components. A striking difference in the variability of clockwise (CW) and counterclockwise (CCW) tidal currents was found. The CW tides are highly variable, have greater amplitude, exhibit a burst-like character associated with wind events and contain about 80% of the total energy of the semidiurnal tidal currents. In contrast, the CCW components have a more regular temporal regime with distinct monthly, fortnightly and 10-day modulation at astronomical periodicities associated with frequency differences M_2–N_2 (0.03629 cpd), S_2–M_2 (0.06773 cpd), and S_2–N_2 (0.10402 cpd). Significant horizontal correlation of the CW current envelopes was found only between stations near the northeast Mackenzie Shelf, indicating this to be the main area of baroclinic internal wave generation.

Lavoie, D., K. L. Denman, and R. W. Macdonald, 2009, Primary productivity and export fluxes on the Canadian shelf of the Beaufort Sea: a modelling study, *Ocean Modelling*, **75**(1-2):17-32, doi:10.1016/j.jmarsys.2008.07.007

We present a coupled sea ice–ocean-biological (including ice algae) model in the Arctic Ocean. The 1D model was developed and implemented on the Canadian Beaufort Sea shelf to examine the importance of different physical processes in controlling the timing and magnitude of primary production and biogenic particle export over an annual cycle (1987). Our results show that the snow and sea ice cover melt and/or break-up controls the timing of the phytoplankton bloom but primary producers (ice algae and phytoplankton) on the outer shelf are essentially nutrient limited. The total annual primary production (22.7 to 27.7 g-C m^{-2}) is thus controlled by nutrient "pre-conditioning" in the previous fall and winter and by the depth of wind mixing that is controlled in part by the supply of fresh water at the end of spring (ice melt or runoff). The spring bloom represents about 40% of the total annual primary production and occurs in a period of the year when sampling is often lacking. Time interpolation of observed values to obtain total annual primary production, as done in many studies, was shown to lead to an underestimation of the actual production. Our simulated ratios of export to primary production vary between 0.42 and 0.44.

Manson, G. K. and S. M. Solomon, 2007, Past and Future Forcing of Beaufort Sea Coastal Change, *Atmos.-Ocean*, **45** (2): 107–122, doi:10.3137/ao.450204

Changes to the Beaufort Sea shoreline occur due to the impact of storms and rising relative sea level. During the open-water season (June to October), storm winds predominantly from the north-west generate waves and storm surges which are effective in eroding thawing ice-rich cliffs and causing overwash of gravel beaches. Climate change is expected to be enhanced in Arctic regions relative to the global mean and include accelerated sea-level rise, more frequent extreme storm winds, more frequent and extreme storm surge flooding, decreased sea-ice extent, more frequent and higher waves, and increased temperatures. We investigate historical records of wind speeds and directions, water levels, sea-ice extent and temperature to identify variability in past forcing and use the Canadian Global Coupled Model ensembles 1 and 2 (CGCM1 and CGCM2) climate modelling results to develop a scenario forcing future change of Beaufort Sea shorelines. This scenario and future return periods of peak storm wind speeds and water levels likely indicate increased forcing of coastal change during the next century resulting in increased rates of cliff erosion and beach migration, and more extreme flooding.

McLaughlin, F. A., E. C. Carmack, W. J. Williams, S. Zimmermann, K. Shimada, and M. Itoh, 2009, Joint effects of boundary currents and thermohaline intrusions on the warming of Atlantic water in the Canada Basin, 1993–2007, *J. Geophys. Res.*, **114**, C00A12, doi:10.1029/2008JC005001

The 1990–1991 influx of Atlantic water, both anomalously warm and in greater volume than in the past, enveloped the Chukchi Borderland in the western Canada Basin by 2002 and spread across the southeastern Canada Basin by 2007. Warmer, younger (more ventilated), and less dense Fram Strait Branch waters have replaced colder, older, and denser waters, increasing the temperature of the Fram Strait Branch core from a 50-year or more mean of ~0.45°C to ~0.7°C.

Physical and geochemical data collected from 1993 to 2007 show that the two main transport mechanisms are the boundary current and thermohaline intrusions, established by large thermal gradients. The boundary current operates in a cyclonic direction whereas the thermohaline intrusions operate in an anticyclonic direction because of the influence of the Beaufort Gyre. This shows that the Beaufort Gyre's effect on ocean circulation extends into the Fram Strait Branch of the Atlantic layer. The boundary current, a fully pan-Arctic structure, is much slower in the Canada Basin than in basins upstream, with an effective speed of ~0.5 cm/s. The effective spreading rate of the thermohaline intrusions, relative to the core, is 0.2 cm/s. Thermohaline intrusions show signs of dissipation near the Northwind Ridge in 2007 suggesting that as temperature gradients between inflowing and resident waters decrease, they will disappear from the Canada Basin.

Pickart, R. S., G. W. K. Moore, D. J. Torres, P. S. Fratantoni, R. A. Goldsmith, and J. Yang, 2009, Upwelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response, *J. Geophys. Res.*, **114**, C00A13, doi:10.1029/2008JC005009

The characteristics of Pacific-born storms that cause upwelling along the Beaufort Sea continental slope, the oceanographic response, and the modulation of the response due to sea ice are investigated. In fall 2002 a mooring array located near 152°W measured 11 significant upwelling events that brought warm and salty Atlantic water to shallow depths. When comparing the storms that caused these events to other Aleutian lows that did not induce upwelling, interesting trends emerged. Upwelling occurred most frequently when storms were located in a region near the eastern end of the Aleutian Island Arc and Alaskan Peninsula. Not only were these storms deep but they generally had northward-tending trajectories. While the steering flow aloft aided this northward progression, the occurrence of lee cyclogenesis due to the orography of Alaska seems to play a role as well in expanding the meridional influence of the storms. In late fall and early winter both the intensity and frequency of the upwelling diminished significantly at the array site. It is argued that the reduction in amplitude was due to the onset of heavy pack ice, while the decreased frequency was due to two different upper-level atmospheric blocking patterns inhibiting the far field influence of the storms.

Proshutinsky, A., R. Krishfield, and D. Barber, 2009, Preface to special section on Beaufort Gyre Climate System Exploration Studies: Documenting key parameters to understand environmental variability, *J. Geophys. Res.*, **114**, C00A08, doi:10.1029/2008JC005162

no abstract; introduction

The Beaufort Gyre (BG) of the Arctic Ocean is one of the most hostile and inaccessible areas of the globe. Until late 1920s most of it had never been measured or even explored. The region's harsh climate, winter darkness, and thick drifting sea ice deterred potential observers and made this area inaccessible to scientific expeditions. The BG is a unique phenomenon comprising a set of specific atmospheric, sea ice, and oceanic conditions that have significant

influence on the Arctic climate. The papers of this special issue focus on the atmospheric, sea ice, oceanographic, and some biogeochemical features of this region and describe the BG system variability at seasonal to decadal timescales, employing historical and the most recent data, simple hypotheses, and models to estimate changes.

Williams, W. J., H. Melling, E. C. Carmack, and R. G. Ingram, 2008, Kugmallit Valley as a conduit for cross-shelf exchange on the Mackenzie Shelf in the Beaufort Sea, *J Geophys. Res.*, **113**, doi:1029/2006JC003591

Kugmallit Valley spans the midsection of a transect across the Mackenzie Shelf of the Beaufort Sea. Its greatest relief is 20 m, and its width is 20 km. Using a yearlong record of ice drift, ocean current, temperature, and salinity acquired near the center of the valley, we describe a pattern of flow that is correlated with wind stress and ice motion and discuss its similarity to flow within larger submarine canyons that cut through the shelf break. As in such canyons, there is enhanced cross-shelf transport within Kugmallit Valley during upwelling-favorable surface stress. The data also document the down-valley flow of dense water from a flaw lead.

2.5 Arctic Circulation and Throughflow

Bacon, S., P. G. Myers, B. Rudels, and D. A. Sutherland, 2008, Accessing the Inaccessible: Buoyancy-Driven Coastal Currents on the Shelves of Greenland and Eastern Canada, Arctic–Subarctic Ocean Fluxes, 703-722, doi:10.1007/978-1-4020-6774-7_29

One reason why the Polar and Sub-polar shelf seas are an important component of the global climate system is that they support the fluxes of large volumes of both solid and liquid freshwater supplied from the cryospheres, the hydrosphere and the atmosphere.

This chapter is about sub-Arctic shelf waters in the western Atlantic sector, the extent of which is illustrated in Fig. 28.1. We will discuss the relevant coasts of Greenland and eastern Canada: specifically, east Greenland from Belgica Bank through Denmark Strait to Cape Farewell; then west Greenland from the Labrador Sea through Davis Strait to Baffin Bay; then Baffin Island and the coast of Labrador. Finally, we will summarise what we think we know, and also what is important that we do not know.

Defossez, M., F. J. Saucier, P.G. Myers, D. Caya, J.-F. Dumais, Analysis of a dense water pulse following mid-winter opening of polynyas in western Foxe Basin, Canada, *Dyn. Atmos. Oceans*, **49(**1): 54-74, doi:10.1016/j.dynatmoce.2008.12.002

A recent study has shown that Foxe Basin's dense waters originate from coastal latent heat polynyas and each year replace 2/3rd of the basin's deep waters by propagating southeastwards in Foxe Channel as a gravity current. The formation mechanisms in 2004 of these dense waters are examined here. Strong meteorological events occurring in mid-winter over the domain are responsible for the simultaneous opening of two large polynyas at Lyon Inlet and along

Melville Peninsula's eastern coast while a third important and recurrent polynya opens earlier at Hall Beach (northwestern Foxe Basin). Large sea-atmosphere heat exchanges take place in these polynyas, leading to the production of 21.2×10^{12} kg of sea-ice and 1.53×10^{12} m^3 of dense water. The ice production rate is on average five to six times higher in the polynyas than in the rest of the basin. Following the topography, the dense waters formed at Hall Beach and along Melville Peninsula cascade into Foxe Channel, while those produced at Lyon Inlet sink directly in the channel through deep convection. The two mechanisms synchronize and combine together when Lyon Inlet and Melville Peninsula polynyas open up. The heat exchanges, sea-ice and brine production rates estimated with a 21-year near-climatology are similar to those found in 2004. The results also show that the produced dense waters can overflow into Hudson Bay.

Dickson, R. R., B. Rudels, S. Dye, M. Karcher, J. Meincke, and I. Yashayaev, 2007, Current estimates of freshwater flux through Arctic and subarctic seas, *Prog. Ocean.*, **73**(3-4): 210 230, doi:10.1016/j.pocean.2006.12.003

As the world warms, the expectation is that the freshwater outflows from the Arctic Ocean to the North Atlantic will strengthen and may act to suppress the rate of the climatically-important Atlantic meridional overturning circulation. Hitherto, however, we have lacked the system of measurements required to estimate the totality of the freshwater flux through subarctic seas. Though observations remain patchy and rudimentary in places, we piece-together the results from recent large-scale observational programmes together with associated modelling, to establish preliminary maps of the rates and pathways of freshwater flux through subarctic seas. These fluxes are calculated according to two reference salinities, $S = 34.8$ to conform with the majority of estimates reported in the literature, and $S = 35.2$, the salinity of the inflowing Atlantic water, to calculate the freshwater balance of the 'Arctic Mediterranean'. We find that 148 mSv of freshwater enters the Nordic Seas across its northern boundary. There it is supplemented by around 54 mSv of freshwater from Baltic runoff, Norwegian runoff, P − E and Greenland ice melt, so that the total freshwater contribution to the Nordic Seas from all sources is 202 mSv. Of this, around 51 mSv of freshwater is estimated to pass south to the deep Atlantic in the dense water overflows leaving an assumed balance of 151 mSv to leave the Nordic Seas in the upper water export through Denmark Strait. The corresponding estimate for the freshwater outflow west of Greenland is 103 mSv relative to 35.2 so that the total freshwater flux reaching the North Atlantic through subarctic seas is around 300 mSv.

Dumont, D., Y. Gratton, T. E. Arbetter, 2010, Modeling Wind-Driven Circulation and Landfast Ice-Edge Processes during Polynya Events in Northern Baffin Bay, *J. Phys. Oceanogr.*, **40**(6): 1356–1372, http://journals.ametsoc.org/doi/abs/10.1175/2010JPO4292.1doi:10.1175/2010JPO4292.1

A high-resolution sea ice–ocean numerical model of the North Water polynya has been developed to study the wind-driven circulation during polynya events. An

idealized three-layer stratified ocean is used to initialize the model to characterize the baroclinic response to realistic wind and ice conditions. The model general circulation pattern is mainly forced by an along-channel sea level gradient between the Arctic Ocean and Baffin Bay, which determines the magnitude of the southward Baffin Current, and by an across-channel sea level gradient in Baffin Bay, which drives the northward West Greenland Current (WGC). These two currents are found to be anticorrelated to each other in the Smith Sound area. During strong northerly wind events, occurring quite frequently in the winter–spring period in the polynya, nutrient-rich Baffin Bay waters transported by the WGC are forced toward the Greenland shelf, coinciding with upwelling events along the Greenland coast. Whenever an ice bridge is present (i.e., the polynya exists and is substantially open), upwelling also occurs at the landfast ice edge. In such cases, the total upwelling area is increased by an amount that depends on the form of the ice bridge but could easily double during certain years. The baroclinic circulation associated with the upwelling response includes the formation of a cyclonic eddy attached to the ice edge that is generated during strong northerly wind events. Primary production estimations reveal that upwelling during polynya events plays a significant role in the early spring phytoplankton bloom, suggesting that the disappearance of the polynya as a result of climate change may have profound implications for the entire ecosystem.

Itoh, M., E. Carmack, K. Shimada, F. McLaughlin, S. Nishino and S. Zimmermann, 2007, Formation and spreading of Eurasian source oxygen-rich halocline water to the Canadian Basin of the Arctic Ocean, *Geophys. Res. Lett.*, **34,** L08603, doi:10.1029/2007Gl029482

We identify the source region and spreading pattern of cold, oxygen-rich water observed in the halocline of the northern Canada Basin using both Joint Western Arctic Climate Studies 2002–2005 and other data. This water originates in the winter mixed-layer in the Nansen Basin and, because of its convective origin, can be traced by its cold, oxygen-rich properties together with a signature of low potential vorticity. This water, a component of the cold halocline complex, spreads into the Makarov Basin across the Lomonosov Ridge between 82°N and 86°N, enters the Canada Basin between the Alpha and Mendeleyev ridges, and continues eastward into the Beaufort Gyre north of Chukchi Plateau.

Melling, H., T. A. Agnew, K. K. Falkner, D. A. Greenberg, C. M. Lee, A. Münchow, B. Petrie, S. J. Prinsenberg, R. M. Samelson, and R. A. Woodgate, 2008, Fresh-Water Fluxes via Pacific and Arctic Outflows Across the Canadian Polar Shelf, Arctic-Subarctic Ocean Fluxes, 193-247, doi:10.1007/978-1-4020-6774-7_10

Observations have revealed persistent flows of relatively low salinity from the Pacific to the Arctic and from the Arctic to the Atlantic (Melling 2000). It is customary to associate fluxes of fresh-water with these flows of brine, as follows: the fresh-water flux is the volume of fresh water that must be combined with a volume of reference-salinity water to yield the volume of seawater of the salinity observed. As with sensible heat flux, the choice of reference is arbitrary, but the value 34.8 is often used in discussions of the Arctic. This value is an estimate of

the mean salinity of the Arctic Ocean by Aagaard and Carmack (1989) for a time period and averaging domain that were not specified. Because the salinity of seawater flowing across the shallow Bering, Chukchi and Canadian Polar shelves is typically lower than 34.8, these flows transport fresh-water from the Pacific to the Atlantic Ocean.

Münchow, A., K. K. Falkner, and H. Melling, 2007,: Spatial continuity of measured seawater and tracer fluxes through Nares Strait, a dynamically wide channel bordering the Canadian Archipelago, *J. Mar. Res.*, **65**(6): 759-788

Freshwater delivered as precipitation and runoff to the North Pacific and Arctic oceans returns to the Atlantic principally via the Canadian polar shelf and Fram Strait. It is conveyed as ice or freshened seawater. Here we use detailed ship-based measurements to calculate a snap-shot of volume, freshwater, and tracer fluxes through Nares Strait, a 500-km long waterway separating Greenland and Ellesmere Island. We use quasi-synoptic observations of current by ship-mounted acoustic Doppler current profiler (ADCP), of salinity and temperature by CTD probe and of dissolved nutrients by rosette bottle sampler on four cross-sections between 82 and 78N latitude. Data were collected during the first half of August 2003. We partition the fluxes into components derived from Pacific and Atlantic inflows into the Arctic Ocean. During the time of the survey, there was a net southward 0.91±0.10 Sv (10^6 m^3 s^{-1}) flux of volume and a net southward 31±4 10^{-3} Sv (977±127 km^3 y^{-1}) flux of freshwater relative to a salinity of 34.8. Much of the volume flux was carried within a strong (40 cm s^{-1}), narrow (10 km) subsurface jet hugging the western (Ellesmere Island) side of the strait. The presence of this jet in four sections spanning the 500-km length of the strait is evidence of a buoyant boundary current through the strait. The jet was coincident with elevated concentrations of phosphate (1.0 mmol m^{-3}) and silicate (11 mmol m^{-3}) which both indicate a Pacific Ocean source. We interpreted the ratio of dissolved total inorganic nitrogen to phosphate in terms of fractional dilution of Atlantic by Pacific waters. About 0.43±0.10 Sv (39%) of the southward flow was of Pacific origin. These results are a snapshot during the summer of 2003 following a prolonged period of northward directed wind stress when ice cover was mobile. Although long-term mean values are likely different, we determined that the major fraction of the through-flow is carried by a jet of scale determined by the internal Rossby radius (5-10 km).

Münchow, A. and H. Melling, 2008, Ocean current observations from Nares Strait to the west of Greenland: Interannual to tidal variability and forcing, *J. Mar. Res.*, **66**(6): 801-833

During 2003-06, as part of the Arctic Sub-Arctic Ocean Flux (ASOF) experiment, an array of oceansensing instruments was deployed at 80.5N latitude to investigate the flux of seawater from the Arctic Ocean via Nares Strait, the pathway to the west of Greenland. Three-year measurements of current from this experiment provide, for the first time at periods longer than a single season, the seawater flux and its variability via this important pathway. Below 30-m depth the average flux of volume 2003-06 was 0.57±0.09 Sv (1 Sv = 10^6 m^3 s^{-1}) southward

over a 38-km wide section reaching 360 m in depth. A linear trend, statistically significant at the 95% confidence level, indicates an increase in the sectionally averaged flow below 30-m depth of 20 ± 10% between 2003 and 2006. The flow is dominated by mixed diurnal and semi-diurnal tidal currents with kinetic energy an order of magnitude larger than that of the subtidal flow. The range of seasonal variation is 30-50% of the long-term mean flow. Variations in flow of daily to monthly period are comparable in magnitude to the average flow. The flow through the cross-section is the net result of a larger southward flux in the deep western two thirds of the strait and a small northward flux within about 5 km of Greenland. The latter is about 5% of the former. Spectral analyses indicates that the cross-channel pressure gradient is highly correlated with the sectionally averaged flow consistent with geostrophy. Along-channel pressure gradient explains 70% of the variance at a 33-day period with a phase lag consistent with a frictional response; at 3-7 day period the response is weaker (<30%) with a phase relation suggestive of contributions by both friction and local acceleration.

Myers, P. G., C. Donnelly, and M. H. Ribergaard, 2009, Structure and variability of the West Greenland Current in Summer derived from 6 repeat standard sections, *Prog. in Oceanogr.*, **80**(1-2): 93-112, doi:10.1016/j.pocean.2008.12.003

Six historical sections across the West Greenland Current are examined. Three sections have been regularly occupied since the late 1950s, while the three southern ones have been taken since 1984. Significant variability is observed for the freshwater core of the coastal current on the shelf, with salinity varying by over 3 units between years. There is also significant variability in the shape and offshore position of the main shelf break front, leading to large variability in Eulerian velocities. Significant presence of Irminger Water is seen during the 1960s and the 2000s, being found right across the sections in recent years. Maximum mean transport relative to the 34.8 isohaline of 5.5 ± 3.9 Sv, relative to 700 db, for 1984–2005, is observed at the Cape Desolation section. Transports decrease to the north, with the majority of the exchange with the interior of the Labrador Sea occurring between Cape Desolation and Fylla Bank. Inter-decadal transport variability is observed at Fylla Bank while a decline in transports since peaks in the early 1990s is seen at Cape Farewell and Cape Desolation. Freshwater transport is largest at Cape Desolation, with a mean Summer transport of 60.2 ± 20.5 mSv. Freshwater transport increases slightly between Cape Farewell and Cape Desolation and we suggest it is related to local discharge by glaciers into Juliannehaab Bight, as well as the melting of sea-ice. We also find that years of high Greenland ice cap melt are consistently associated with years of high freshwater transport at Cape Desolation, suggesting a portion of the freshwater transport of the West Greenland Current may be associated with melt from the Greenland ice sheet. Finally, significantly enhanced freshwater transports (33 mSv at Cape Desolation compared to the long term mean) are seen in 2008, probably a signature of the record Arctic Ocean ice melt and export in 2007.

Prinsenberg, S., J. Hamilton, I. Peterson, and R. Pettipas, 2009, Observing and interpreting the seasonal variability of the oceanographic fluxes passing through Lancaster Sound of the Canadian Arctic Archipelago, Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions NATO Science for Peace and Security Series, 125-143, doi:10.1007/978-1-4020-9460-6_10

As part of the Arctic/Sub-Arctic Ocean Flux (ASOF) and the International Polar Year (IPY) programs, a research project consisting of mooring and analysis work has studied the ocean and ice fluxes passing through Lancaster Sound, one of the three main pathways through the Canadian Arctic Archipelago (CAA) since 1998. The aim is to understand the variability in ocean and sea ice volume, heat and freshwater fluxes passing through the CAA and to determine their relationship to the ocean and ice budgets of the Arctic Ocean itself and to the circulation and vertical ventilation of the North Atlantic Ocean. Eight years of mooring data have now been processed and analyzed. The volume, freshwater and heat fluxes exhibit large seasonal and interannual variabilities with small fluxes in the fall and early winter and large fluxes in the summer. The seasonal mean volume flux estimates range from a low of 0.0 Sv in the fall of 1998 to a maximum of 1.3 Sv in the summer of 2000 (1Sverdrup = 1.0×10^{6} m^3 s^{-1}). It has an 8 year annual mean of 0.7 Sv and varies interannually by ±0.3 Sv. Model simulations indicate that fluxes through Lancaster Sound make up 40–50% of the fluxes through the entire Canadian Arctic Archipelago, and that they are dependent on the sea level difference between the Beaufort Sea and Baffin Bay and on the horizontal density gradients across the CAA, observations of which are scarce or non-existent. Regression analysis with the Arctic Ocean wind field shows that the fluxes through the NW Passage measured in Lancaster Sound are significantly correlated with the far field wind forcing in the Beaufort Sea. The northeastward winds in the Beaufort Sea, parallel to the western side of the Canadian Arctic Archipelago, show the highest correlation on monthly to interannual time scales. This result is consistent with the transport being driven by a sea level difference between opposite ends of the NW Passage, and the difference being determined by setup caused by alongshore winds in the Beaufort Sea.

Straneo, F. and F. J. Saucier, 2008, The Outflow From Hudson Strait and Its Contribution to the Labrador Current, *Deep Sea Res. Part I*, **55**: 926-946, doi:10.1016/j.dsr.2008.03.012

This study describes the first year round observations of the outflow from Hudson Strait as obtained from a moored array deployed mid-strait from August 2004–2005, and from a high-resolution hydrographic section conducted in September 2005. The outflow has the structure of a buoyant boundary current spread across the sloping topography of its southern edge. The variability in the flow is dominated by the extreme semi-diurnal tides and by vigorous, mostly barotropic, fluctuations over several days. The fresh water export is seasonally concentrated between June and March with a peak in November–December, consistent with the seasonal riverine input and sea-ice melt. It is highly variable on weekly timescales because of synchronous salinity and velocity variations. The estimated volume and liquid fresh water transports during 2004–2005 are, respectively, of 1–1.2 Sv

and 78–88 (28–29) mSv relative to a salinity of 34.8 (33). This implies that the Hudson Strait outflow accounts for approximately 15% of the volume and 50% of the fresh water transports of the Labrador Current. This larger than previously estimated contribution is partially due to the recycling, within the Hudson Bay System, of relatively fresh waters that flow into Hudson Strait, along its northern edge. It is speculated that the source of this inflow is the outflow from Davis Strait.

2.6 Deep Water and Deepwater Renewal

Defossez, M., F. J. Saucier, P. G. Myers, D. Caya, and J.-F. Dumais, 2008, Multi-Year Observations of Deep Water Renewal in Foxe Basin, Canada, *Atmos.-Ocean*, **46**(3): 377–390, doi:10.3137/ao.460306

New oceanographic mooring data recorded between 2004 and 2006 show an abrupt arrival of cold and saline water at the bottom of Foxe Channel each year. Foxe Channel is the deepest part of Foxe Basin, an Arctic/Subarctic inland sea in the Hudson Bay system. This dense water mass is detected at depth in the middle of the channel at the beginning of spring. It is characterized by a sharp temperature drop and salinity rise. This pulse-like phenomenon is recurrent, although there is some interannual variability depending on the severity of the preceding winter. The dense water probably originates from the coastal polynyas of western Foxe Basin. A gravity current in Foxe Channel flows southeastwards and significantly modifies the water column along the channel by raising isotherms by 140 m. The water column responds to the dense water pulse with a time lag of one month. Although the pulse lasts only three months, it renews more than two-thirds of the deep water in Foxe Channel and is therefore an important component of the general circulation in Foxe Basin. This shows that the pulse is an energetic event and that the newly advected dense water may have enough kinetic energy to overflow the sill between Foxe Basin and Hudson Bay.

Timmermans, M. L., H. Melling, and L. Rainville, 2007, Dynamics in the deep Canada Basin, Arctic Ocean, inferred by thermistor-chain time series, *J. Phys. Oceanogr.*, **37**(4): 1066-1076, doi:10.1175/JPO3032.1

A 50-day time series of high-resolution temperature in the deepest layers of the Canada Basin in the Arctic Ocean indicates that the deep Canada Basin is a dynamically active environment, not the quiet, stable basin often assumed. Vertical motions at the near-inertial (tidal) frequency have amplitudes of 10-20 m. These vertical displacements are surprisingly large considering the downward near-inertial internal wave energy flux typically observed in the Canada Basin. In addition to motion in the internal-wave frequency band, the measurements indicate distinctive subinertial temperature fluctuations, possibly due to intrusions of new water masses.

2.6.1 Thermohaline Variability

Walsh, D., I. Polyakov, L. Timokhov, and E. Carmack, 2007, Thermohaline Structure and Variability in the Eastern Nansen Basin as seen from Historial Data, *J. Mar. Res.*, **65**(5): 685-714, doi:10.1357/002224007783649466

Newly available historical Russian data are used to quantify year-to-year variations in the structure and properties of the halocline and Atlantic Water layers in the eastern Nansen Basin. The data come from a series of aerial surveys of the central Arctic Ocean done during winter between 1973 and 1979, and repeated "Polygon" surveys of the shelf, slope, and basin north of Severnaya Zemlya in the 1980s, and thus allow a perspective on shelf-basin exchange. A water-mass census shows substantial survey-to-survey variability in several water-mass categories, with volumetric fluctuations of ~17% in the Upper Polar Deep Water category, ~14% in Atlantic Water, and ~39% for cold surface waters with T < −1.5°C. Mean water-mass production rates in the polygon area are found to be 0.6-1.2 Sv for Upper Polar Deep Water, and an effective loss rate of 0.75-1.5 Sv is found for Atlantic Waters. On average Atlantic Water loses 16% of its initial heat content within the 350 km-long survey area, possibly enhanced by double-diffusive processes. Mean upward heat fluxes above the Atlantic Water are estimated to be between 4 and 6 W /m^2, based on heat budget considerations. Upward heat fluxes of this magnitude would have a major effect on sea ice, which is regularly observed to be thinner in this area of the Nansen Basin. Shallow-water profiles taken close to Severnaya Zemlya show cold and salty waters denser than offshore waters at similar depths, and evidence of convection is seen in many profiles taken over the continental shelf and slope, reflecting deep convective events extending in some cases below the deepest observed depth of 1000 m.

2.7 Freshwater Content

Carmack, E., 2007, The alpha/beta ocean distinction: a perspective on freshwater fluxes, ventilation, nutrients and primary productivity in high-latitude seas, *Deep-Sea Res. II*, **54**(23-26): 2578-2598, doi:10.1016/j.dsr2.2007.08.018

Stratification is perhaps the most important attribute of oceans with regards to climate and biology. Two simple aspects of the ocean's climate system appear to have a surprisingly important role in transforming waters that feed the global thermohaline circulation, dominating patterns of biogeochemical flux and establishing macroecological domains. First, largely because of meridional distillation (mainly due to the atmospheric transport of freshwater across the Isthmus of Panama) the North Pacific is fresher than the North Atlantic. Second, largely because of zonal distillation (e.g., warming and evaporation at low latitudes and poleward transport of latent heat and moisture by the atmosphere) the upper layers of subtropical seas are permanently stratified by temperature ($N_T^2=g\alpha dT/dz>0$; here called *alpha oceans*), while the upper layers of high-latitude seas are permanently stratified by salinity ($N_S^2=g\beta dS/dz>0$; here called *beta oceans*). The physical basis for the boundary separating alpha and beta oceans is unclear, but may lie in the thermodynamical equations published by

Fofonoff [1961. Energy transformations in the sea. Fisheries Research Board of Canada, Report Series 109, 82pp]. Nevertheless, it is clear that the resulting thermohaline distributions establish a 'downhill journey' of low-salinity (and nutrient-rich) waters from the North Pacific to the Arctic and then into the North Atlantic. The Arctic Ocean—itself—acts a double estuary, whereby waters entering from the North Atlantic become either denser through cooling (negative estuary) or lighter by freshening (positive estuary) as they circulate within the basin and then return to the North Atlantic as a variety of components of the ocean's conveyor. Intermediate and deep waters generally form within cyclonic beta oceans in close proximity to alphas systems. Similar patterns of stratification, nutrients and biogeographical boundaries persist in the Southern Hemisphere. It is thus argued that this simple distinction—alpha versus beta oceans—provides a broad, conceptual framework for simple interpretation of key physical and biological processes and rates, including the impacts of climate variability.

Dmitrenko, I. A., S. A. Kirillov, and L. B. Tremblay, 2008, The long-term and interannual variability of summer fresh water storage over the eastern Siberian shelf: Implication for climatic change, *J. Geophys. Res.*, **113**, C03007, doi:10.1029/2007JC004304

A time series of summer fresh water content anomalies (FWCA) over the Laptev and East Siberian sea shelves was constructed from historical hydrographic records for the period from 1920 to 2005. Results from a multiple regression between FCWA and various atmospheric and oceanic indices show that the fresh water content on the shelves is mainly controlled by atmospheric vorticity on quasi-decadal timescales. When the vorticity of the atmosphere on the shelves is anticyclonic, approximately 500 km^3 of fresh water migrates from the eastern Siberian shelf to the Arctic Ocean through the northeastern Laptev Sea. When the vorticity of the atmosphere is cyclonic, this fresh water remains on the southern Laptev and East Siberian sea shelves. This FWCA represents approximately 35% of the total fresh water inflow provided by river discharge and local sea-ice melt, and is about ten times larger than the standard deviation of the Lena River summer long-term mean discharge. However, the large interannual and spatial variability in the fresh water content of the shelves, as well as the spatial coverage of the hydrographic data, makes it difficult to detect the long-term tendency of fresh water storage associated with climate change.

Fortin, D., and S. F. Lamoureux, 2009, Multidecadal hydroclimatic variability in northeastern North America since 1550 AD, *Clim. Dyn.*, **33**: 427-432, doi:10.1007/s00382-008-0422-6

A network of varve and dendrochronological time series that provide annual resolution of Boreal tree growth conditions and Arctic snow pack and melt variability were used to investigate the imprint of the Atlantic Multidecadal Oscillation (AMO) on continental hydroclimatic variability in northeastern and northern North America from 1550 to 1986 AD. The hydroclimatic proxies show a coherent, AMO-like spectral pattern active since the late sixteenth and the early eighteenth century in the Canadian Arctic and southeastern Boreal regions,

respectively. Positive AMO phases are associated with more intense spring runoff in the Arctic and with longer growth season and increased summer moisture availability in the southeastern boreal forest. These results offer new insights about the widespread response of North American hydroclimate to low frequency changes in North Atlantic sea surface temperatures.

Jahn, A., B. Tremblay, L. A. Mysak, and R. Newton, 2010, Effect of the large-scale atmospheric circulation on the variability of the Arctic Ocean freshwater export, *Clim. Dyn.*, **34**: 201-222, doi:10.1007/s00382-009-0558-z

Freshwater (FW) leaves the Arctic Ocean through sea-ice export and the outflow of low-salinity upper ocean water. Whereas the variability of the sea-ice export is known to be mainly caused by changes in the local wind and the thickness of the exported sea ice, the mechanisms that regulate the variability of the liquid FW export are still under investigation. To better understand these mechanisms, we present an analysis of the variability of the liquid FW export from the Arctic Ocean for the period 1950–2007, using a simulation from an energy and mass conserving global ocean–sea ice model, coupled to an Energy Moisture Balance Model of the atmosphere, and forced with daily winds from the NCEP reanalysis. Our results show that the simulated liquid FW exports through the Canadian Arctic Archipelago (CAA) and the Fram Strait lag changes in the large-scale atmospheric circulation over the Arctic by 1 and 6 years, respectively. The variability of the liquid FW exports is caused by changes in the cyclonicity of the atmospheric forcing, which cause a FW redistribution in the Arctic through changes in Ekman transport in the Beaufort Gyre. This in turn causes changes in the sea surface height (SSH) and salinity upstream of the CAA and Fram Strait, which affect the velocity and salinity of the outflow. The SSH changes induced by the large-scale atmospheric circulation are found to explain a large part of the variance of the liquid FW export, while the local wind plays a much smaller role. We also show that during periods of increased liquid FW export from the Arctic, the strength of the simulated Atlantic meridional overturning circulation is reduced and the ocean heat transport into the Arctic is increased. These results are particularly relevant in the context of global warming, as climate simulations predict an increase in the liquid FW export from the Arctic during the twenty-first century.

Jahn, A., L. B. Tremblay, R. Newton, M. M. Holland, L. A. Mysak, and I. A. Dmitrenko, 2010, A tracer study of the Arctic Ocean's liquid freshwater export variability, *J. Geophys. Res.*, **115**, C07015, doi:10.1029/2009JC005873

We present an analysis of the variability of the liquid Arctic freshwater (FW) export, using a simulation from the Community Climate System Model Version 3 (CCSM3) that includes passive tracers for FW from different sources. It is shown that the FW exported through the western Canadian Arctic Archipelago (CAA) comes mainly from the Pacific and from North American runoff. The variability of the FW export from both of these sources is generally in phase, due to the strong influence of variations of the velocity anomaly on the CAA FW export variability. The velocity anomaly in the CAA is in turn mainly governed by

variations in the large-scale atmospheric circulation (i.e., the Arctic Oscillation). In Fram Strait, the FW export is mainly composed of Eurasian runoff and FW of Pacific origin. The variability of the Fram Strait FW export is governed both by changes in the velocity and in the FW concentration, and the variability of the FW concentration from the two largest sources is not in phase. The Eurasian runoff export through Fram Strait depends strongly on the release of FW from the Eurasian shelf, which occurs during years with an anticyclonic circulation anomaly (negative Vorticity index) and takes 3 years to reach Fram Strait after leaving the shelf. In contrast, the variability of the Pacific FW export through Fram Strait is mainly controlled by changes in the Pacific FW storage in the Beaufort Gyre, with an increased export during years with a cyclonic circulation anomaly (positive Vorticity index).

Jones, E. P., L. G. Anderson, J. Jutterström, and J. H. Swift, 2008, Sources and distribution of fresh water in the East Greenland Current, *Prog. Oceanogr.*, **78**: 37-44, doi:10.1016/j.pocean.2007.06.003

Fresh water flowing from the Arctic Ocean via the East Greenland Current influences deep water formation in the Nordic Seas as well as the salinity of the surface and deep waters flowing from there. This fresh water has three sources: Pacific water (relatively fresh cf. Atlantic water), river runoff, and sea ice meltwater. To determine the relative amounts of the three sources of fresh water, in May 2002 we collected water samples across the East Greenland Current in sections from 81.5°N to the Irminger Sea south of Denmark Strait. We used nitrate–phosphate relationships to distinguish Pacific waters from Atlantic waters, salinity to obtain the sum of sea ice melt water and river runoff water, and total alkalinity to distinguish the latter. River runoff contributed the largest part of the total fresh water component, in some regions with some inventories exceeding 12 m. Pacific fresh water (Pacific source water S 32 cf. Atlantic source water S 34.9) typically provided about 1/3 of the river runoff contribution. Sea ice meltwater was very nearly non-existent in the surface waters of all sections, likely at least in part as a result of the samples being collected before the onset of the melt season. The fresh water from the Arctic Ocean was strongly confined to near the Greenland coast. We thus conjecture that the main source of fresh water from the Arctic Ocean most strongly impacting deep convection in the Nordic Seas would be sea ice as opposed to fresh water in the liquid phase, i.e., river runoff, Pacific fresh water, and sea ice meltwater.

Jones, E. P., L. G. Anderson, S. Jutterström, L. Mintrop, and J. H. Swift, 2008, Pacific freshwater, river water and sea ice meltwater across Arctic Ocean basins: Results from the 2005 Beringia Expedition, *J. Geophys. Res.*, **113**, C08012, doi:10.1029/2007JC004124

Pacific water, sea ice meltwater, and river water are the primary sources of freshwater in the Arctic Ocean. We have determined their relative fractions on a transect across the Arctic Ocean Section 2005 Expedition onboard IB Oden, which took place from 21 August to 23 September 2005. The transect began north of Alaska, continued through the central Canada Basin to the Alpha Ridge and

into the Makarov Basin, and ended in Amundsen Basin. Pacific freshwater and river water were the major sources of freshwater throughout the central Canada Basin and into Makarov Basin, with river water fractions sometimes considerably higher than Pacific water in the top ~50 m. Pacific freshwater extended to depths of about 200 m. Pacific water found over the Alpha Ridge and in the Amundsen Basin is suggested to have been transported there in the Transpolar Drift. The inventories of Pacific freshwater and river water were roughly constant along the section through most of the Canada and Makarov basins. River water fractions were greater than those of Pacific freshwater in the Amundsen Basin. Sea ice meltwater fractions were negative (reflecting net ice formation) or near zero throughout most of the section. A comparison of freshwater inventories with those at stations occupied during expeditions in 1991, 1994, and 1996 indicated an increase in river water inventories in the Makarov and Amundsen basins on the Eurasian side of the Arctic Ocean.

Proshutinsky, A., R. Krishfield, M.-L. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K. Shimada, 2009b, Beaufort Gyre freshwater reservoir: state and variability from observations, *J. Geophys. Res.*, **114**, C00A10, doi:10.1029/2008JC005104

We investigate basin-scale mechanisms regulating anomalies in freshwater content (FWC) in the Beaufort Gyre (BG) of the Arctic Ocean using historical observations and data collected in 2003–2007. Specifically, the mean annual cycle and interannual and decadal FWC variability are explored. The major cause of the large FWC in the BG is the process of Ekman pumping (EP) due to the Arctic High anticyclonic circulation centered in the BG. The mean seasonal cycle of liquid FWC is a result of interplay between the mechanical (EP) and thermal (ice transformations) factors and has two peaks. One peak occurs around June–July when the sea ice thickness reaches its minimum (maximum ice melt). The second maximum is observed in November–January when wind curl is strongest (maximum EP) and the salt input from the growing ice has not yet reached its maximum. Interannual changes in FWC during 2003–2007 are characterized by a strong positive trend in the region varying by location with a maximum of approximately 170 cm a^{-1} in the center of EP influenced region. Decadal FWC variability in the period 1950–2000 is dominated by a significant change in the 1990s forced by an atmospheric circulation regime change. The center of maximum FWC shifted to the southeast and appeared to contract in area relative to the pre-1990s climatology. In spite of the areal reduction, the spatially integrated FWC increased by over 1000 km^3 relative to climatology.

Sutherland, D. A., R. S. Pickart, E. Peter Jones, K. Azetsu-Scott, A. Jane Eert, and J. Ólafsson, 2009, Freshwater composition of the waters off southeast Greenland and their link to the Arctic Ocean, *J. Geophys. Res.*, **114**, C05020, doi:10.1029/2008JC004808

The freshwater composition of waters on the southeast Greenland shelf and slope are described using a set of high-resolution transects occupied in summer 2004, which included hydrographic, velocity, nutrient, and chemical tracer measurements. The nutrient and tracer data are used to quantify the fractions of

Pacific Water, sea ice melt, and meteoric water present in the upper layers of the East Greenland Current (EGC) and East Greenland Coastal Current (EGCC). The EGC/EGCC system dominates the circulation of this region and strongly influences the observed distribution of the three freshwater types. Sea ice melt and meteoric water fractions are surface intensified, reflecting their sources, and generally increase southward from Denmark Strait to Cape Farewell, as well as shoreward. Significant fractions of Pacific Water are found in the subsurface layers of the EGCC, supporting the idea that this inner shelf branch is directly linked to the EGC and thus to the Arctic Ocean. A set of historical sections is examined to investigate the variability of Pacific Water content in the EGC and EGCC from 1984 to 2004 in the vicinity of Denmark Strait. The fraction of Pacific Water increased substantially in the late 1990s and subsequently declined to low levels in 2002 and 2004, mirroring the reduction in Pacific Water content reported previously at Fram Strait. This variability is found to correlate significantly with the Arctic Oscillation index, lagged by 9 years, suggesting that the Arctic Ocean circulation patterns bring varying amounts of Pacific Water to the North Atlantic via the EGC/EGCC.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, and K. Shimada, 2008, Freshwater budget of the Canada Basin, Arctic Ocean from salinity, $\delta^{18}O$ and nutrients, *J. Geophys. Res,* **113**, C1, doi:10.1029/2006JC003858

The contribution of freshwatercomponents (e.g. meteoritic, sea ice and Pacific water) in the Canada Basin is quantified using salinity, d18O and nutrient data collected in 2003 and 2004. The penetration depth of sea ice meltwater is limited to the upper 30 m and brine, rejected during sea ice formation, is observed from 30 to 250 m depth. The fraction of meteoric water is high in the upper 50 m and decreases with depth. Pacific water entering via Bering Strait is the main source of freshwater below 50 m depth. Bering Strait throughflow, which transports Pacific water with salinity 32.5 together with meteoric water supplied upstream of the Bering Strait, contributes up to 75 % of freshwater input (> 3,200 km3 yr-1) to the Canada Basin. The mean residence time of Pacific water in the Canada Basin is estimated to be 11 years. Precipitation and river runoff from both North American and Eurasian continents add > 800 km 3 yr-1 and sea ice formation removes < 900 km 3 yr-1 (< 0.6 m yr-1) of fresh water. The export of ice and liquid fresh water from the Canada Basin contributes ~40 % of the freshwater flux from the Arctic Ocean to the North Atlantic Ocean.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, K. Shimada, and N. Kurita, 2009, Surface freshening of the Canada Basin, 2003–2007: River runoff versus sea ice meltwater, *J. Geophys. Res.*, **114**, C00A05, doi:10.1029/2008JC005000

The extent of summer Arctic sea ice has reduced dramatically in recent years and, simultaneously, we have observed surface freshening over the Canada Basin in 2006 and 2007. In order to identify the source of this fresh water, either meteoric or sea ice meltwater, salinity, $\delta^{18}O$, and alkalinity were analyzed. Results show that sea ice meltwater increased in the surface water over the central part of the basin in 2006 and 2007, corresponding to the melting of an additional 2.7 m (1.3

m a^{-1}) of sea ice. Anomalously fresh surface water observed in the southern part in 2007, however, was mostly attributed to Mackenzie River water extending into the basin interior, a source that was mainly absent in the early 2000s. Comparison with previous data shows that the meltwater component of surface water in the southern part of the Canada Basin has progressively increased at a mean rate of 0.27 m a^{-1} since 1987. This can be explained by a reduction of winter sea ice formation rate by 0.45 m or more during the past two decades. The runoff component showed larger variability in the southern basin but no obvious temporal trend. In the central basin, the river runoff component showed an increasing trend of 0.7 m a^{-1}.

2.8 Shelf Waters and Other Water Masses

Dmitrenko, I. A., S. A. Kirillov, L. B. Tremblay, D. Bauch, J. A. Hölemann, T. Krumpen, H. Kassens, C. Wegner, G. Heinemann, and D. Schröder, 2010, Impact of the Arctic Ocean Atlantic water layer on Siberian shelf hydrography, *J. Geophys. Res.*, **115**, C08010, doi:10.1029/2009JC006020

This paper examines the role of the Arctic Ocean Atlantic water (AW) in modifying the Laptev Sea shelf bottom hydrography on the basis of historical records from 1932 to 2008, field observations carried out in April–May 2008, and 2002–2009 cross-slope measurements. A climatology of bottom hydrography demonstrates warming that extends offshore from the 30–50 m depth contour. Bottom layer temperature-time series constructed from historical records links the Laptev Sea outer shelf to the AW boundary current transporting warm and saline water from the North Atlantic. The AW warming of the mid-1990s and the mid-2000s is consistent with outer shelf bottom temperature variability. For April–May 2008 we observed on-shelf near-bottom warm and saline water intrusions up to the 20 m isobath. These intrusions are typically about 0.2°C warmer and 1–1.5 practical salinity units saltier than ambient water. The 2002–2009 cross-slope observations are suggestive for the continental slope upward heat flux from the AW to the overlying low-halocline water (LHW). The lateral on-shelf wind-driven transport of the LHW then results in the bottom layer thermohaline anomalies recorded over the Laptev Sea shelf. We also found that polynya-induced vertical mixing may act as a drainage of the bottom layer, permitting a relatively small portion of the AW heat to be directly released to the atmosphere. Finally, we see no significant warming (up until now) over the Laptev Sea shelf deeper than 10–15 m in the historical record. Future climate change, however, may bring more intrusions of Atlantic-modified waters with potentially warmer temperature onto the shelf, which could have a critical impact on the stability of offshore submarine permafrost.

Myers, P. G., N. Kulan, and M. H. Ribergaard, 2007, Irminger Water variability in the West Greenland Current, *Geophys. Res. Lett.*, **34**, L17601, doi:10.1029/2007GL030419

We examine the historical variability of Irminger Water (IW) along 3 sections across the West Greenland Current over 1950–2005. Significant variability in the salinity, size and position of the IW core are seen over time. Some of the saltiest and warmest IW ever recorded have been seen since 1995 (comparable to

previous maximums in the 1960s). During these periods, the volume of IW is also larger, leading to larger transports in to the Labrador Sea. For the period 1984–2005 transports at Cape Farewell are 3.8 ± 0.9 Sv, 7.5 ± 2.2 × 10^{13} J and 8.5 ± 1.8 mSv of salt referenced to 35.0. LSW formation is also correlated to IW transport at Cape Farewell with a lag of one year (0.51).

Nishino, S., K. Shimada, M. Itoh, M. Yamamoto-Kawai, and S. Chiba, 2008, East–west differences in water mass, nutrient, and chlorophyll *a* distributions in the sea ice reduction region of the western Arctic Ocean, *J. Geophys. Res.*, **113**, C00A01, doi:10.1029/2007JC004666

The *R/V* Mirai conducted hydrographic surveys in the western Arctic Ocean during summer 2004 across a front between cold Arctic water and warm water from the Pacific Ocean where sea ice cover has been largely reduced in recent summers. The hydrographic data indicate a new type of vertical temperature minimum water west of the front along isohaline surfaces with approximate salinity (*S*) of 32, which is fresher than the typical temperature minimum ($S \approx 33$) caused by spreading of Pacific winter water (PWW) mainly to the east of the front. Both of the temperature minimum waters are characterized by low potential vorticity with near-freezing temperature, suggesting that they are formed by winter convection with sea ice formation. A difference between the waters results from a large contribution of sea ice meltwater to the fresh temperature minimum (frTmin) water of $S \approx 32$. The distributions of the sea ice meltwater contribution and nitrogen deficit suggest that summer shelf water, largely influenced by the sea ice melt in the Chukchi Sea, is modified by winter convection on its way to the Chukchi Abyssal Plain to form the frTmin water. This water supplies nutrients through the water distribution to the west of the front at depths shallower than the nutrient maximum layer caused by the PWW spreading. The shallower nutrient supply by the frTmin water combined with light penetration without sea ice cover could produce a prominent chlorophyll *a* maximum layer west of the front.

2.9 Atmosphere-Ocean

Guo, S., H. Leighton, and M. MacKay, 2007, Surface Absorbed and Top-of-Atmosphere Radiation Fluxes for the Mackenzie River Basin from Satellite Observations and a Regional Climate Model and an Evaluation of the Model, *Atmos.-Ocean*, **45**(3): 129–139, doi:10.3137/ao.450301

Both the earth-reflected shortwave and outgoing longwave radiation (OLR) fluxes at the top of the atmosphere (TOA) as well as surface-absorbed solar fluxes from Canadian Regional Climate Model (CRCM) simulations of the Mackenzie River Basin for the period March 2000 to September 2003 are compared with the radiation fluxes deduced from satellite observations. The differences between the model and satellite solar fluxes at the TOA and at the surface, which are used in this paper to evaluate the CRCM performance, have opposite biases under clear skies and overcast conditions, suggesting that the surface albedo is underestimated while cloud albedo is overestimated. The slightly larger differences between the model and satellite fluxes at the surface compared to those at the TOA indicate the existence of a small positive atmospheric absorption

bias in the model. The persistent overestimation of TOA reflected solar fluxes and underestimation of the surface-absorbed solar fluxes by the CRCM under all sky conditions are consistent with the overestimation of cloud fraction by the CRCM. This results in a larger shortwave cloud radiative forcing (CRF) both at the TOA and at the surface in the CRCM simulation. The OLR from the CRCM agrees well with the satellite observations except for persistent negative biases during the winter months under all sky conditions. Under clear skies, the OLR is slightly underestimated by the CRCM during the winter months and overestimated in the other months. Under overcast conditions the OLR is underestimated by the CRCM, suggesting an underestimation of cloud-top temperature by the CRCM. There is an improvement in differences between model and satellite fluxes compared to previously reported results largely because of changes to the treatment of the surface in the model.

Lukovich, J. V., M. G. Asplin, and D. G. Barber, 2009, Atmospheric forcing of the Beaufort Sea ice gyre: Surface-stratosphere coupling, *J. Geophys. Res.*, **114**, C00A03, doi:10.1029/2008JC004849

In a companion article we examined the nature of correspondence between synoptic weather patterns and reversals in the Beaufort Sea ice gyre. In this paper we extend this analysis to examine the role of stratospheric forcing on surface phenomena. Investigated in particular is the correspondence between reversals in stratospheric winds at 10 mbar during winter as defined by stratospheric sudden warmings (SSW) and mean sea level pressure synoptic types in the Beaufort Sea region. Connections between stratospheric and surface events are characterized using relative vorticity and the square of strain computed at different pressure levels from the stratosphere to the surface in the Beaufort Sea region. We quantify the correspondence between stratospheric flow and surface phenomena through investigation of the frequency in synoptic types derived in a companion article during stratospheric sudden warming events. Investigation of stratospheric wind gradients averaged over the Beaufort Sea region demonstrates a prevalence in anticyclonic activity during SSWs that persists for approximately 20 days. Examination of the evolution in synoptic types in the Beaufort Sea region also shows an increase in the number of synoptic types associated with anticyclonic activity during SSWs.

Martin, R., and G. W. K. Moore, 2007, Air-sea interaction associated with a Greenland reverse tip jet, *Geophys. Res. Lett.*, **34**, L24802, doi:10.1029/2007GL031093

Greenland lies in close proximity to the North Atlantic storm track, and as such can be a point of strong orographic interaction with atmospheric flow. For several years now, it has been known that the interaction of synoptic scale cyclones with Greenland's orography can spawn localized high wind speed events, known as tip jets off its southernmost point. Climatologies of these events have shown that tip jets can have either a westerly (normal) or easterly (reverse) sense. In this paper, we present the first simulation of a reverse tip jet presenting an examination of the air-sea interaction that occurs during this event. The strength of this interaction

demonstrates the potential influence that these events can have on the region's surface and abyssal oceanic circulation.

Moore, G. W. K., R. S. Pickart, and I. A. Renfrew, 2008, Buoy observations from the windiest location in the world ocean, Cape Farewell, Greenland, *Geophys. Res. Lett.*, **35**, L18802, doi:10.1029/2008GL034845

Cape Farewell, Greenland's southernmost point, is a region of significant interest in the meteorological and oceanographic communities in that atmospheric flow distortion associated with the high topography of the region leads to a number of high wind speed jets. The resulting large air-sea fluxes of momentum and buoyancy have a dramatic impact on the region's weather and ocean circulation. Here the first in-situ observations of the surface meteorology in the region, collected from an instrumented buoy, are presented. The buoy wind speeds are compared to 10 m wind speeds from the QuikSCAT satellite and the North American Regional Reanalysis (NARR). We show that the QuikSCAT retrievals have a high wind speed bias that is absent from the NARR winds. The spatial characteristics of the high wind speed events are also presented.

Pickart, R. S., L. J. Pratt, D. J. Torres, T. E. Whitledge, A. Y. Proshutinsky, K. Aagaard, T. A. Agnew, G. W. K. Moore, and H. J. Dail, 2010, Evolution and dynamics of the flow through Herald Canyon in the western Chukchi Sea, *Deep Sea Res. Part II*, **57(**1-2): 5-26, doi:10.1016/j.dsr2.2009.08.002

The flow of summer and winter Pacific water masses through Herald Canyon is investigated using data from a high-resolution hydrographic/velocity survey conducted in summer 2004. The survey was part of the Russian-American Long Term Census of the Arctic (RUSALCA) program, and consisted of four cross-canyon transects occupied over a 2-day period. At the time of the survey dense winter water was entering the western side of the canyon from the Chukchi Sea, flowing alongside a poleward jet of summer water on the canyon's eastern flank. As the dense water progressed northward it switched sides of the canyon and underwent a sudden increase in layer thickness. This coincided with vertical mixing near the interface of the winter and summer water, producing a new water mass mode exiting the canyon. All of these features are consistent with the notion of hydraulic activity occurring in the canyon. A three-layer hydraulic theory is applied to the flow, which suggests that it is supercritical and that hydraulic control is likely. A lock-exchange formulation accurately predicts the northward transport of the winter water. The origin of the winter water and the manner in which it drains into the canyon is investigated using satellite ice-concentration data, atmospheric re-analysis fields, historical in-situ data, and a simple circulation model. Finally, the fate of the Pacific water exiting the canyon, and its connection to the Chukchi shelfbreak current, is discussed.

Renfrew, I. A., S. D. Outten, and G. W. K. Moore., 2009, An easterly tip jet off Cape Farewell, Greenland. I: Aircraft observations. *Quart. J. Roy. Met. Soc.*, **135**: 1919–1933, doi:10.1002/qj.513

An easterly tip jet event off Cape Farewell, Greenland, is described and analysed in considerable detail. In Part I of this study (this paper) comprehensive aircraft-based observations are described, while in Part II of this study numerical simulations and a dynamical analysis are presented. The easterly tip jet of 21 February 2007 took place during the Greenland Flow Distortion experiment. It resulted through the interaction of a barotropic synoptic-scale low pressure system in the central North Atlantic and the high topography of southern Greenland. *In situ* observations reveal a jet core at the coast with peak winds of almost 50 m s^{-1}, about 600–800 m above the sea surface, and of 30 m s^{-1} at 10 m. The depth of the jet increased with wind speed from ~1500 m to ~2500 m as the peak winds increased from 30 to 50 m s^{-1}. The jet accelerated and curved anticyclonically as it reached Cape Farewell and the end of the barrier. The easterly tip jet was associated with a tongue of cold and dry air along the coast of southeast Greenland, general cloud cover to the east, and cloud streets to the south of Cape Farewell. Precipitation was observed during the low-level components of the flight. The very high wind speeds generated a highly turbulent atmospheric boundary layer and resulted in some of the highest surface wind stresses ever observed over the ocean.

Scinocca, J. F., M. C. Reader, D. A. Plummer, M. Sigmond, P. J. Kushner, T. G. Shepherd, and A. R. Ravishankara, 2009, Impact of sudden Arctic sea-ice loss on stratospheric polar ozone recovery, *Geophys. Res. Lett.*, **36**, L24701, doi:10.1029/2009GL041239

We investigate the sensitivity of Northern Hemisphere polar ozone recovery to a scenario in which there is rapid loss of Arctic summer sea ice in the first half of the 21st century. The issue is addressed by coupling a chemistry climate model to an ocean general circulation model and performing simulations of ozone recovery with, and without, an external perturbation designed to cause a rapid and complete loss of summertime Arctic sea ice. Under this extreme perturbation, the stratospheric response takes the form of a springtime polar cooling which is dynamical rather than radiative in origin, and is caused by reduced wave forcing from the troposphere. The response lags the onset of the sea- ice perturbation by about one decade and lasts for more than two decades, and is associated with an enhanced weakening of the North Atlantic meridional overturning circulation. The stratospheric dynamical response leads to a 10 DU reduction in polar column ozone, which is statistically robust. While this represents a modest loss, it has the potential to induce a delay of roughly one decade in Arctic ozone recovery estimates made in the 2006 Scientific Assessment of Ozone Depletion.

2.10 Sea Ice

Barber, D. G., R. Galley, M. G. Asplin, R. De Abreu, K.-A. Warner, M. Pućko, M. Gupta, S. Prinsenberg, and S. Julien, 2009, Perennial pack ice in the southern Beaufort Sea was not as it appeared in the summer of 2009, *Geophys. Res. Lett.*, **36**, L24501, doi:10.1029/2009/GL041434

In September 2009 we observed a much different sea icescape in the Southern Beaufort Sea than anticipated, based on remotely sensed products. Radarsat derived ice charts predicted 7 to 9 tenths multi-year (MY) or thick first-year (FY) sea ice throughout most of the Southern Beaufort Sea in the deep water of the Canada Basin. In situ observations found heavily decayed, very small remnant MY and FY floes interspersed with new ice between floes, in melt ponds, thaw holes and growing over negative freeboard older ice. This icescape contained approximately 25% open water, predominantly distributed in between floes or in thaw holes connected to the ocean below. Although this rotten ice regime was quite different that the expected MY regime in terms of ice volume and strength, their near-surface physical properties were found to be sufficiently alike that their radiometric and scattering characteristics were almost identical.

Bonnet, S. , A. de Vernal, C. Hillaire-Marcel, T. Radi, and K. Husum, Variability of sea-surface temperature and sea-ice cover in the Fram Strait over the last two millennia, *Marine Micropaleontology*, **74**(3-4): 59-74, doi:10.1016/j.marmicro.2009.12.001

A sediment core located on the West Spitzbergen margin in the Fram Strait (78°54.931′N, 6°46.005′E, water depth: 1497 m) was analyzed for its dinocyst content in order to reconstruct hydroclimatic variations of the last 2500 years. The relative abundance of dinocyst taxa and principal component analysis show a major transition at about 300 cal. years BP. It is characterized by the disappearance of thermophilic taxa *Spiniferites mirabilis-hyperacanthus* and *Impagidinium sphaericum* and the increase of polar–subpolar taxa *Impagidinium pallidum* and *Pentapharsodinium dalei*. Sea-surface temperature (SST) estimates suggest warmer conditions than present (anomaly ~+2 °C) averaging at 7 °C in summer until 300 cal. years BP, although cooling pulses are recorded around 1700, 1500, 1200 and 800 cal. years BP. The last 300 years were marked by a cooling from 7.6 to 3.5 °C and sea-ice cover increasing up to 7 months/yr. The results demonstrate that the Fram Strait area is sensitive to hydroclimatic variations, notably with respect to sea-ice and SSTs, which are linked to the relative strength of northward flow of North Atlantic waters to the East and southward outflow of cold and fresh waters from the Arctic Ocean. Based on our data, the warmest part of our record around 1320 cal. years BP is the only interval of the last 2500 years that provides a possible analogue for the modern post-AD 2000 interval, which is characterized by sea-ice free conditions.

Copland, L., D. R. Mueller, and L. Weir, 2007, Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada, *Geophys. Res. Lett.*, **34**, L21501, doi:10.1029/2007GL031809

On August 13, 2005, almost the entire Ayles Ice Shelf (87.1 km^2) calved off within an hour and created a new 66.4 km^2 ice island in the Arctic Ocean. This loss of one of the six remaining Ellesmere Island ice shelves reduced their overall area by ~7.5%. The ice shelf was likely weakened prior to calving by a long-term negative mass balance related to an increase in mean annual temperatures over the past 50+ years. The weakened ice shelf then calved during the warmest summer on record in a period of high winds, record low sea ice conditions and the loss of a semi-permanent landfast sea ice fringe. Climate reanalysis suggests that a

threshold of >200 positive degree days year $^{-1}$ is important in determining when ice shelf calving events occur on N. Ellesmere Island.

Dmitrenko, I. A., S. A. Kirillov, L. B. Tremblay, D. Bauch, and S. Willmes, 2009, Sea-ice production over the Laptev Sea shelf inferred from historical summer-to-winter hydrographic observations of 1960s–1990s, *Geophys. Res. Lett.*, **36**, L13605, doi:10.1029/2009GL038775

The winter net sea-ice production (NSIP) over the Laptev Sea shelf is inferred from continuous summer-to-winter historical salinity records of 1960s–1990s. While the NSIP strongly depends on the assumed salinity of newly formed ice, the NSIP quasi-decadal variability can be linked to the wind-driven circulation anomalies in the Laptev Sea region. The increased wind-driven advection of ice away from the Laptev Sea coast when the Arctic Oscillation (AO) is positive implies enhanced coastal polynya sea-ice production and brine release in the shelf water. When the AO is negative, the NSIP and seasonal salinity amplitude tends to weaken. These results are in reasonable agreement with sea-ice observations and modeling.

Dumas, J. A., H. Melling, and G. M. Flato, 2007, Late-Summer Pack Ice in the Canadian Archipelago: Thickness Observations from a Ship in Transit, *Atmos-Ocean*, **45**(1): 57-70, http://www.cmos.ca/Ao/articles/v450105.pdf

A digital video camera was used to photograph ice blocks turned on edge by the passage of the icebreaker CCGS Des Groseilliers operating in the Canadian High Arctic in August 2002. Ice thickness was derived from photogrammetry to an accuracy of about 10%, with a possible negative bias of about 3%. Further (presumably negative) bias related to route selection is unknown. The average thickness of blocks measured during half-hour intervals of observation varied between 0.35 and 0.70 m; the higher values are likely indicative of second-year ice. The greatest thickness of any single block was less than 2 m. Histograms of thickness were nearly symmetric and approximately Gaussian. There is evidence to indicate that the scarcity of ridged ice reflects the ice conditions of the area and is not an artefact of the method. Based on ancillary wintertime data, the pack ice in open waters of the north-eastern Archipelago thawed at about 0.02 m d–1 in the summer of 2002, about three times less rapidly than ice near the shore. Whereas coastal ice had vanished five weeks prior to our voyage, pack ice in Norwegian Bay, though thin, persisted until the end of September and became second-year ice. The difference is likely a consequence of the different microclimate near land, particularly with respect to the time of onset of the thaw season.

Dyck, S., L. B. Tremblay, and A. de Vernal, 2010, Arctic sea-ice cover from the early Holocene: The role of atmospheric circulation patterns, *Quat. Sci. Rev.*,

Proxy evidence suggests that a mean atmospheric state, reminiscent of the positive phase of the North Atlantic/Arctic Oscillation (NAO), persisted throughout the early Holocene and resulted in a dipole pattern in sea-ice concentration between the north-eastern and north-western North Atlantic. A dynamic thermodynamic coupled sea-ice–ocean model is used to simulate the sea-

ice concentration and thickness in the Arctic during the early Holocene. It is forced with winds, ocean currents and surface air temperatures (SAT) from recent years with a positive phase of the NAO in conjunction with altered long and shortwave radiation and surface air/ocean temperatures. The simulation reproduces an east/west dipole in sea-ice cover of the Arctic and is compatible with reconstructed sea-ice conditions in the Chukchi Sea (inferred from dinoflagellate cyst analysis of ocean sediment cores). Sensitivity studies were performed to investigate the individual effects of radiation, ocean forcing, SAT and winds on sea-ice cover. Results show that in the East Siberian Sea, SAT is the dominant forcing for changes in sea-ice thickness, whereas winds and SAT are the dominant factors in sea-ice concentration anomalies. In the Barents Sea, sea-ice anomalies are influenced by air and sea surface temperatures, and ocean currents.

England, J. H., T. R. Lakeman, D. S. Lemmen, J. M. Bednarski, T. G. Stewart, and D. J. A. Evans, 2008, A millennial‐scale record of Arctic Ocean sea ice variability and the demise of the Ellesmere Island ice shelves, *Geophys. Res. Lett.*, **35**, L19502, doi:10.1029/2008GL034470

Sea‐ice ice shelves, at the apex of North America (>80° N), constitute the oldest sea ice in the Northern Hemisphere. We document the establishment and subsequent stability of the Ward Hunt Ice Shelf, and multiyear landfast sea ice in adjacent fiords, using 69 radiocarbon dates obtained on Holocene driftwood deposited prior to coastal blockage. These dates (47 of which are new) record a hiatus in driftwood deposition beginning ~5500 cal yr BP, marking the inception of widespread multiyear landfast sea ice across northern Ellesmere Island. This chronology, together with historical observations of ice shelf breakup (~1950 to present), provides the only millennial‐scale record of Arctic Ocean sea ice variability to which the past three decades of satellite surveillance can be compared. Removal of the remaining ice shelves would be unprecedented in the last 5500 years. This highlights the impact of ongoing 20th and 21st century climate warming that continues to break up the remaining ice shelves and soon may cause historically ice‐filled fiords nearby to open seasonally.

Fortier, L., and J. K. Cochran, 2008, Introduction to special section on Annual Cycles on the Arctic Ocean Shelf, *J. Geophys. Res.*, **113**, C03S00, doi:10.1029/2007JC004457

The perennial sea-ice cover of the Arctic Ocean is shrinking rapidly in response to the anthropogenic warming of Earth's lower atmosphere. From September 2002 to September 2004 the Canadian Arctic Shelf Exchange Study (CASES) logged over 14,500 scientist-days at sea to document the potential impacts of a shift in sea-ice regime on the ecosystem of the Mackenzie Shelf in the southeastern Beaufort Sea. In particular, teams from Canada, Denmark, Japan, Norway, Spain, the United Kingdom, and the United States totalling over 200 scientists took rotations on the CCS *Amundsen* to study all aspects of the ecosystem during a 385-day over-wintering expedition in the region from September 2003 to September 2004. The resulting wealth of information has revealed an unexpectedly active food web under the winter sea ice of the coastal Beaufort Sea. From the thermodynamics of

snow to the reconstruction of local paleo- climate, this special section focuses on how sea-ice cover dynam ics dictate bi ological processes and biogeochem ical fluxes on and at the margin of the shallo w Arctic continental shelf. The highly successful CASES pr ogram has ini tiated ongoing tim e series of key measurements of the response of the m arine ecosystem to change that have been expanded to other Arctic regions th rough the ArcticN et project and the International Polar Year.

Fukamachi, Y., K. Shirasawa, A. M. Po lomoshnov, K. I. Ohshi ma, E. Kalinin, S. Nihashi, H. Melling, G. Mizuta, and M. W akatsuchi, 2009, Direct observations of sea-ice thickness and brine rejection off Sakhalin in the Sea of Okhotsk, *Cont. Shelf Res.*, **29**(11-12): 1541-1548, doi:10.1016/j.csr.2009.04.005

From December to June 2002–2003, sea-ice an d oceanic data were obtained from moorings near Sakhalin in the west centr al Okhotsk Sea. Ice draft m easured by sonar reveals distinct periods of thin and thick ice. Th in-ice periods in January–March corresponded to offshore ice m ovement and increasing seawater salinity. The measured change in salinity corres ponds well with that derived from heat-flux calculations using the observed ice thickness. Brine rejection f rom ice growing in a coastal polynya off northern Sa khalin is responsible for m uch of the observed salinity increase. The simultane ous observation of dense shelf water (>26.7σ_θ) suggests that this region is one possi ble source. The periods of thick-ice incursion are likely indicative of heavily deformed pack formed further north and drifting south with the curre nt. The mean draft (1.95 m), thick-ice ratio, and kee l frequency during these periods are close to values observed in the Beaufort Sea. Freshwater transport estimated from the observed ice thickness and velocity is larger than that of the Amur River discharge.

Galley, R. J., E. Key, D. G. Barber, B. J. Hwang, and J. K. Ehn, 2008, Spatial and temporal variability of sea ice in the southern B eaufort Sea and Am undsen Gulf: 1980–2004, *J. Geophys. Res.*, **113**, C05S95, doi:10.1029/2007JC004553

Changing extent, location, and m otion of th e Arctic perennial pack affect the annual evolution of seasonal ice zones. Ca nadian Ice Service digital ice charts covering the southern Beauf ort Sea and Amundsen Gulf are used to illustrate summer and winter conditions and tre nds between 1980 and 2004 for several sea ice stages of development. Results illustrate average sea ice c onditions within the region in summer and winter for predom inant sea ice types and chang es in the relative concentration of sea ice types in summer and winter. In summe r, a trend toward increased old sea ice concentrati on occurred near the mouth of Amundsen Gulf, with a trend towar d decreasing summer first-year sea ice farth er west. In winter, increasing thick first-year sea ice extent appears to be replacing young sea ice within the flaw lead system in the region. The dynam ically driven breakup of sea ice in spring in the Amundsen Gulf is a highly variab le event taking anywhere between 2 and 22 weeks to com pletely remove ice from the gulf. The timing and duration of the open water season depends upon the extent and tim ing of old ice influx. Freeze-up occurs very quickly, procee ding from west to east with little temporal variability. The results of this paper are used to s et the contex t for the

Canadian Arctic Shelf Exchange Study (CASES) in terms of sea ice dynamic and thermodynamic processes.

Howell, S. E. L., A. Tivy, J. J. Yackel, and S. McCourt, 2008, Multi-year sea-ice conditions in the western Canadian arctic archipelago region of the northwest passage: 1968–2006, *Atmosphere-Ocean*, **46**(2): 229-242. doi:10.3137/ao.460203

Numerous studies have reported decreases in Arctic sea-ice cover over the past several decades and General Circulation Model (GCM) simulations continue to predict future decreases. These decreases — particularly in thick perennial or multi-year ice (MYI) — have led to considerable speculation about a more accessible Northwest Passage (NWP) as a transit route through the Canadian Arctic Archipelago (CAA). The Canadian Ice Service Digital Archive (CISDA) is used to investigate dynamic import/export and in situ growth of MYI within the western CAA regions of the NWP from 1968 to 2006. This analysis finds that MYI conditions in the western CAA regions of the NWP have remained relatively stable because the M'Clintock Channel and Franklin regions continuously operate as a drain-trap mechanism for MYI. Results also show that in addition to the Queen Elizabeth Islands (QEI) region, the Western Parry Channel and the M'Clintock Channel are also regions where a considerable amount of MYI forms in situ and combined with dynamic imports contributes to heavy MYI conditions. There is also evidence to suggest that more frequent dynamic import of MYI appears to have occurred since-1999 compared to the formation of more MYI in situ before 1999. As a result, the drain-trap mechanism that has historically maintained heavy MYI conditions in the NWP is perhaps operating faster now than it was in the past. Based on the 38-year MYI record examined in this study, it is likely that the mechanisms operating within the western CAA regions of the NWP can facilitate the continued presence of MYI for quite some time.

Howell, S. E. L., C. R. Duguay, and T. Markus, 2009, Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979-2008, *Geophys. Res. Lett.*, **36**, L10502, doi:10.1029/2009GL037681

Sea ice conditions and melt season duration within the Canadian Arctic Archipelago (CAA) were investigated from 1979–2008. The CAA is exhibiting statistically significant decreases in average September total sea ice area at -8.7% decade-1. The melt season duration within the CAA is increasing significantly at 7 days decade-1. 2008 represented the longest melt season duration within the CAA over the satellite record at 129 days. Average September multi-year ice (MYI) area is decreasing at -6.4 % decade-1 but has yet to reach statistical significance as a result of increasing MYI dynamic import from the Arctic Ocean. Results also find that the Western Parry Channel (WPC) region of the Northwest Passage (NWP) will continue to be susceptible to MYI as the transition to a summer-time sea ice free Arctic continues. The processes responsible for the temporary clearing of the WPC region of the NWP in 2007 were also identified.

Howell, S. E. L., A. Tivy, T. Agnew, T. Markus, and C. Derksen, 2010, Extreme low sea ice years in the Canadian Arctic Archipelago: 1998 versus 2007, *J. Geophys. Res.*, **115**, C10053, doi:10.1029/2010JC006155

Extreme sea ice minima were observed within the Canadian Arctic Archipelago (CAA) during 1998 and 2007. The September average sea ice area was 2.90 and 2.65 standardized anomalies below the historical 1968–1996 climatology for 1998 and 2007, respectively. October sea ice area for 1998 was a staggering 4.45 standardized anomalies below the historical 1968–1996 climatology and 2007 was lower by 3.36 standardized anomalies. We examine the role of thermodynamic and dynamic forcing on CAA sea ice that was responsible for its extreme loss in 1998 and 2007. Thermodynamic forcing on the sea ice was concentrated over 1 month in 2007 facilitating rapid melt, contrasted against a long melt season in 1998. This variation was attributed to anomalously warm air temperatures in June, September, and October for 1998 compared to anomalously warm temperatures in July for 2007. Sea ice dynamics contributed to the 1998 minimum by inhibiting replenishment from the Arctic Ocean but actually facilitated replenishment in 2007 thereby preventing record low conditions. Replenishment was driven by dissimilarities in sea level pressure patterns over the CAA during these extreme years. Evidence for preconditioned thinning was apparent leading up to 2007 but not strongly apparent for 1998. Remarkably, at the onset of 1998 melt season, multi-year ice area within the CAA was 11% more than the historical climatology and 48% more than at the start of the 2007 melt season yet an extreme minima was still reached.

Kinnard, C., C. M. Zdanowicz, R. M. Koerner, and D. A. Fisher, 2008, A changing Arctic seasonal ice zone: Observations from 1870–2003 and possible oceanographic consequences, *Geophys. Res. Lett.*, **35**, L02507, doi:10.1029/2007GL032507

Changes in the extent of seasonal ice were investigated using historical and satellite observations for the period 1870–2003. The seasonal ice zone (SIZ) has been gradually expanding since 1870, with a marked acceleration over the past three decades, and has migrated north to encompass all peripheral Arctic seas. The expansion of the SIZ may be increasing the salinity of the upper Arctic Ocean, consistent with recent observations. The migration of the SIZ over continental shelves may also be enhancing the formation rate and salinity of Arctic deep waters, which are subsequently advected to the convective region of the Greenland-Iceland-Norwegian Sea, thereby influencing the formation of North Atlantic deep waters and related global thermohaline circulation.

Lukovich, J. V. and D. G. Barber, 2007, On the spatiotemporal behavior of sea ice concentration anomalies in the Northern Hemisphere, *J. Geophys. Res.*, **112**, D13117, doi:10.1029/2006JD007836

Reduction in the aerial extent and thickness of sea ice in the Northern Hemisphere is an important element in understanding how the arctic responds to global-scale climate variability and change. Previous studies have demonstrated a significant reduction in minimum sea ice extent [Serreze et al., 2003] with record reduction in 2005. Observational studies attribute this phenomenon to variations in sea level

pressure and large-scale atmospheric teleconnection patterns such as the Northern Annular Mode (NAM) [Deser et al., 2000; Serreze et al., 2003]. In this study we examine variations in sea ice in the context of spatiotemporal variability of sea ice concentration (SIC) anomalies in the Northern Hemisphere during the onset of ice formation. Examined in particular are timescales associated with coherent regions of persistence in an *e*-folding time spatial distribution (EFSD). Annual variations of weekly SIC anomalies are studied and spatial relations between positive and negative SIC anomalies are explored on a hemispheric scale. The results from this investigation demonstrate coherent SIC persistence patterns throughout the Northern Hemisphere, with timescales ranging from 3 to 7 weeks. Spatial correspondence between negative trends in SIC anomalies and the EFSD suggests that the same mechanism may be responsible for both increased ice reduction and persistence in this region. Examination of spatial coherence in SIC anomalies indicates that maximum SIC anomalies prevail near the Kara Sea, Beaufort Sea, and Chukchi Sea regions during late summer/early fall from 1979 to 2004. A latitudinal assessment at 80°, 70°, and 60° N indicates a poleward shift and retreat in SIC anomalies, while also underlining the decadal shift in variability often attributed to the NAM.

Min, S.-K., X. Zhang, F. W. Zwiers, and T. Agnew, 2008, Human influence on Arctic sea ice detectable from early 1990s onwards, *Geophys. Res. Lett.*, **35**, L21701, doi:10.1029/2008GL035725

Human influence has previously been identified in the observed loss of Arctic sea ice, but this hypothesis has not yet been tested with a formal optimal detection approach. By comparing observed and multi-model simulated changes in Arctic sea ice extent during 1953–2006 using an optimal fingerprinting method, we find that the anthropogenic signal first emerged in the early 1990s, indicating that human influence could have been detected even prior to the recent dramatic sea ice decline. The anthropogenic signal is also detectable for individual months from May to December, suggesting that human influence, strongest in late summer, now also extends into colder seasons.

Polyakov, I. V., L. A. Timokhov, V. A. Alexeev, S. Bacon, I. A. Dmitrenko, L. Fortier, I. E. Frolov, J.-C. Gascard, E. Hansen, V. V. Ivanov, S. Laxon, C. Mauritzen, D. Perovich, K. Shimada, H. L. Simmons, V. T. Sokolov, M. Steele, and J. Toole, 2010, Arctic Ocean Warming Contributes to Reduced Polar Ice Cap, *J. Phys. Oceanogr.*, **40**, 2743–2756, doi:10.1175/2010JPO4339.1

Analysis of modern and historical observations demonstrates that the temperature of the intermediate-depth (150–900 m) Atlantic water (AW) of the Arctic Ocean has increased in recent decades. The AW warming has been uneven in time; a local ~1°C maximum was observed in the mid-1990s, followed by an intervening minimum and an additional warming that culminated in 2007 with temperatures higher than in the 1990s by 0.24°C. Relative to climatology from all data prior to 1999, the most extreme 2007 temperature anomalies of up to 1°C and higher were observed in the Eurasian and Makarov Basins. The AW warming was associated with a substantial (up to 75–90 m) shoaling of the upper AW boundary in the

central Arctic Ocean and weakening of the Eurasian Basin upper-ocean stratification. Taken together, these observations suggest that the changes in the Eurasian Basin facilitated greater upward transfer of AW heat to the ocean surface layer. Available limited observations and results from a 1D ocean column model support this surmised upward spread of AW heat through the Eurasian Basin halocline. Experiments with a 3D coupled ice–ocean model in turn suggest a loss of 28–35 cm of ice thickness after ~50 yr in response to the 0.5 W m^{-2} increase in AW ocean heat flux suggested by the 1D model. This amount of thinning is comparable to the 29 cm of ice thickness loss due to local atmospheric thermodynamic forcing estimated from observations of fast-ice thickness decline. The implication is that AW warming helped precondition the polar ice cap for the extreme ice loss observed in recent years.

Prinsenberg, S. J. and R. Pettipas. 2008, Ice and ocean mooring data statistics from Barrow Strait, the central section of the NW Passage in the Canadian Arctic Archipelago, *Int. J. Offshore Pol. Eng.*, **18**(4): 277-281

Since August 1998, personnel from the Bedford Institute of Oceanography have deployed year-long moorings in Barrow Strait of the Canadian Arctic Archipelago (CAA) to monitor the seasonal and inter-annual variabilities of ocean and pack ice parameters. Data from these moorings provide statistics on ice drafts and on ocean and ice velocities. This statistical information is presented here for bi-monthly subsets of the total eight year time series. Maximum ocean and ice velocities of 150 cm/sec were observed and ice drafts of up to 22 m. The 8-yr bi-monthly mean currents were stronger along the southern shore (15 cm/sec) where most of Arctic surface waters pass eastwards through the Barrow Strait.

Qian, M., C. Jones, R. Laprise, and D. Caya, 2008, The influences of NAO and Hudson Bay sea-ice on the climate of eastern Canada, *Clim. Dyn.*, **31**: 169-182, doi:10.1007/s00382-007-0343-9

Sea-ice cover over the Hudson Bay (HB) exhibits large variability in the freeze-up season normally starting in November. Its influence on the climate over eastern Canada has been studied with the Canadian Regional Climate Model (CRCM) in three steps. First, a 30-year continuous simulation from 1970 to 1999 was performed as a control run to evaluate the simulated climate variability over eastern Canada, in particularly variability associated with the North Atlantic oscillation (NAO). Then, 50 additional 1 month experiments were performed with modified sea-surface conditions prescribed over the HB. These integrations allowed us to quantify the contribution of HB sea-ice anomalies versus large scale NAO atmospheric variability (as defined by prescribed lateral boundary conditions) in inducing climate variability over eastern Canada. Results show that the NAO is the dominant factor controlling climate variability over eastern Canada. The contribution of HB sea-ice anomalies is significant only in the immediate coastal region. Under the influence of different phases of NAO, HB sea-ice anomalies do co-vary with temperature and precipitation anomalies downstream of the HB over eastern Canada. The ultimate cause of this co-variability is NAO variability which

forces variability in both HB sea-ice cover as well as temperature/precipitation over eastern Canada.

Rabenstein, L., S. Hendricks, T. Martin, A. Pfaffhuber, and C. Haas, 2010, Thickness and surface-properties of different sea-ice regimes within the Arctic Trans Polar Drift: Data from summers 2001, 2004 and 2007, *J. Geophys. Res.*, **115**, C12059, doi:10.1029/2009JC005846

Large-scale sea-ice thickness and surface property data were obtained in three summers and in three different sea-ice regimes in the Arctic Trans-Polar Drift (TPD) by means of helicopter electromagnetic sounding. Distribution functions *P* of sea-ice thickness and of the height, spacing, and density of sails were analyzed to characterize ice regimes of different ages and deformations. Results suggest that modal ice thickness is affected by the age of a sea-ice regime and that the degree of deformation is represented by the shape of *P*. Mean thickness changes with both age and deformation. Standard error calculations showed that representative mean and modal thickness could be obtained with transect lengths of 15 km and 50 km, respectively, in less deformed ice regimes such as those around the North Pole. In heavier deformed ice regimes closer to Greenland, 100 km transects were necessary for mean thickness determination and a representative modal thickness could not be obtained at all. Mean sail height did not differ between ice regimes, whereas sail density increased with the degree of deformation. Furthermore, the fraction of level ice, open melt ponds, and open water along the transects were determined. Although overall ice thickness in the central TPD was 50% thinner in 2007 than in 2001, first-year ice (FYI) was not significantly thinner in 2007 than FYI in 2001, with a decrease of only 0.3 m. Thinner FYI in 2007 only occurred close to the sea-ice edge, where open water covered more than 10% of the surface. Melt pond coverage retrieved from laser measurements was 15% in both the 2004 MYI regime and the 2007 FYI regime.

Scott, D. B., T. Schell, G. St-Onge, A. Rochon, and S. Blasco, 2009, Foraminiferal assemblage changes over the last 15,000 years on the Mackenzie-Beaufort Sea Slope and Amundsen Gulf, Canada: Implications for past sea ice conditions, *Paleoceanography*, **24**, PA2219, doi:10.1029/2007PA001575

Two cores, one from the Beaufort Sea Slope at 1000 m water depth (core 750) and one from the Amundsen Gulf at 426 m (core 124), were collected to help determine paleo–ice cover in the Holocene and late glacial of this area. Site 750 is particularly sensitive to changes in paleo–ice cover because it rests beneath the present ice margin of the permanent Arctic ice pack. Core 124 was sampled just in front of the former glacier that moved out into the Amundsen Gulf and started to recede about 13 ka B.P. Both cores have a strong occurrence of calcareous foraminifera in the upper few centimeters, but these disappear throughout most of the Holocene, suggesting more open water in that time period than present. In the sediments representing the end of the last glacial period (dated at ˜11,500–14,000 calibrated years B.P. (cal B.P.)) a calcareous fauna with an abundant planktic foraminiferal fauna suggests a return to almost permanent ice cover, much like the central Arctic today. Together with the foraminifera there was also

abundant ice-rafted debris (IRD) in both cores between 12,000 cal B.P. and ~14,000 cal B.P., but those units are of different ages between cores, suggesting different events. The IRD in both cores appears to have the same magnetic and chemical signals, but their origins cannot be determined exactly until clay mineralogy is completed. There is abundant organic debris in both cores below the IRD units: the organics in core 750 are very diffuse and not visually identifiable, but the organic material in core 124 is clearly identifiable with terrestrial root fragments; these are ^{14}C dated at over 37,000 years B.P. This is a marine unit as it also has glacial front foraminifera in the sediment with the organic debris that must have been originating from subglacial streams. The seismic and multibeam data both indicate glaciers did not cross the core 124 site.

2.10.1 Polynyas

Dumont, D., Y. Gratton, T. E. Arbetter, 2009, Modeling the Dynamics of the North Water Polynya Ice Bridge, *J. Phys. Oceanogr.*, **39**(6): 1448–1461

The North Water polynya, the largest polynya in the world, forms annually and recurrently in Smith Sound in northern Baffin Bay. Its formation is governed in part by the formation of an ice bridge in the narrow channel of Nares Strait below Kane Basin. Here, the widely used elastic–viscous–plastic elliptical rheology dynamic sea ice model is applied to the region. The idealized case is tested over a range of values for $e = [1.2, 2.0]$ and initial ice thicknesses from 0.75 to 3.5 m, using constant northerly winds over a period of 30 days, to evaluate long-term stability of different rheological parameterizations. Idealized high-resolution simulations show that the formation of a stable ice bridge is possible for $e \leq 1.8$. The dependence of the solution in terms of grid discretization is studied with a domain rotated 45°. A realistic domain with realistic forcing is also tested to compare time-variant solutions to actual observations. Cohesion has a remarkable impact on if and when the ice bridge will form and fail, assessing its importance for regional and global climate modeling, but the lack of observational thickness data during polynya events prevents the authors from identifying an optimal value for e.

Ehn, J. K., B. J. Hwang, R. Galley, and D. G. Barber, 2007, Investigations of newly formed sea ice in the Cape Bathurst polynya: 1. Structural, physical, and optical properties, *J. Geophys. Res.*, **112**, C05002, doi:10.1029/2006JC003702

The physical, structural, and optical properties of newly formed ice types were studied in the Cape Bathurst polynya (71°N, 127° W) during fall freezeup in October to early November 2003. Variable meteorological conditions with occasional snowfall resulted in the formation of numerous ice types and surface conditions. Ice samples were collected from horizontally homogeneous surfaces representative of the area. Crystallographic analysis on 33 ice cores revealed highly variable growth conditions and formation mechanisms in the area. The mean fraction of granular ice was 33%, while intermediate granular-columnar and columnar ice contributed 37% and 30%, respectively. Salinity profiles in the ice were C-shaped and as the ice grew thicker, bulk salinities decreased according to $4.582 + 13.358/h_i$ (cm). These conditions resulted in brine volumes ranging from

4% to 46%. Bare ice surfaces commonly formed a high salinity brine skim layer due to brine expulsion. Salinities up to 40‰ were observed in this layer. Under suitable conditions frost flowers formed on the ice, and their presence was related to characteristic ice microstructure with crystals that appeared disc-like in shape. Fine-grained snow-ice was formed when snow merged with surface brine to create a complex hypersaline surface at the snow/ice interface. The spectral reflectance for the thin ice types was most strongly related to surface conditions. The presence of frost flowers significantly increased the reflectance independent of snow precipitation. Any increase in ice thickness was found to have little effect on the reflectance once a 20–30 mm thick snow layer was present.

Galley, R. J., D. G. Barber. and J. Yackel, 2007, On the Link Between SAR-Derived Sea Ice Melt and Development of the Summer Upper Ocean Mixed Layer in the North Open Water Polynya, *Int. J. Rem. Sens.*, **28**(18): 3979-3994, doi:10.1080/01431160601105900

We examine the ability of SAR-derived landfast sea ice thermodynamic state surrounding the North Water Polynya to predict the timing of a shallow, stably stratified summer ocean mixed layer in the region. Radarsat-1 ScanSAR is used to derive melt and pond onset dates over landfast sea ice surrounding the polynya, describing its thermodynamic evolution. Salinity and temperature profiles, connected in time and space, are complemented by potential density profiles and mixed layer depths, which describe the evolution of the upper ocean mixed layer between 4 April and 21 July 1998. Surface salinity driven potential density stratification and summer mixed layer depths are temporally coincident. Sea ice-ocean connection is first described at the local scale, then regionally. At the local scale, a reduction in surface salinity occurs between the melt and pond onsets over landfast sea ice. At the polynya scale, interpolated pond onset date is highly effective at predicting the timing of a thin, stably stratified summer ocean mixed layer; this has consequences for the potential prediction of timing of maximum ecosystem productivity.

Hwang, B. J., J. K. Ehn, D. G. Barber, R. Galley, and T. C. Grenfell, 2007, Investigations of newly formed sea ice in the Cape Bathurst polynya: 2. Microwave emission, *J. Geophys. Res.*, **112**, C05003, doi:10.1029/2006JC003703

This study examines the role of newly formed sea ice geophysical state on microwave emission. Coincident with sea ice geophysical sampling, ship-based passive microwave emission data (dual-polarized at 19, 37 and 85 GHz) were collected in the Cape Bathurst Polynya during 18 October and 13 November 2003. Using polarization ratios (PRs), we found that bare thin ice was separable from snow-covered ice. Thin snow (equal to 0.02–0.13 m) thickness is significantly correlated with the spectral gradient ratios GRV(85,19) ($R^2 = 0.55$, P-value <0.05) and GRV(85,37) ($R^2 = 0.66$, P-value < 0.05), but not with GRV(37,19) ($R^2 = 0.19$, P-value > 0.2). The relationship between atmospherically corrected R37 and bare ice thickness showed an exponential relationship very comparable to that reported by *Martin et al.* [2004], which is ascribed to the reduction of bare ice surface salinity based on both observational and modeling studies. However, the relationship quickly becomes invalid for even thin snow

covered ice, due to significant impact of thin wet (liquid water fraction ~0.02–0.04) snow on microwave emission. Our results suggest that the sea ice algorithms NASA Team and NASA Team 2 could underestimate total ice concentration over thin bare ice by 35% on average, while both algorithms underestimate the total ice concentration by 20% over snow-covered ice. Using PR(85) sea ice could be delineated from open water using a properly adjusted threshold value accounting for cloud or fog effects, possibly with the exception of dark nilas and/or bare consolidated pancakes.

Smith, W. O. and D. G. Barber, 2007, Polynyas and Climate Change. A view to the Future, In. W.O. Smith and D. G. Barber (eds.): Polynyas: Windows to the World. Elsevier Oceanography Series, **74**: 411-419, doi:10.1016/S0422-9894(06)74013-2

There is no longer doubt that the climate of polar systems is changing, but the changes are far from uniform in time and space. Similarly, the changes of climate give rise to direct and indirect alterations of processes within polynyas. Arctic systems are undergoing the largest, most rapid change, and it is expected that polynyas within the Arctic will largely respond by a decrease in the duration of existence each season. This in turn will increase the maritime nature of Arctic polynyas, and simultaneously reduce their polar features. Antarctic polynyas might be expected to have a larger gradient of responses because the direction and magnitude of climate change is not uniform. It is suggested that changes in hemispheric characteristics of deep water will result in substantial changes in the duration of periods of polynya existence, as well as possibly major alterations of the biogeochemical cycles and food webs of the polynyas. Arctic polynyas will likely respond to polar climate change based on the type of polynya they represent. The flaw lead polynya system will likely become larger and exist for a longer duration over the annual cycle; ice-edge polynyas have already begun to change (e.g., North East Water) and in the future we may see these types of polynyas become more like marginal ice zones than true polynyas. Polynyas, by nature of their largely ephemeral nature, are indeed "indicator" regions for large-scale change, and by monitoring changes within these sensitive areas, we suggest that polynyas can act as a model system for changes in polar marine environments.

Willmes, S., T. Krumpen, S. Adams, L. Rabenstein, C. Haas, J. Hoelemann, S. Hendricks, and G. Heinemann, Cross-validation of polynya monitoring methods from multisensor satellite and airborne data: a case study for the Laptev Sea, Can, J, Rem, Sens,, **36**: S196-S210, doi:10.5589/m10-012

Wind-driven coastal polynyas in the polar oceans are recognized as regions of extensive new ice formation in the cold season. Hence, they may play an increasing role in the uncertain future of the sea-ice budget in the polar oceans. The Laptev Sea polynyas in the Siberian Arctic are well recognized as being significant ice producers and might gain special attention with regards to ice volume changes in the Arctic. Long-term monitoring and characterization of these polynyas require stable methods to detect the area of open water and the growth, thickness, and evolution of thin ice. We examine different parameters and

methods to observe polynya area and thin ice thickness during a prominent polynya event in the Laptev Sea in April 2008. These are derived from visible, infrared, and microwave satellite data. Airborne electromagnetic ice thickness measurements with high spatial resolution and aerial photography taken across the polynya are used to assess the feasibility of the methods for long-term and large-scale polynya monitoring within this area. Our results indicate that in the narrow flaw polynyas of the Laptev Sea the coarse resolution of commonly used microwave channel combinations provokes sources of error through mixed signals at the fast- and pack-ice edges. Polynya monitoring results can be significantly improved using enhanced resolution data products. This implies that previously suggested methods for the retrieval of polynya area, thin ice thickness, and ice production are not transferable in space and time. Data as well as method parameterizations have to be chosen carefully to avoid large errors due to regional peculiarities.

2.10.2 Modeling Sea Ice

Dunlap, E, B. M. DeTracey, and C. L. Tang, 2007, Short-Wave Radiation and Sea-Ice in Baffin Bay, *Atmos.-Ocean*, **45**(4): 195–210, doi:10.3137/ao.450402

The sensitivity of the annual cycle of ice cover in Baffin Bay to short-wave radiation is investigated. The Princeton Ocean Model (POM) is used and is coupled with a multi-category, dynamic-thermodynamic seaice model in which the surface energy balance governs the growth rates of ice of varying thickness. During spring and summer the short-wave radiation flux dominates other surface heat fluxes and thus has the greatest effect on the ice melt. The sensitivity of model results to short-wave radiation is tested using several, commonly used, shortwave parameterizations under climatological, as well as short-term, atmospheric forcing. The focus of this paper is short-term and annual variability. It is shown that simulated ice cover is sensitive to the short-wave radiation formulation during the melting phase. For the Baffin Bay simulation, the differences in the resulting ice area and volume, integrated from May to November, can be as large as 45% and 70%, respectively. The parameterization of the effect of cloud cover on the short-wave radiation can result in the sea-ice area and volume changes reaching 20% and 30%, respectively. The variation of the cloud amount represents cloud data error, and has a relatively small effect (less then ±4%) on the simulated ice conditions. This is due to the fact that the effect of cloud cover on the short-wave radiation flux is largely compensated for by its effect on the net near-surface long-wave radiation flux.

Iacozza, J. and D. G. Barber. 2009, An examination of snow redistribution over smooth land-fast sea ice, *Hydrological Processes*, **24**(7): 850-865, doi:10.1002/hyp.7526

An understanding of temporal evolution of snow on sea ice at different spatial scales is essential for improvement of snow parameterization in sea ice models. One of the problems we face, however, is that long-term climate data are routinely available for land and not for sea ice. In this paper, we examine the temporal evolution of snow over smooth land-fast first-year sea ice using observational and modelled data. Changes in probability density functions

indicate that depositional and drifting events control the evolution of snow distribution. Geostatistical analysis suggests that snowdrifts increased over the study period, and the orientation was related to the meteorological conditions. At the microscale, the temporal evolution of the snowdrifts was a product of infilling in the valleys between drifts.

Results using two shore-based climate reporting stations (Paulatuk and Tuktoyuktuk, NWT) suggest that on-ice air temperature and relative humidity can be estimated using air temperature recorded at either station. Wind speed, direction and precipitation on ice cannot be accurately estimated using meteorological data from either station. The temporal evolution of snow distribution over smooth land-fast sea ice was modelled using *SnowModel* and four different forcing regimes. The results from these model runs indicate a lack of agreement between observed distribution and model outputs. The reasons for these results are lack of meteorological measurements prior to the end of January, lack of spatially adequate surface topography and discrepancies between meteorological variables on land and ice.

Lemieux, J.-F., B. Tremblay, S. Thomas, J. Sedláček, and L. A. Mysak, 2008, Using the preconditioned Generalized Minimum RESidual (GMRES) method to solve the sea-ice momentum equation, *J. Geophys. Res.*, **113**, C10004, doi:10.1029/2007JC004680

We introduce the preconditioned generalized minimum residual (GMRES) method, along with an outer loop (OL) iteration to solve the sea-ice momentum equation. The preconditioned GMRES method is the linear solver. GMRES together with the OL is used to solve the nonlinear momentum equation. The GMRES method has low storage requirements, and it is computationally efficient and parallelizable. It was found that the preconditioned GMRES method is about 16 times faster than a stand-alone successive overrelaxation (SOR) solver and three times faster than a stand-alone line SOR (LSOR). Unlike stand-alone SOR and stand-alone LSOR, the cpu time needed by the preconditioned GMRES method for convergence weakly depends on the relaxation parameter when it is smaller than the optimal value. Results also show that with a 6-hour time step, the free drift velocity field is a better initial guess than the previous time step solution. For GMRES, the symmetry of the system matrix is not a prerequisite. The Coriolis term and the off-diagonal part of the water drag term can then be treated implicitly. The implicit treatment eliminates an instability characterized by a residual oscillation in the total kinetic energy of the ice pack that can be present when these off-diagonal terms are handled explicitly. Treating these terms explicitly prevents one from obtaining a high-accuracy solution of the sea-ice momentum equation unless a corrector step is applied. In fact, even after a large number of OL iterations, errors in the drift of the same magnitude as the drift itself can be present when these terms are treated explicitly.

Lemieux, J.-F. and B. Tremblay, 2009, Numerical convergence of viscous-plastic sea ice models, *J. Geophys. Res.*, **114**, C05009, doi:10.1029/2008JC005017

We investigate the convergence properties of the nonlinear solver used in viscous-plastic (VP) sea ice models. More specifically, we study the nonlinear solver that is based on an implicit solution of the linearized system of equations and an outer loop (OL) iteration (or pseudo time steps). When the time step is comparable to the forcing time scale, a small number of OL iterations leads to errors in the simulated velocity field that are of the same order of magnitude as the mean drift. The slow convergence is an issue at all spatial resolution but is more severe as the grid is refined. The metrics used by the sea ice modeling community to assess convergence are misleading. Indeed, when performing 10 OL iterations with a 6 h time step, the average kinetic energy of the pack is always within 2% of the fully converged value. However, the errors on the drift are of the same order of magnitude as the mean drift. Also, while 40 OL iterations provide a VP solution (with stress states inside or on the yield curve), large parts of the domain are characterized by errors of 0.5–1.0 cm s^{-1}. The largest errors are localized in regions of large sea ice deformations where strong ice interactions are present. To resolve those deformations accurately, we find that more than 100 OL iterations are required. To obtain a continuously differentiable momentum equation, we replace the formulation of the viscous coefficients with capping with a tangent hyperbolic function. This reduces the number of OL iterations required to reach a certain residual norm by a factor of ~2.

Lemieux, J. F, L. B. Tremblay, J. Sedlacek, P. Tupper, S. Thomas, D. Huard, and J. P. Auclair, 2010, Improving the numerical convergence of viscous-plastic sea ice models with the Jacobian-free Newton-Krylov method, *J. Comp. Phys.,* **229**(8): 2840-2852, doi:10.1016/j.jcp.2009.12.011

We have implemented the Jacobian-free Newton–Krylov (JFNK) method to solve the sea ice momentum equation with a viscous-plastic (VP) formulation. The JFNK method has many advantages: the system matrix (the Jacobian) does not need to be formed and stored, the method is parallelizable and the convergence can be nearly quadratic in the vicinity of the solution. The convergence rate of our JFNK implementation is characterized by two phases: an initial phase with slow convergence and a fast phase for which the residual norm decreases significantly from one Newton iteration to the next. Because of this fast phase, the computational gain of the JFNK method over the standard solver used in existing VP models increases with the required drop in the residual norm (termination criterion). The JFNK method is between 3 and 6.6 times faster (depending on the spatial resolution and termination criterion) than the standard solver using a preconditioned generalized minimum residual method. Resolutions tested in this study are 80, 40, 20 and 10 km. For a large required drop in the residual norm, both JFNK and standard solvers sometimes do not converge. The failure rate for both solvers increases as the grid is refined but stays relatively small (less than 2.3% of failures). With increasing spatial resolution, the velocity gradients (sea ice deformations) get more and more important. Nonlinear solvers such as the JFNK method tend to have difficulties when there are such sharp structures in the solution. This lack of robustness of both solvers is however a debatable problem as it mostly occurs for large required drops in the residual norm. Furthermore,

when it occurs, it usually affects only a few grid cells, i.e., the residual is small for all the velocity components except in very localized regions. Globalization approaches for the JFNK solver, such as the line search method, have not yet proven to be successful. Further investigation is needed.

Sou, T. and G. Flato, 2009, Sea ice in the Canadian Arctic Archipelago: modeling the past (1950-2004) and the future (2041-2060), *J. Clim.*, **22**: 2181-2198, doi:10.1175/2008JCLI2335.1

Considering the recent losses observed in Arctic sea ice and the anticipated future warming due to anthropogenic greenhouse gas emissions, sea ice retreat in the Canadian Arctic Archipelago (CAA) is expected and indeed is already being observed. As most global climate models do not resolve the CAA region, a fine-resolution ice–ocean regional model is developed and used to make a projection of future changes in the CAA sea ice. Results from a historical run (1950–2004) are used to evaluate the model. The model does well in representing observed sea ice spatial and seasonal variability, but tends to underestimate summertime ice cover. The model results for the future (2041–60) show little change in wintertime ice concentrations from the past, but summertime ice concentrations decrease by 45%. The ice thickness is projected to decrease by 17% in the winter and by 36% in summer. Based on this study, a completely ice-free CAA is unlikely by the year 2050, but the simulated ice retreat suggests that the region could support some commercial shipping.

Tang, C. and E. Dunlap, 2007, Modeling the annual variation of sea-ice cover in Baffin Bay, *Int. J. Offsh. Polar Eng.*, **17(3)**: 176-181, http://www.isope.org/publications/journals/ijope-17-3/abst-17-3-p176-RF-36-Tang.pdf

Baffin Bay is partially covered by sea ice all year except in September. The distribution of sea ice and its annual variation are controlled mainly by the meteorological conditions and ocean currents. To model the annual variation of sea ice, a coupled ice-ocean model has been developed. The ocean model is the Princeton Ocean Model, formulated in sigma coordinates with 16 levels; it uses 2nd-order turbulence closure to parameterize vertical mixing. The ice model is based on Hibler's viscousplastic rheology and contains multiple ice categories defined by thickness range. The heat and salt fluxes between ice and ocean are based on the formulation of Mellor and Kantha. The model domain encompasses Baffin Bay and the Labrador Sea with a grid resolution of 1/3_ longitude and is variable in latitude to maintain approximately square grid cells. Forcing fields are computed from 3-hourly meteorological variables provided by the Canadian Meteorological Centre. The model is integrated from September 2004 to January 2006. The main features of the model simulations include an increasing ice cover from October to February; an approximately constant ice cover from February to May; and a decreasing ice cover from June to August. In mid-May, a polynya starts to develop in northern Baffin Bay (North Water Polynya),which is maintained through July. Ice as thick as 2.5 m appears off the coast of Baffin Island and Melville Bay in April and May. The concentration and thickness in western Baffin Bay are higher than in eastern Baffin Bay due to the influence of

the warm West Greenland Current flowing into Baffin Bay. The ice velocities are relatively high in the northern straits, off the Baffin Island coast and in western Davis Strait, reflecting the seasonal wind conditions and surface circulation. The modeled ice distribution is compared with satellite data, and good agreement is obtained.

Terwisscha van Scheltinga, A. D., P. G. Myers, and J. D. Pietrzak, 2010, A finite element sea ice model of the Canadian Arctic Archipelago, *Ocean Dynamics*, **60**(6): 1539-1558, doi:10.1007/s10236-010-0356-5

The Canadian Arctic Archipelago (CAA) is a complex area formed by narrow straits and islands in the Arctic. It is an important pathway for freshwater and sea-ice transport from the Arctic Ocean to the Labrador Sea and ultimately to the Atlantic Ocean. The narrow straits are often crudely represented in coupled sea-ice–ocean models, leading to a misrepresentation of transports through these straits. Unstructured meshes are an alternative in modelling this complex region, since they are able to capture the complex geometry of the CAA. This provides higher resolution in the flow field and allows for more accurate transports (but not necessarily better modelling). In this paper, a finite element sea-ice model of the Arctic region is described and used to estimate the sea-ice fluxes through the CAA. The model is a dynamic–thermodynamic sea-ice model with elastic–viscous–plastic rheology and is coupled to a slab ocean, where the temperature and salinity are restored to climatology, with no velocities and surface elevation. The model is spun-up from 1973 to 1978 with NCEP/NARR reanalysis data. From 1979 to 2007, the model is forced by NCEP/DoE reanalysis data. The large scale sea-ice characteristics show good agreement with observations. The total sea-ice area agrees very well with observations and shows a sensitivity to the Arctic oscillation (AO). For 1998–2002, we find estimates for the sea-ice volume and area fluxes through Amundsen Gulf, McClure Strait and the Queen Elizabeth Islands that compare well with observation and are slightly better than estimates from other models. For Nares Strait, we find that the fluxes are much lower than observed, due to the missing effect of topographic steering on the atmospheric forcing fields. The 1979–2007 fluxes show large seasonal and interannual variability driven primarily by variability in the ice velocity field and a sensitivity to the AO and other large-scale atmospheric variability, which suggests that accurate atmospheric forcing might be crucial to modelling the CAA.

2.10.3 Remote Sensing of Sea Ice

Agnew, T., A. Lambe, and D. Long, 2008, Estimating sea ice area flux across the Canadian Arctic Archipelago using enhanced AMSR-E, *J. Geophys. Res.*, **113**, C10011, doi:10.1029/2007JC004582

Enhanced resolution Advanced Microwave Scanning Radiometer (AMSR-E) imagery is used to estimate daily sea ice area fluxes between the Canadian Arctic Archipelago and the Arctic Ocean and Baffin Bay for the period September 2002 to June 2007. Over the period, Amundsen Gulf and M'Clure Strait exported 54 × 10^3 km^2 of sea ice area or roughly 77 km^3 of sea ice volume each year into the Arctic Ocean. Export/import into the Arctic Ocean through the Queen Elizabeth

Islands is small and uncertain since no estimates for July and August could be made due to atmospheric attenuation of the microwave signal. Lancaster Sound exported 68×10^3 km^2 of sea ice area or roughly 102 km^3 of ice volume into Baffin Bay. This produced a net loss of sea ice area of about 122×10^3 km^2 or roughly 174 km^3 a^{-1} which is presumed to be generated from within the Archipelago itself mainly through the stationary and transient polynyas and leads that form each winter. Daily ice area fluxes for Amundsen Gulf (AG) and Lancaster Sound (LS) were as high as ±2500 km^2 d^{-1} and were event driven depending on synoptic scale atmospheric circulation and the mobility of the sea ice. Mean sea level pressure difference across each gate is moderately correlated with daily sea ice area fluxes despite the fact that free ice drift conditions are not always met in the region. Cross-gradient and daily sea ice area flux for Lancaster Sound show a large number of counter gradient ice flux occurrences suggesting that local mesoscale winds (nongeostrophic) and perhaps ocean currents play a role in transporting sea ice through this gate. Monthly ice fluxes for the AG and MS gate were positively correlated with the AO index indicating that a strong Beaufort Sea high pressure and gyre corresponded to more export into the Beaufort Sea. Monthly fluxes for the LS gate were positively correlated with the NAO index indicating that strong southerly atmospheric circulation over Baffin Bay increases ice export into Baffin Bay from Lancaster Sound.

Ehn, J. K., C. J. Mundy, and D. G. Barber, 2008, Bio-optical and structural properties inferred from irradiance measurements within the bottommost layers in an Arctic landfast sea ice cover, *J. Geophys. Res.*, **113**, C03S03, doi:10.1029/2007JC004194

Irradiance spectra were measured at vertical increments within the bottommost layers of landfast sea ice with the aid of divers in Franklin Bay, Canada, in an effort to obtain input parameters for bio-optical modeling of sea ice. The study took place between 22 April and 9 May 2004 during the overwintering stage of CASES (Canadian Arctic Shelf Exchange Study). The ice was about 1.8 m thick with a snow cover of variable thickness (~0.04 to 0.4 m). Ice surface temperatures increased from about −12° to −6.4°C during the sampling period, while ice temperatures within the bottommost portion under study ranged from −3.0° to −1.2°C. Ice algae were visible within the bottommost centimeters of the sea ice. This algae layer had a marked effect on the spectral distribution of transmitted irradiance beneath the ice. Particulate absorption spectra, $a_p(\lambda)$, measured from melted ice samples showed evidence of chloroplastic pigment degradation and could not fully explain the shape of the in situ diffuse attenuation coefficient, $K_d(\lambda)$, for the algal layer. Interior ice layers, however, did show absorption curves similar to $a_p(\lambda)$ from samples, suggesting the presence of degraded algal pigments within these layers. The discrete ordinates radiative transfer (DISORT) code was iterated in an inverse approach to estimate $a_p(\lambda)$ and the scattering coefficient, b_{tot}, from the irradiance profiles. For the bottom 0.1 m of the sea ice, b_{tot} was around 400 m^{-1}, while at the 0.1- to 0.2-m layer from the ice bottom it decreased to 165 m^{-1}. Using $a_p(\lambda)$ combined with wavelength independent b_{tot} as inputs to DISORT seem to adequately explain the radiative transfer near the

bottom of first-year sea ice provided that adjustments were made to the brine volume fraction.

Ehn, J. K., T. N. Papakyriakou, and D. G. Barber, 2008, Inference of optical properties from radiation profiles within melting landfast sea ice, *J. Geophys. Res.*, **113**, C09024, doi:10.1029/2007JC004656

Vertical in-ice spectral radiation profiles were measured within melting 1.5- to 1.7-m-thick landfast sea ice in western Hudson Bay on 25 April 2005. Because the surface ice was subject to extensive melting and refreezing, the sea ice had fractioned into two main types, i.e., areas of more reflective white ice and less reflective blue ice. The shortwave albedo was about 0.69 for white ice and 0.47 for bare blue ice. The corresponding shortwave transmittance through the ice cover was about 0.02 and 0.09, respectively. The inherent optical properties of the sea ice were inferred by tying the input and output of radiative transfer simulations to the radiation profiles and the ice physical properties, as well as to the irradiance measurements above and below the ice cover. To explain observed spectral albedo and transmittance simultaneously, the ice/snow above the interior ice was divided into three layers on the basis of the following observations: snow (white ice) or a thin soot containing layer (blue ice), drained ice above and saturated ice below the waterline. Similarly, the bottom portion was divided on the basis of the presence of a living ice algae layer adjacent to the seawater interface and a layer extending 30 cm above the bottom containing mostly detrital matter. The interior of the ice, i.e., roughly 20–40 cm from boundaries, was well-represented by a single layer of pure sea ice as the radiation field was nearly asymptotic and the absorption spectra showed little evidence of impurities. Representative values for the scattering coefficient ranged 600–800 m^{-1}, with a Henyey-Greenstein asymmetry parameter of 0.995. Observations within white ice suggest that about 40% of the energy responsible of the internal melting was provided directly by shortwave radiation, while the rest is due to heat conduction.

Galley, R. J., M. Trachtenberg, A. Langlois, D. G. Barber, and L. Shafai, 2009, Observations of geophysical and dielectric properties and ground penetrating radar signatures for discrimination of snow, sea ice and freshwater ice thickness, *Cold Reg. Sci. Tech.*, doi:10.1016/j.coldregions.2009.01.003

Separate snow and ice thickness at the same location are important parameters in determining the flux of heat and light between the atmosphere and ocean in Arctic marine environments, but physical sampling requires a great deal of effort to yield few results spatially and temporally. Here, ground penetrating radar (GPR) at 250 MHz and 1 GHz reliably measured snow, river ice and sea ice thickness and compared well with physical and dielectric properties of the media in spite of their spatial and temporal variation. GPR velocities were calculated for snow, river ice and sea ice from both dielectric information and GPR returns for snow river ice and sea ice. In snow on river ice, physical sampling yielded permittivity (ε') of 1.68 at 1 GHz while the apparent ε' (derived from GPR measurements) at 1 GHz from GPR returns ranged from 1.6 to 2.1 resulting in snow thickness overestimations of 6.7% to 11%. River ice ε' at both frequencies from physical

samples was 3.17, while apparent ε′ ranged from 2.94 to 3.11, underestimating ice thickness by less than 3.6%. Snow on sea ice on 4 March 2006 had a ε′ of 1.94 at 1 GHz calculated from physical samples, and 1.9 derived from GPR measurements, resulting in near-identical thicknesses. Snow on sea ice 3 days later had an ε′ of 1.67 at 1 GHz calculated from physical samples, while its apparent ε′ was 1.9 at 1 GHz, leading to a GPR-predicted snow thickness which was 1 cm (8.3%) greater than physically measured. Physical samples of sea ice on 4 March yielded ε′ of 3.8 at 1 GHz, while GPR returns yielded an apparent ε′ of 3.35, underestimating sea ice thickness by 5.6%. GPR returns at 250 MHz returned a snow-plus-sea ice thickness which was 5.9% less than physically measured. In cases when the 1 GHz radar did resolve the sea ice–seawater interface, the 250 MHz system was used to measure the snow-plus-sea ice thickness and the snow thickness resulting from the 1 GHz radar was subtracted to make separate snow and sea ice thickness measurements at the same location.

Geldsetzer, T., J. B., Mead, J. J. Yackel, R. K. Scharien, and S. E. L. Howell, 2007, Surface-Based Polarimetric C-Band Scatterometer for Field Measurements of Sea Ice, IEEE Trans. Geosci. Rem. Sens., **45**(11): 3405-3416, doi:10.1109/TGRS.2007.907043

A portable surface-based polarimetric C-band scatterometer for field deployment over sea ice is presented. The scatterometer system, its calibration, signal processing, and near-field correction are described. The near-field correction is shown to be effective for both linear polarized and polarimetric backscatter. Field methods for the scatterometer are described. Sample linear polarized and polarimetric backscatter results are presented for snow-covered first-year sea ice (FYI), multiyear hummock ice, and rough melt pond water on FYI. The magnitude of backscatter signature variability due to system effects is presented, providing the necessary basis for quantitative analysis of field data.

Geldsetzer, T. and J. J. Yackel, 2010, Sea ice type and open water discrimination using dual co-polarized C-band SAR, *Can. J. Rem. Sens.*, **35**(1): 73-84

We investigate the utility of dual co-polarized C-band synthetic aperture radar (SAR) imagery for discriminating sea ice types and open water during winter. We base our analysis on ENVISAT ASAR alternating vertical and horizontal polarization (VV, HH) medium-resolution imagery of thin sea ice, first-year sea ice, multiyear sea ice, and open water in the Canadian Arctic. We introduce a methodology for generating colour composite imagery (based on VV, HH, and copolarization ratio channels) that substantially enhances visual discrimination. We statistically compare sampled vertical and horizontal backscatter from sea ice types and open water to assess backscatter magnitudes and polarization differences. The latter are presented as co-polarized ratio (VV/HH) values in decibels (dB). We conclude by presenting a decision-tree classifier using estimated statistical thresholds. Open water is unambiguously discriminated (>99% accuracy) from all sea ice types, except thin sea ice, using a co-polarized ratio threshold of 2 dB. Thin sea ice exhibits high variability in backscatter magnitude and polarization difference, making its discrimination from multiyear sea ice, rough first-year sea ice, and open water ambiguous. Thin sea ice is

effectively discriminated (93% accuracy) from smooth first-year sea ice using a co-polarized ratio threshold of 1.3 dB. Smooth snow-covered first-year sea ice exhibits polarization differences that are attributed to volume scattering mechanisms within the brine-wetted snow cover.

Haas, C., J. Lobach, S. Hendricks, L. Rabenstein, A. Pfaffling, 2009, Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system, J. Appl. Geophys., **67**(3): 234-241, doi:10.1016/j.jappgeo.2008.05.005

Sea ice is an important climate variable and is also an obstacle for marine operations in polar regions. We have developed a small and lightweight, digitally operated frequency-domain electromagnetic-induction (EM) system, a so-called EM bird, dedicated for measurements of sea ice thickness. It is 3.5 m long and weighs only 105 kg, and can therefore easily be shipped to remote places and operated from icebreakers and small helicopters. Here, we describe the technical design of the bird operating at two frequencies of $f1$ = 3.68 kHz and $f2$ = 112 kHz, and study its technical performance. On average, noise amounts to ± 8.5 ppm and ± 17.5 ppm for $f1$ and $f2$, respectively. Electrical drift amounts to 200 ppm/h and 2000 ppm/h for $f1$ and $f2$, during the first 0.5 h of operation. It is reduced by 75% after 2 h. Calibration of the Inphase and Quadrature ppm signals varies by 2 to 3%. A sensitivity study shows that all these signal variations do affect the accuracy of the ice thickness retrieval, but that it remains better than ± 0.1 m over level ice in most cases. This accuracy is also confirmed by means of comparisons of the helicopter EM data with other thickness measurements. The paper also presents the ice thickness retrieval from single-component Inphase data of $f1$.

Haas, C., S. Hendricks, H. Eicken, and A. Herber, 2010, Synoptic airborne thickness surveys reveal state of Arctic sea ice cover, *Geophys. Res. Lett.*, **37**, L09501, doi:10.1029/2010GL042652

While summer Arctic sea-ice extent has decreased over the past three decades, it is subject to large interannual and regional variations. Methodological challenges in measuring ice thickness continue to hamper our understanding of the response of the ice-thickness distribution to recent change, limiting the ability to forecast sea-ice change over the next decade. We present results from a 2400 km long pan-Arctic airborne electromagnetic (EM) ice thickness survey in April 2009, the first-ever large-scale EM thickness dataset obtained by fixed-wing aircraft over key regions of old ice in the Arctic Ocean between Svalbard and Alaska. The data provide detailed insight into ice thickness distributions characteristic for the different regions. Comparison with previous EM surveys shows that modal thicknesses of old ice had changed little since 2007, and remained within the expected range of natural variability.

Hendricks, S., S. Gerland, L. H. Smedsrud, C. Haas, A. A. Pfaffhuber, and F. Nilsen, F. 2010, Sea Ice Thickness Variability in Storfjorden, Svalbard, *Annals of Glaciology*, **52**(57: 61-68, http://www.igsoc.org/annals/v52/57/a57a125.pdf

Results from electromagnetic induction surveys of sea-ice thickness in Storfjorden,

Svalbard, reveal large interannual ice-thickness variations in a region which is typically characterized by a reoccurring polynya. The surveys were performed in March 2003, May 2006 and March 2007 with helicopter- and ship-based sensors. The thickness distributions are influenced by sea-ice and atmospheric boundary conditions 2 months prior to the surveys, which are assessed with synthetic aperture radar (SAR) images, regional QuikSCAT backscatter maps and wind information from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis dataset. Locally formed thin ice from the Storfjorden polynya was frequently observed in 2003 and 2007 (mean thickness 0.55 and 0.37 m, respectively) because these years were characterized by prevailing northeasterly winds. In contrast, the entire fjord was covered with thick external sea ice in 2006 (mean thickness 2.21 m), when ice from the Barents Sea was driven into the fjord by predominantly southerly winds. The modal thickness of this external ice in 2006 increased from 1.2m in the northern fjord to 2.4m in the southern fjord, indicating stronger deformation in the southern part. This dynamically thickened ice was even thicker than multi-year ice advected from the central Arctic Ocean in 2003 (mean thickness 1.83 m). The thermodynamic ice thickness of fast ice as boundary condition is investigated with a one dimensional sea-ice growth model (1DICE) forced with meteorological data from the weather station at the island of Hopen, southeast of Storfjorden. The model results are in good agreement with the modal thicknesses of fast-ice measurements in all years.

Howell, S. E. L., A. Tivy, J. J. Yackel, B. G. T. Else, and C. R. Duguay, 2008, Changing sea ice melt parameters in the Canadian Arctic Archipelago: Implications for the future presence of multiyear ice, *J. Geophys. Res.*, **113**, C09030, doi:10.1029/2008JC004730

Estimates of annual sea ice melt onset, freeze onset, and melt duration are made within the Canadian Arctic Archipelago (CAA) using SeaWinds/QuikSCAT data from 2000 to 2007. The average date of melt onset occurred on day 150, the average freeze onset occurred on day 266, and the average number of days of melt was 116. Melt onset occurred first, and freeze onset occurred last within the Amundsen, Western Arctic Waterway, and Eastern Parry Channel regions, whereas the reverse occurred in the Queen Elizabeth Islands (QEI) and the M'Clure and Viscount-Melville regions. Multiyear sea ice (MYI) increases occurred from 2000 to 2004 because of dynamic import and first-year sea ice (FYI) being promoted to MYI, but this replenishment virtually stopped from 2005 to 2007, coincident with longer melt seasons. Only after two consecutive long melt seasons (2005–2006) and almost no replenishment were regions to the south of the QEI cleared of MYI. We argue that this is because MYI must slowly ablate on the underside while in transit within the CAA from the small oceanic heat flux and can therefore survive for several years in southern regions without replenishment. Net positive dynamic MYI import into the CAA was observed in 2007 following MYI removal during 2005–2006. Longer melt seasons will continue to reduce the inventory of FYI in the CAA following the melt season. Longer melt seasons within the CAA will likely not reduce MYI dynamic import, but it remains to be seen whether or not this MYI will be able to survive longer melt seasons as it migrates to the southern regions.

Hwang, B. J., A. Langlois, D. G. Barber, and T. N. Papakyriakou, 2007, On Detection of the Thermophysical State of Landfast First-Year Sea Ice Using In-Situ Microwave Emission During Spring Melt, *Rem. Sens. of Env.*, **111**(2-3):148-159, doi:10.1016/j.rse.2007.02.033

In this study we examine the critical linkages between thermophysical properties and microwave emissions of landfast snow-covered first-year sea ice during spring melt. For this we analyzed the temporal evolution of radiation fluxes, electro-thermophysical properties and microwave emissions, and perform model simulations to evaluate the observations. The results show five major microwave signature events: brine-rich, blowing snow, melt onset, the onset of funicular regime, and freezing. A brine-rich snow basal layer can considerably increase the snow wetness in the upper and mid layers, resulting in a significant increase in complex permittivity that in turn increases in polarization difference (δp) at 19 and 37 GHz. A dense ($\sim$ 0.40 g cm^{-3}) wind-packed snow surface layer, during a blowing snow event, was found to increase the permittivity (i.e., surface reflectivity) that in turn increases δp in microwave emissions. Melt onset caused by sustained warming (above − 5 °C) corresponded to increased δp of $\sim$ 9 K at 19 GHz. The most dramatic increase in δp (up to 17 K at 19 GHz) coincided with the occurrence of a rainstorm. During a freezing, melt-freeze events enlarged snow grains and led to formation of ice lenses and layers within the snow, thereby significantly decreasing microwave emissions. We found that these five factors state above were critical to the melt indicators (i.e., $\Delta T_B(H)$ ($T_B(19H) - T_B(37H)$) and XPGR ([$T_B(19H) - T_B(37V)$]/[$T_B(19H) + T_B(37V)$])) commonly used in the satellite melt detection algorithms. The results suggests that the absolute value of $T_B(19H)$ (brightness temperature of horizontal polarization at 19 GHz) would be a good indicator along with $\Delta T_B(H)$ (or XPGR) to delineate the melt onset from ambiguous factors (i.e., a brine-rich slush layer or wind-packed layer), and that the funicular stage of snow melt on sea ice could be unambiguously detected by either $\Delta T_B(H)$ or XPGR.

Hwang, B. J., J. K. Ehn, and D. G. Barber, 2008, Impact of ice temperature on microwave emissivity of thin newly formed sea ice, *J. Geophys. Res.*, **113**, C02021, doi:10.1029/2006JC003930

This study examines the impact of ice temperature on microwave emissivity over thin, newly formed sea ice at 6, 19, and 37 GHz during October 2003 in the southern Beaufort Sea, where the physical properties of newly formed sea ice were coincidently measured with microwave emissions. Six ice stations with distinct properties were selected and divided according to ice surface temperature into warm (above –3°C) or cold (below –3°C) stations. The warm stations had a lower emissivity at the vertical polarization by 0.1 than the cold stations and a corresponding difference in brine volume and dielectric properties. Significant correlations were observed between brine volume and ice emissivity ($R^2 = 0.8$, p value < 0.05). A sensitivity study showed that decreasing ice temperatures from −2.1° to −5.0°C explained the observed difference of 0.1 in ice emissivity between warm and cold stations. The results suggest that the temperature of thin

bare ice could be the critical factor in determining ice emissivity near the melting point (about −2°C). Furthermore, a slight decrease in ice temperature (i.e., from −2° to −5°C) significantly reduces the brine volume, thus resulting in high ice emissivity. Finally, we demonstrate the potential of newly formed ice to cause errors in estimating sea ice concentrations using Advanced Microwave Scanning Radiometer–E data.

Hwang, B. J. and D. G. Barber, 2008, On the Impact of Ice Emissivity on Sea Ice Temperature Retrieval Using Passive Microwave Radiance Data, IEEE *Geosci. Rem. Sens. Lett.*, **5**(3): 448-452, doi:10.1109/LGRS.2008.917266

This letter examines the performance of two Advanced Microwave Scanning Radiometer-EOS (AMSR-E) ice temperature algorithms over first-year sea ice during the spring transition period where ice concentrations are close to 100%. The results showed, before snow melt, that the old AMSR-E algorithm overestimated the ice temperature by up to 18 K, which is relative to *in situ* and thermodynamically calculated snow/ice interface temperatures (T_{si}). An adjustment of vertically polarized ice emissivity of 6.9 GHz [$epsiv_I$(6V)] to 0.98, which was identical to the constant value used in the latest version of the AMSR-E ice temperature algorithm (posted July 2007), demonstrated a significant improvement in ice temperature retrieval. However, after snow melt, the ice temperature retrieval with any constant $epsiv_I$(6V) failed to correctly estimate the ice temperatures due to large variability in the physical properties of snow and, in turn, penetration depth and $epsiv_I$(6V). The results suggest that a local adjustment of $epsiv_I$(6V), which is by incorporating a simple thermodynamic model into the AMSR-E ice temperature algorithm, would be useful in improving the performance of the algorithm.

Isleifson, D., A. Langlois, D. G. Barber, and L. Shafai, 2009, C-Band Scatterometer Measurements of Multiyear Sea Ice Before Fall Freeze-Up in the Canadian Arctic *IEEE Trans. Geosci. Rem. Sens.*, **47**(6): 1651-1661, doi:10.1109/TGRS.2008.2006566

Backscatter signatures of multiyear sea ice (MYI) during the late summer and early fall season before the fall freeze-up in the Canadian Arctic Archipelago (CAA) have been obtained through the use of a ship-based polarimetric scatterometer. The device operates in C-band, and measurements were conducted in swaths from incidence angles of 20°–60°. Three characteristic sites on MYI floes were investigated in the high Arctic and the central Arctic regions. *In situ* snow and sea-ice thermophysical data were collected at each site in conjunction with local scatterometer measurements. The thermophysical data were subsequently analyzed using dielectric modeling techniques and coupled with the backscattering measurements (σ°). Observed backscatter values and ratios were found to be in agreement with literature data, with volumetric scattering as the dominant scattering mechanism.

Isleifson, D., B. Hwang, D. G. Barber, R. K. Scharien, and L. Shafai, 2010, C-Band Polarimetric Backscattering Signatures of Newly Formed Sea Ice During Fall Freeze-Up,

IEEE Trans Geosci Remote Sensing, **48**(8): 3256–3267, doi:10.1109/TGRS.2010.2043954

A study of the polarimetric backscattering response of newly formed sea ice types under a large assortment of surface coverage was conducted using a ship-based C-band polarimetric radar system. Polarimetric backscattering results and physical data for 40 stations during the fall freeze-up of 2003, 2006, and 2007 are presented. Analysis of the copolarized correlation coefficient showed its sensitivity to both sea ice thickness and surface coverage and resulted in a statistically significant separation of ice thickness into two regimes: ice less than 6 cm thick and ice greater than 8 cm thick. A case study quantified the backscatter of a layer of snow infiltrated frost flowers on new sea ice, showing that the presence of the old frost flowers can enhance the backscatter by more than 6 dB. Finally, a statistical analysis of a series of temporal-spatial measurements over a visually homogeneous frost-flower-covered ice floe identified temperature as a significant, but not exclusive, factor in the backscattering measurements.

Kaleschke, L., N. Maaß, C. Haas, S. Hendricks, G. Heygster, and R. T. Tonboe, 2010, A sea-ice thickness retrieval model for 1.4 GHz radiometry and application to airborne measurements over low salinity sea-ice, *The Cryosphere*, **4**: 583-592, doi:10.5194/tc-4-583-2010

In preparation for the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission, we investigated the potential of L-band (1.4 GHz) radiometry to measure sea-ice thickness.

Sea-ice brightness temperature was measured at 1.4 GHz and ice thickness was measured along nearly coincident flight tracks during the SMOS Sea-Ice campaign in the Bay of Bothnia in March 2007. A research aircraft was equipped with the L-band Radiometer EMIRAD and coordinated with helicopter based electromagnetic induction (EM) ice thickness measurements.

We developed a three layer (ocean-ice-atmosphere) dielectric slab model for the calculation of ice thickness from brightness temperature. The dielectric properties depend on the relative brine volume which is a function of the bulk ice salinity and temperature.

The model calculations suggest a thickness sensitivity of up to 1.5 m for low-salinity (multi-year or brackish) sea-ice. For Arctic first year ice the modelled thickness sensitivity is less than half a meter. It reduces to a few centimeters for temperatures approaching the melting point.

The campaign was conducted under unfavorable melting conditions and the spatial overlap between the L-band and EM-measurements was relatively small. Despite these disadvantageous conditions we demonstrate the possibility to measure the sea-ice thickness with the certain limitation up to 1.5 m.

The ice thickness derived from SMOS measurements would be complementary to

ESA's CryoSat-2 mission in terms of the error characteristics and the spatiotemporal coverage. The relative error for the SMOS ice thickness retrieval is expected to be not less than about 20%.

Krumpen, T., C. Haas, S. Hendricks, J. A. Holemann, D. Kalmbach, and R. Gerdes, HELIOS, a nadir-looking sea ice monitoring camera, *Cold Reg. Sci. Tech.*, **65**(3): 308-313, doi:10.1016/j.coldregions.2010.11.007

We present the prototype of a simplified photogrammetric system (HELicopter-borne Ice Observation System, HELIOS) and demonstrate how it can be used to document ground-based and airborne sea ice surveys. The aerial unit consists of a nadir-looking digital camera mounted on a gimbal, a GPS receiver and a computer. It is of low-cost and weight and is designed such that it withstands low temperatures, operates autonomously and fits to any standard helicopter skid. The accuracy of the georeferenced photographs is about ± 15 m for a flight height of 85 m, flight speed of 130 km/h and a GPS sampling rate of 4 Hz. Systematic errors arise from the GPS-based determination of the camera position, the pointing accuracy of the gimbal, and the camera alignment in flight direction. Because most sea ice mapping projects require lesser accuracies than conventional mapping standards (e.g. ≤ 0.5 m for a map scale of 1:600, ASPRS (1994)), HELIOS offers a broad range of applications. This includes the photogrammetric documentation of experimental sites as well as the verification of satellite-, and model-based estimates of sea ice and snow cover properties. Images taken simultaneously with other airborne observations provide a valuable tool to assess the accuracy of those measurements.

Langlois, A. and D. G. Barber, 2007, Passive Microwave Remote Sensing of Seasonal Snow Covered Sea Ice, *Prog. Phys. Geogr.*, **31**(6):539-573, doi:10.1177/0309133307087082

The Arctic is thought to be an area where we can expect to see the first and strongest signs of global-scale climate variability and change. We have already begun to see a reduction in: (1) the aerial extent of sea ice at about 3% per decade and (2) ice thickness at about 40%. At the current rate of reduction we can expect a seasonally ice-free Arctic by midway through this century given the current changes in thermodynamic processes controlling sea-ice freeze-up and decay. Many of the factors governing the thermodynamic processes of sea ice are strongly tied to the presence and geophysical state of snow on sea ice, yet snow on sea ice remains poorly studied. In this review, we provide a summary of the current state of knowledge pertaining to the geophysical, thermodynamic and dielectric properties of snow on sea ice. We first give a detailed description of snow thermophysical properties such as thermal conductivity, diffusivity and specific heat and how snow geophysical/electrical properties and the seasonal surface energy balance affect them. We also review the different microwave emission and scattering mechanisms associated with snow-covered first-year sea ice. Finally, we discuss the annual evolution of the Arctic system through snow thermodynamic (heat/mass transfer, metamorphism) and aeolian processes, with

linkages to microwave remote sensing that have yet to be defined from an annual perspective in the Arctic.

Langlois, A., T. Fisico, D. G. Barber, and T. N. Papakyriakou, 2008, Response of snow thermophysical processes to the passage of a polar low-pressure system and its impact on in situ passive microwave radiometry: A case study, *J. Geophys. Res.*, 113, C03S04, doi:10.1029/2007JC004197

Recent reductions in both the aerial extent and thickness of sea ice have focused attention on the effect climate change is having on the polar marine system. Concomitant with a reduction in sea ice has been an increased frequency of low-pressure depressions at high latitudes. Recent studies have shown that we can expect both increased in situ cyclogenesis and advection into the arctic region. Since theses cyclones are associated with warm air advection, increased wind speed, relative humidity, and cloud cover, their impact on snow surface energy balance may be significant. The thermophysical response of snow-covered first-year sea ice to a low-pressure disturbance is investigated along with its impact on surface-based radiometer brightness temperature measurements. The data were collected during the Canadian Arctic Shelf Exchange Study (CASES) between year days 33 and 34 of 2004. Snow grain size increased throughout the sampling period with growth rates of 1.28 and 2.3 mm ^{2} d^{-1} for thin and thick snow covers, respectively. This rate was much faster than expected on the basis of other similar experiments documented in the literature. Furthermore, brine volume migrated upward in both snowpacks owing to the action of wind pumping affecting the dielectric constant of the snow middle layers. This increase in permittivity caused a decrease in brightness temperatures at 85 GHz of approximately 5 K and 10 K in the vertical and horizontal polarizations, respectively. This signal is sufficiently large to impact interpretation of passive microwave signatures from space.

Mundy, C. J., J. K. Ehn, D. G. Barber, and C. Michel, 2007, Influence of snow cover and algae on the spectral dependence of transmitted irradiance through Arctic landfast first-year sea ice, *J. Geophys. Res.*, **112**, C03007, doi:10.1029/2006JC003683

Extensive spatial and temporal observations of sea ice algae remain limited due in part to current destructive and time intensive sampling techniques. In this paper we examine the influence of snow cover and ice algal biomass on the spectral dependence of photosynthetically available radiation transmitted through the snow-ice matrix using a data set collected in Resolute Passage, Canada, from 3 to 21 May 2003. The relationships between a normalized difference index (NDI) of transmitted irradiance with ice algal biomass and with snow cover provided a means to examine and compare observational and modeled data. In contrast to the dominant scattering properties of snow, absorption largely controls the spectral diffuse attenuation coefficient of algae. Our results show that snow has little effect on the distribution of transmitted spectral irradiance at wavelengths between 400 and 550 nm, whereas algae have a strong absorption peak near 440 nm that dominates changes in spectral transmission across this wavelength range. Up to 89% of the total variation in algae biomass was accounted for with a single NDI wavelength combination. Therefore the blue wavelength peak in algal

spectral absorption lends particularly well to the remote estimation of algae biomass using transmitted irradiance. Deviations between observed and modeled data highlight the need for improvements to model inputs and therefore more detailed observations of processes controlling snow, ice, and algae in situ optical properties.

Partington, K., J. D. Flach, D. Barber, D. Isleifson, P. Meadows, P., and P. Verlaan, 2010, Dual-Polarization C-Band Radar Observations of Sea Ice in the Amundsen Gulf, *IEEE Transactions on Geoscience and Remote Sensing*, **48**(6): 2685-2691, doi:10.1109/TGRS.2009.2039577

Polarimetric observations of sea ice from synthetic aperture radar can, in principle, assist in sea-ice classification and ice-water discrimination. In this paper, we use dual-polarization ground-based scatterometer observations of sea ice to assess the potential value of spaceborne dual-polarization observations of sea ice for operational ice analysis, focusing on C-band and, in particular, the contribution of the HV backscatter coefficient and HH/VV polarization ratios. Results show that signature variability resulting from frost flowers, ice deformation, and snow cover can overwhelm systematic differences between younger ice types, up to first-year thin. As a result of this and noise floor limitations of spaceborne sensors, the HV backscatter coefficient makes visual ice type and open water discrimination easier only below about 30?? incidence angle. The HH/VV ratio is less impacted by the noise floor of spaceborne sensors but retains similar ambiguities for sea-ice classification.

Peterson, I. K., S. J. Prinsenberg, and J. S. Holladay, 2008, Observations of sea ice thickness, surface roughness and ice motion in Amundsen Gulf, *J. Geophys. Res.*, **113**, C06016, doi:10.1029/2007JC004456

Ice thickness and surface roughness measurements of first-year (FY) sea ice were collected with a fix-mounted helicopter-borne electromagnetic (HEM)-laser system in Amundsen Gulf in April to May 2004. The modal ice thickness values are in good qualitative agreement with different ice types identified in synthetic aperture radar (SAR) imagery and shown on ice charts produced by the Canadian Ice Service. Modal ice thickness values which generally represent level ice thicknesses were about 2.0 m over landfast ice. A large range of modal ice thicknesses was observed in the mobile ice region, with values of about 0.2 m (young ice) in leads (where there was high radar backscatter), 0.6 m (thin FY ice) in the polynya (where there was medium to high backscatter), and about 1.1–1.9 m (thick FY ice) elsewhere. High surface roughnesses are strongly associated with high radar backscatter in SAR imagery, and are observed in areas of large shear. The ratio of the standard deviations of ice draft and averaged roughness in an area of landfast ice is in good agreement with the ratio of the standard deviations of ice draft and ice-equivalent roughness expected from isostasy, with constant level ice and snow thickness. However, the standard deviation of ice-equivalent roughness may be significantly underestimated, due to differences in snow thickness between level and deformed ice, and limitations of the laser

processing method. Modal ice (plus snow) thicknesses measured with the HEM system are within the range of historical values measured at Cape Parry.

Scharien, R. K., J. J Yackel, M. A. Granskog, and B. G. Else, 2007, Coincident high resolution optical - SAR image analysis for surface albedo estimation of first - year sea ice during summer melt, *Rem. Sens. Env.*, **111**(2-3): 160-171, doi:10.1016/j.rse.2006.10.025

The parameterization of sea ice albedo during summer, when fluctuations in the fractional coverage of melt ponds change on a variety of spatial and temporal scales, represents a significant challenge for both the modelling and remote sensing communities. Ubiquitous cloud cover in summer inhibits the use of optical sensors for providing large-scale estimates of sea ice surface albedo. C-band (5.3 GHz) Synthetic Aperture RADAR (SAR) data from ENVISAT-ASAR is compared to coincident surface climatological albedo (α) estimates derived from high-resolution Quickbird VIS-NIR imagery in order to demonstrate the utility of high-resolution, dual-polarized (VV, HH) SAR for detecting variations in α of melt pond covered landfast first-year sea ice (FYI) adjacent to Hudson Bay. Variations in ice α are detected from SAR imagery using the co-polarization ratio (γ), shown to be significantly correlated (− 0.81) with α when melt ponds are in liquid form. Results show the use of γ represents a substantial increase in correlation to α when compared to conventional like-polarized SAR backscattering coefficients. A regression model demonstrates that γ can be used as an estimator for landfast-FYI α to within ± 5.2% provided: (1) The SAR images at a shallow enough incidence angle to induce separation between like-polarized channels; and (2) the conditions of Bragg surface scattering, characteristic of relatively shallow FYI melt ponds, is met.

Scharien, R. K., T. Geldsetzer, D. G. Barber, J. J. Yackel, and A. Langlois, 2010, Physical, dielectric, and C band microwave scattering properties of first-year sea ice during advanced melt, *J. Geophys. Res.*, **115**, C12026, doi:10.1029/2010JC006257

This paper investigates the influence of solar heating and intermittent cloud cover on the physical and dielectric properties of naturally snow-free, warm (>−2°), first-year sea ice (FYI) in the southeastern margin of the Beaufort Sea during advanced melt. A simple three-layer physical model describing the surface is introduced and copolarized C band microwave signatures are simulated using a multilayer scattering model forced with four sets of measured surface parameters. Modeled backscatter signatures are compared to coincident surface-based C band scatterometer signatures in order to elucidate the signature controlling properties of the ice. Results show that 50 MHz impedance probe dielectric measurements of desalinated upper ice layers exhibit statistically significant diurnal variations due to the link between solar forcing and the availability of free water in brine-free upper ice layers. Enhanced downwelling longwave radiation to the surface from low-level stratus clouds is positively linearly associated (r = 0.709) with volumetric moisture m_v detected in upper ice layers. Model results show that desalinated upper ice layers contribute volume scattering from smooth, snow-free FYI under the observed surface m_v range. Sustained cloud-free periods result in

the formation of a 0.5–2.5 cm granular surface layer, composed of 5.2 mm ice grains, which enhances backscatter under relatively dry conditions. Sensitivity analyses show that layer thickness plays a significant role in scattering due to the increased number density of inclusions which act as discrete scatterers, and sufficient energy may penetrate to, and scatter from, the saline columnar ice layer under relatively dry conditions only ($m_v < 2\%$).

Tonboe, R.T., L. T. Pedersen, C. Haas, 2010, Simulation of the CryoSat-2 satellite radar altimeter sea ice thickness retrieval uncertainty, Can. J. Rem. Sens., **36**(1): 55-67

Although it is well known that radar waves penetrate into snow and sea ice, the exact mechanisms for radar altimeter scattering and its link to the depth of the effective scattering surface from sea ice are not well known. Previously proposed mechanisms linked the snow–ice interface, i.e., the dominating scattering horizon, directly with the depth of the effective scattering surface. However, simulations using a multilayer radar scattering model show that the effective scattering surface is affected by snow-cover and ice properties. With the coming CryoSat-2 (planned launch in 2010) satellite radar altimeter, it is proposed that sea ice thickness can be derived during winter by measuring its freeboard. In this study we evaluate the radar altimeter sea ice thickness retrieval uncertainty in terms of floe buoyancy, radar penetration, and ice type distribution using both a scattering model and Archimedes' principle. The effect of the snow cover on the floe buoyancy and radar penetration and on the ice cover spatial and temporal variability is assessed from field campaign measurements in the Arctic resulting in ice thickness uncertainties of about 0.3 m for the snow depth variability and 0.3 m for the snow density variability. In addition to these well-known uncertainties, we use high resolution RADARSAT synthetic aperture radar (SAR) data to simulate errors due to the variability of the effective scattering surface as a result of the subfootprint spatial backscatter and elevation distribution, sometimes called preferential sampling. In particular, in areas where ridges represent a significant part of the ice volume (e.g., the Lincoln Sea), the average simulated altimeter thickness estimate of 2.68 m is lower than the real average footprint thickness of 3.85 m, making preferential sampling the single most important error source. This means that the errors are large and yet manageable if the relevant quantities are known a priori. Radar altimeter ice thickness retrieval uncertainties are discussed.

Yackel, J. J., D. G. Barber, T. N. Papakyriakou, and C. Breneman, 2007, First-year sea ice spring melt transitions in the Canadian Arctic Archipelago from time series SAR data, 1992-2002, *Hydrological Processes*, **21**(2): 253-265, doi:10.1002/hyp.6240

This paper synthesizes 10-years' worth of interannual time-series space-borne ERS-1 and RADARSAT-1 synthetic aperture radar (SAR) data collected coincident with daily measurement of snow-covered, land-fast first-year sea ice (FYI) geophysical and surface radiation data collected from the Seasonal Sea Ice Monitoring and Modeling Site, Collaborative-Interdisciplinary Cryospheric Experiment and 1998 North Water Polynya study over the period 1992 to 2002. The objectives are to investigate the seasonal co-relationship of the SAR time-series dataset with selected surface mass (bulk snow thickness) and climate state

variables (surface temperature and albedo) measured *in situ* for the purpose of measuring the interannual variability of sea ice spring melt transitions and validating a time-series SAR methodology for sea ice surface mass and climate state parameter estimation. We begin with a review of the salient processes required for our interpretation of time-series microwave backscatter from land-fast FYI. Our results suggest that time-series SAR data can reliably measure the timing and duration of surface albedo transitions at daily to weekly time-scales and at a spatial scales that are on the order of hundreds of metres. Snow thickness on FYI immediately prior to melt onset explains a statistically significant portion of the variability in timing of SAR-detected melt onset to pond onset for SAR time-series that are made up of more than 25 images. Our results also show that the funicular regime of snowmelt, resolved in time-series SAR data at a temporal resolution of approximately 2·5 images per week, is not detectable for snow covers less than 25 cm in thickness.

Yu, P., S. E. L. Howell, and D. A. Clausi, 2009, <![CDATA[Fusing AMSR-E and QuikSCAT Imagery for Improved Sea Ice Recognition]]>, *IEEE Trans Geosci Remote Sensing*, **47**(7): 1980-1989, doi:10.1109/TGRS.2009.2013632

The benefits of augmenting Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) image data with Quick Scatterometer (QuikSCAT) image data for supervised sea ice classification in the Western Arctic region are investigated. Experiments compared the performance of a maximum likelihood classifier when used with the AMSR-E-only data set against using the combined data. The preferred number of bands to use for classification was examined, as well as whether principal component analysis (PCA) can be used to reduce the dimensionality of the data. The reliability of training data over time was also investigated. Adding QuikSCAT often improves classifier accuracy in a statistically significant manner and never decreases it significantly when a sufficient number of bands are used. Combining these data sets is beneficial for sea ice mapping. Using all available bands is recommended, data fusion with PCA does not offer any benefit for these data, and training data from a specific date remains reliable within 30 days.

2.11 Water Properties

Holland, D. M., R. H. Thomas, B. deYoung, B. Lyberth, and M. Ribergaard, 2008, Acceleration of Jakobshavn Isbrae triggered by warm subsurface Irminger waters, *Nature Geosciences* **1**: 659-664, doi:10.1038/ngeo316

Observations over the past decades show a rapid acceleration of several outlet glaciers in Greenland and Antarctica [1]. One of the largest changes is a sudden switch of Jakobshavn Isbræ, a large outlet glacier feeding a deep-ocean fjord on Greenland's west coast, from slow thickening to rapid thinning [2] in 1997, associated with a doubling in glacier velocity [3]. Suggested explanations for the speed-up of Jakobshavn Isbræ include increased lubrication of the ice–bedrock interface as more meltwater has drained to the glacier bed during recent warmer summers[4] and weakening and break-up of the floating ice tongue that buttressed the glacier[5]. Here we present hydrographic data that show a sudden increase in

subsurface ocean temperature in 1997 along the entire west coast of Greenland, suggesting that the changes in Jakobshavn Isbræ were instead triggered by the arrival of relatively warm water originating from the Irminger Sea near Iceland. We trace these oceanic changes back to changes in the atmospheric circulation in the North Atlantic region. We conclude that the prediction of future rapid dynamic responses of other outlet glaciers to climate change will require an improved understanding of the effect of changes in regional ocean and atmosphere circulation on the delivery of warm subsurface waters to the periphery of the ice sheets.

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram, 2010, Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, *J. Geophys. Res.*, **115**, C05021, doi:10.1029/2009JC005265

Sea ice in the Canada Basin of the Arctic Ocean has decreased significantly in recent years, and this will likely change the properties of the surface waters. A near-surface temperature maximum (NSTM) at typical depths of 25–35 m has been previously described; however, its formation mechanisms, seasonal evolution, and interannual variability have not been established. Based on summertime conductivity, temperature, and depth surveys and year-round Ice-Tethered Profiler data from 2005 to 2008, we found that the NSTM formsw hen sufficient solar radiation warms the upper ocean. A seasonal halocline forms in summer once enough sea ice melt has accumulated to separate the surface mixed layer from the NSTM. The NSTM becomes trapped below the summer halocline, thereby storing heat from solar radiation. This heat can be stored year-round in the Canada Basin if the halocline is strong enough to persist through winter. In addition, energy from storm-driven mixing can weaken the summer halocline and entrain the NSTM, thereby melting sea ice in winter. Throughout this cycle, Ekman pumping within the convergent Beaufort Gyre acts to deepen the NSTM. From 1993 through 2007, the NSTM warmed and expanded northward and both the NSTM and the summer halocline formed at successively shallower depths. North of 75°N, the temperature of the NSTM increased from 2004 to 2007 by 0.13°C/yr, and the NSTM and summer halocline shoaled by 2.1 m/yr and 1.7 m/yr, respectively, from 1997 to 2007. The formation and dynamics of the NSTM are manifestations of both the ice-albedo feedback effect and changes to the freshwater cycle in the Canada Basin.

Rabe, B, A. Münchow, H. Johnson, and H. Melling, 2010, Nares Strait hydrography and salinity from a three-year moored array, *J. Geophys. Res.*, **115**, C07010, doi:10.1029/2009JC005966

Nares Strait to the west of Greenland facilitates the exchange of heat and freshwater between the Arctic and Atlantic Oceans. This study focuses on salinity, temperature, and density measurements from Nares Strait from a mooring array deployed from 2003 to 2006. Innovative moorings requiring novel analysis methods measured seawater properties near 80.5°N, at spacing sufficient to resolve the internal Rossby deformation radius. The 3-year mean geostrophic

velocity has a surface-intensified southward flow of 0.20 m s^{-1} against the western side of the strait and a secondary core flowing southward at 0.14 m s^{-1} in the middle of the strait. Data show warm salty water on the Greenland side and cold fresher water on the Ellesmere Island side, especially in the top layers. There was a clear difference in hydrographic structure between times when sea ice was drifting and when it was land fast. Ice was drifting in late summer, fall, and early winter with a strong surface-intensified geostrophic flow in the middle of the strait. Ice was land fast in late winter, spring, and early summer, when there was a subsurface core of strong geostrophic flow adjacent to the western side of the strait. Salinity variations of about 2 psu in time and space reflect a variable freshwater outflow from the Arctic Ocean. One particularly strong pulse occurred at the end of July 2005. For several days, steeply sloping isohalines indicated strong geostrophic flow down the middle of the strait coinciding with an amplified ice export from the Arctic due to strong southward winds.

Vincent, R. F., R. F. Marsden, P. J. Minnett, K. A. M. Creber, and J. R. Buckley, 2008, Arctic waters and marginal ice zones: A composite Arctic sea surface temperature algorithm using satellite thermal data, *J. Geophys. Res.*, **113**, C04021, doi:10.1029/2007JC004353

The retrieval of Arctic sea surface temperatures (SSTs) using satellite radiometric imagery has not been well documented owing to the paucity of match-ups with in situ data. SST algorithms developed in temperate regions lead to positive biases in high latitudes due to an overestimation of atmospheric IR absorption. The composite arctic sea surface temperature algorithm (CASSTA) presented in this paper was developed from concurrent satellite and shipborne radiometric data collected in the North Water Polynya between April and July 1998. This algorithm considers three temperature regimes: seawater above freezing, the transition zones of water and ice, and primarily ice. These regimes, which are determined by advanced very high resolution radiometer (AVHRR) calibrated brightness temperatures, require different calculations for temperature estimates. For seawater above freezing, a specific Arctic SST algorithm was produced through a linear regression of AVHRR against in situ data. Areas consisting mainly of ice use an established ice surface temperature (IST) algorithm. The transition zone uses a combination of the Arctic SST and IST algorithms. CASSTA determines the Channel 4 brightness temperature for each pixel in a calibrated AVHRR image and then applies the appropriate algorithm to create a thermal image. The mean deviation of CASSTA compared to in situ data was 0.17 K with a standard deviation of 0.21 K. This represents a significant improvement over SST values using McClain coefficients for temperate waters, which overestimate the same data set by an average of 2.40 K. Application of CASSTA to the North Water imagery gives superior results compared to existing SST or IST algorithms.

Vincent, R. F., R. F. Marsden, P. J. Minnett, and J. R. Buckley, 2008, Arctic waters and marginal ice zones: 2. An investigation of arctic atmospheric infrared absorption for

advanced very high resolution radiometer sea surface temperature estimates, *J. Geophys. Res.*, **113**, C08044, doi:10.1029/2007JC004354

The derivation of sea surface temperatures (SST) from satellite radiometric data is well established in temperate latitudes. Water vapor is typically the greatest clear sky absorber of infrared (IR) energy between the emitting surface and spaceborne sensor, necessitating a corrective term for SST calculation. Algorithms developed for advanced very high resolution radiometers (AVHRR) use the difference in brightness temperatures between Channel 4 (10.3 to 11.3 μm) and Channel 5 (11.5 to 12.5 μm), or T45, to estimate the amount of IR absorption in the atmosphere. While relatively accurate in temperate latitudes, this approach is not applicable to Arctic waters, typically overestimating the SST by 2 to 3 K as a result of high T45 values that are not indicative of IR absorption by water vapor. The high T45 values in the Arctic may be attributable to atmospheric ice crystals. The attenuation of IR energy increases sharply across Channel 4 and 5 for ice crystals, the amount of which is a function of crystal size, shape and orientation. In the development of the Composite Arctic Sea Surface Temperature Algorithm in the North Water polynya (NOW), it was demonstrated that when T45 exceeded a threshold of 2 K the surface temperature could not be estimated owing to the presence of a clear sky absorptive feature. Observations from the NOW study led to the assessment that areas where T45 > 2K were covered by ice fog. This is a significant finding since these regions must be identified to achieve an accurate mapping of the surface temperature.

2.12 Mackenzie River and Delta

Carmack, E. C. and R. W. Macdonald, 2008, Water and ice related phenomena in the coastal region of the Beaufort Sea: some parallels between native experience and western science, *Arctic*, **61**(3): 265-280

Information gained through Native experience is combined here with scientific measurements to describe aspects of the wintertime oceanography of the Eskimo Lakes and Mackenzie River delta regions of the Canadian Beaufort Sea. The experiences of Jimmy Jacobson, a Tuktoyaktuk elder who lived in this region for over 70 years, were used as the basis for scientific planning and measurement. We focus on phenomena of special relevance to winter travel and fishing in four specific examples of Native insight guiding scientific inquiry. First, we examine local knowledge of ice characteristics and fish abundance in terms of tidal dispersion and its effect on mixing patterns during winter. Second, we relate the maintenance of a small ice-free area, used by caribou as a salt lick, to the vertical heat flux associated with flow through narrow channels. Third, we look at potentially dangerous episodes of overflooding of snow and ice in the nearshore zone in midwinter, caused by strong westerly winds, through the analysis of oxygen isotope distributions in ice cores. Fourth, we discuss the important influence of wind direction on ice conditions, lead formation, and brine production in semi-enclosed coastal bays. Finally, we note certain circulation features of ecological significance relevant to concerns about development and the transport of pollutants. We conclude that by not requiring agreement between

indigenous knowledge and Western science, or ranking one above the other, we can realize the values of each approach. Specifically, indigenous knowledge can provide direction to scientific inquiry, while Western science can be used to measure, model, and predict where development or change might have the most serious impact.

Prinsenberg, S. J., I. K. Peterson, and S. Holladay. 2008, Measuring Freshwater-layer Plume Depths and Ice Thicknesses of and Beneath the Land-fast Ice Region of the Mackenzie Delta with Helicopter-borne Sensors, *J. Mar. Systems* CASES Special Issue, 74, 783-793, doi:10.1016/j.jmarsys.2008.02.009

Helicopter-borne sensors have been used since the early 1990s to monitor ice properties in support of winter marine transportation along the east coast of Canada. The observations are used in ice chart production and to validate ice hazard identification algorithms using satellite advanced synthetic aperture radar (ASAR) imagery. In this study we evaluated the sensors' additional capability to monitor the freshwater plume characteristic beneath land-fast ice. During the Canadian Arctic Shelf Exchange Study (CASES) data were collected over the Mackenzie Delta in the southern Beaufort Sea where a buoyant river plume exists. Results showed that the electromagnetic–laser system could describe not only the ice properties but also the horizontal distribution of the freshwater plume depths that decreased in depth stepwise offshore as the flow of the buoyant plume was restricted by a series of ridge-rubble fields running parallel to the coast. Relative to the 2 m mean ice thickness, the plume layer depth varied from zero under mobile offshore pack ice to 3 m inshore of the third set of ridge-rubble fields.

Stevens, C. W., B. J. Moorman, S. M. Solomon, and C. H. Hugenholtz, 2009, Mapping subsurface conditions within the nearshore zone of an Arctic delta using ground penetrating radar, *Cold Regions Science and Technology*, **56**(1): 30-38, doi:10.1016/j.coldregions.2008.09.005

This paper demonstrates the capabilities of ground penetrating radar (GPR) to map and resolve shallow subsurface features in the near-shore zone: (i) ice conditions (floating or bottom fast); (ii) water bathymetry; (iii) sedimentary structures; and (iv) interfaces between frozen and unfrozen sediment. These features were resolved in the near-shore zone of the Mackenzie Delta, N.W.T., Canada, using multi-frequency (50, 100 and 250 MHz) GPR data collected in winter (2005 and 2006). The capability of GPR to resolve subsurface features in the near-shore zone was strongly controlled by bottom-fast and floating ice conditions. The latter were discriminated using a novel approach involving the energy return from the base of ice and the presence of ice-bottom multiples. Beneath zones of bottom-fast ice, sedimentary structures and interfaces between frozen and unfrozen sediment were discriminated by reflection geometry and amplitude. Beneath floating ice, water depths were measured to depths greater than 5 m using a multi-layer depth calculation. Overall, this research demonstrates that baseline information for geotechnical investigations and climate change research in Arctic coastal zones can be greatly enhanced with GPR data.

Walker, T. R., J. Grant, P. Cranford, D. G. Lintern, P. Hill, P. Jarvis, J. Barrell, and C. Nozais, 2008, Suspended sediment and erosion dynamics in Kugmallit Bay and Beaufort Sea during ice-free conditions, *J. Mar. Syst.*, **74**(3-4): 794-809, doi:10.1016/j.jmarsys.2008.01.006

The Mackenzie River is the largest river on the North American side of the Arctic and its huge freshwater and sediment load impacts the Canadian Beaufort Shelf. Huge quantities of sediment and associated organic carbon are transported in the Mackenzie plume into the interior of the Arctic Ocean mainly during the freshet (May to September). Changing climate scenarios portend increased coastal erosion and resuspension that lead to altered river-shelf-slope particle budgets. We measured sedimentation rates, suspended particulate matter (SPM), particle size and settling rates during ice-free conditions in Kugmallit Bay (3–5 m depth). Additionally, measurements of erosion rate, critical shear stress, particle size distribution and resuspension threshold of bottom sediments were examined at four regionally contrasting sites (33–523 m depth) on the Canadian Beaufort Shelf using a new method for assessing sediment erosion. Wind induced resuspension was evidenced by a strong relationship between SPM and wind speed in Kugmallit Bay. Deployment of sediment traps showed decreasing sedimentation rates at sites along an inshore–offshore transect ranging from 5400 to 3700 g m^{-2} day^{-1}. Particle settling rates and size distributions measured using a Perspex settling chamber showed strong relationships between equivalent spherical diameter (ESD) and particle settling rates ($r^2 = 0.91$). Mean settling rates were 0.72 cm s^{-1} with corresponding ESD values of 0.9 mm. Undisturbed sediment cores were exposed to shear stress in an attempt to compare differences in sediment stability across the shelf during September to October 2003. Shear was generated by vertically oscillating a perforated disc at controlled frequencies corresponding to calibrated shear velocity using a piston grid erosion device. Critical (Type I) erosion thresholds (u_*) varied between 1.1 and 1.3 cm s^{-1} with no obvious differences in location. Sediments at the deepest site Amundsen Gulf displayed the highest erosion rates (22–54 g m^{-2} min^{-1}) with resuspended particle sizes ranging from 100 to 930 μm for all sites. There was no indication of biotic influence on sediment stability, although our cores did not display a fluff layer of unconsolidated sediment. Concurrent studies in the delta and shelf region suggest the importance of a nepheloid layer which transports suspended particles to the slope. Continuous cycles of resuspension, deposition, and horizontal advection may intensify with reduction of sea ice in this region. Our measurements coupled with studies of circulation and cross-shelf exchange allow parameterization and modeling of particle dynamics and carbon fluxes under various climate change scenarios.

2.13 Hudson Bay

Else, B. G. T., J. J. Yackel, and T. N. Papakyriakou, 2008, Application of satellite remote sensing techniques for estimating air-sea CO_2 fluxes in Hudson Bay, Canada during the ice-free season, Remote Sensing of Environment, **112**(9): 3550-3562, doi:10.1016/j.rse.2008.04.013

The role of coastal seas as either a sink or a source of CO_2 is subject to a great deal of uncertainty. This uncertainty largely arises from a lack of observations in the coastal zones. Remote sensing offers an avenue for expanding these observations by allowing for the extrapolation of relatively limited data sets of dissolved CO_2 (pCO_{2sw}). In this paper, predictive algorithms for pCO_{2sw} that could be applied to remote sensing products were created from a field data set collected from September–October, 2005 in Hudson Bay, Canada. The field data showed that an effective pCO_{2sw} interpolation algorithm could be created using sea surface temperature (SST) as a predictor, and that a slight improvement of the algorithm could be achieved if measurements of absorption due to coloured dissolved organic material (a_{CDOM}) were included. Unfortunately, satellite retrievals of a_{CDOM} did not match well with in situ observations, and so only SST (obtained from the MODIS Aqua sensor) was used to create monthly maps of pCO_{2sw} for the period of August–October. To estimate fluxes of CO_2, constructed surfaces of pCO_{2sw} were combined with estimates of gas transfer velocity derived from QuikSCAT wind retrievals, and pCO_{2air} based on field observations. The results of these calculations revealed that Hudson Bay acts as a source of CO_2 during August and September, but reverts to a sink of CO_2 in October as the water temperature decreases. Overall, a positive flux of 1.60 TgC was estimated for the region during the ice-free season. This result is in contrast to most Arctic or sub-Arctic continental shelf seas, where usually strong absorptions of CO_2 are observed.

Granskog, M. A., R. W. Macdonald, C.-J. Mundy, and D. G. Barber, 2007, Distribution, characteristics and potential impacts of chromophoric dissolved organic matter (CDOM) in Hudson Strait and Hudson Bay, Canada, *Cont. Shelf Res.*, **27**(15): 2032-2050, doi:10.1016/j.csr.2007.05.001

The characteristics of chromophoric dissolved organic matter (CDOM) were studied in Hudson Bay and Hudson Strait in the Canadian Arctic. Hudson Bay receives a disproportionately large influx of river runoff. With high dissolved organic matter (DOM) concentrations in Arctic rivers the influence of CDOM on coastal and ocean systems can be significant, yet the distribution, characteristics and potential consequences of CDOM in these waters remain unknown. We collected 470 discrete water samples in offshore, coastal, estuarine and river waters in the region during September and October 2005. Mixing of CDOM appeared conservative with salinity, although regional differences exist due to variable DOM composition in the rivers discharging to the Bay and the presence of sea-ice melt, which has low CDOM concentrations and low salinity. There were higher concentrations of CDOM in Hudson Bay, especially in coastal waters with salinities <28, due to river runoff. Using CDOM composition of water masses as a tracer for the freshwater components revealed that river runoff is largely constrained to nearshore waters in Hudson Bay, while sea-ice melt is distributed more evenly in the Bay. Strong inshore–offshore gradients in the bio-optical properties of the surface waters in the Hudson Bay cause large variation in penetration of ultraviolet radiation and the photic depth within the bay, potentially controlling the vertical distribution of biomass and occurrence of deep chlorophyll

maxima which are prevalent only in the more transparent offshore waters of the bay. The CDOM distribution and associated photoprocesses may influence the thermodynamics and stratification of the coastal waters, through trapping of radiant heating within the top few meters of the water column. Photoproduction of biologically labile substrates from CDOM could potentially stimulate the growth of biomass in Hudson Bay coastal waters. Further studies are needed to investigate the importance of terrestrial DOM in the Hudson Bay region, and the impact of hydroelectric development and climate change on these processes.

Granskog, M. A., R. W. Macdonald, Z. Z. A. Kuzyk, S. Senneville, C.-J. Mundy, D. G. Barber, G. A. Stern, and F. Saucier, 2009, Coastal conduit in southwestern Hudson Bay (Canada) in summer: Rapid transit of freshwater and significant loss of colored dissolved organic matter, *J. Geophys. Res.*, **114**, C08012, doi:10.1029/2009JC005270

Distributions of freshwater (sea-ice melt and runoff) were investigated along inshore-offshore sections in southwestern Hudson Bay for fall conditions. Conductivity-temperature-density profiles and bottle samples collected for salinity, oxygen isotope ($\delta^{18}O$), and colored dissolved organic matter (CDOM) analyses were used to discriminate between contributions of river water (RW) and sea-ice melt (SIM). Stations had a fresh summer surface mixed layer 5–25 m thick overlying a cold subsurface layer indicative of the previous winter's polar mixed layer (PML). The fraction of RW decreased strongly with distance from shore, while the opposite was true for SIM. The majority of RW was constrained in a coastal domain within 100–150 km from shore, which, because of high alongshore velocities, accounts for the majority of freshwater and volume transports. On the basis of freshwater inventories and composition, brine and RW accumulate in the PML over winter because of ice formation and downward mixing. The summer surface circulation results in an annual net export of SIM from the region. Residence times for freshwater components in the southwestern sector of the bay, based on currents derived from a 3-D ocean model for Hudson Bay, are about 1–10 months, implying rapid transit of freshwater. Despite the short residence time for RW (1–3 months), CDOM is significantly photobleached and provides an unreliable tracer for RW. Photobleaching represents an important sink for dissolved organic carbon entering from rivers and could, in part, explain why Hudson Bay is only a minor sink for atmospheric CO_2 in the open water season.

Hochheim, K. P. and D. G. Barber, 2010, Atmospheric forcing of sea ice in Hudson Bay during the fall period, 1980–2005, *J. Geophys. Res.*, **115**, C05009, doi:10.1029/2009JC005334

The principal objective of this study is to describe the autumn sea ice regime of Hudson Bay in the context of atmospheric forcing from 1980 to 2005. Both gridded Canadian Ice Service (CIS) data and Passive Microwave (PMW) data are used to examine the freezeup period for weeks of year (WOY) 43–52. Sea ice concentration (SIC) anomalies reveal statistically significant trends, ranging from −23.3% to −26.9% per decade, during WOY 43–48 using the CIS data and trends ranging from −12.7% to −16.8% per decade during WOY 45–50 using the PMW

data. Surface air temperature (SAT) anomalies are highly correlated with SIC anomalies (r^2 = 0.52–0.72) and with sea ice extents (r^2 = 0.53–0.72). CIS data show that mean sea ice extents based on SICs ≥80% (consolidated ice) have decreased by 1.05×10^5 to 1.17×10^5 km^2 for every 1°C increase in temperature in late November; PMW data show similar results. Regression analysis between SAT and standardized climate indices over the 1951–2005 period show that the East Pacific/North Pacific index is highly predictive of interannual SATs followed by the North Atlantic Oscillation and Arctic Oscillation indices. The data show that the Hudson Bay area has recently undergone a climate regime shift, in the mid 1990s, which has resulted in a significant reduction in sea ice during the freezeup period and that these changes appear to be related to atmospheric indices.

Kuzyk, Z. A., M. A. Goni, G. A. Stern and R. W. Macdonald, 2008, Sources, pathways and sinks of particulate organic matter in Hudson Bay: evidence from lignin distributions, *Marine Chemistry*, **112**(3-4): 215-229, doi:10.1016/j.marchem.2008.08.001

Hudson Bay is a large, estuarine, shelf-like sea at the southern margin of the Arctic, where changes in seasonal ice cover and river discharge appear already to be underway. Here we present lignin data for dated sediments from eleven box cores and evaluate sources of terrigenous carbon, transport pathways, and whether terrigenous organic matter has been influenced by recent environmental change. Lignin yields (0.04 to 1.46 mg/100 mg organic carbon) decreased from the margin to the interior and from south to north, broadly reflecting the distribution of river inputs. Lignin compositional patterns indicated distinct regional sources with boreal forest (woody gymnosperm) vegetation an important source in the south, vs. tundra (non-woody angiosperm) in the north. Lignin patterns suggest redistribution of a fine-grained, mineral-associated fraction of the southern-derived terrigenous carbon to the northeast part of the Bay and ultimately into west Hudson Strait with the Bay's cyclonic coastal circulation. A small component of the carbon makes it to the central basins of Hudson Bay but most of the terrigenous organic material in that area appears to derive from resuspension of older, isostatically-rebounding coastal and inner shelf deposits. Most modern plant debris appears to be retained near river mouths due to hydrodynamic sorting, with the exception of the southwest inner shelf, where these materials extend > 30 km from shore. Temporal changes in the composition of terrigenous organic carbon recorded in most of the southern Hudson Bay cores perhaps reflect increases in erosion and cross-shelf transport from coastal deposits, possibly mediated by change in ice climate. In contrast, temporal changes in the northwest may relate to changes in the supply of modern plant debris under recent warmer conditions. On the western shelf, changes may relate to ice climate and the distribution of northern coastal water and/or changes in the delivery of materials by the Churchill River due to water diversion. Although the cores show evidence of change related to the ice climate, there is little evidence that ice itself transports terrigenous organic carbon within the system.

Kuzyk, Z. A., R. W. Macdonald, M. A. Granskog, R. K. Scharien, R. J. Galley, C. Michel, D. G. Barber and G. A. Stern, 2008, Sea ice, hydrological, and biological processes in the Churchill River estuary region, Hudson Bay, *Est., Coastal Shelf Sci.*, **77**(3): 369-384, doi:10.1016/j.ecss.2007.09.030

A conceptual scheme for the transition from winter to spring is developed for a small Arctic estuary (Churchill River, Hudson Bay) using hydrological, meteorological and oceanographic data together with models of the landfast ice. Observations within the Churchill River estuary and away from the direct influence of the river plume (Button Bay), between March and May 2005, show that both sea ice (production and melt) and river water influence the region's freshwater budget. In Button Bay, ice production in the flaw lead or polynya of NW Hudson Bay result in salinization through winter until the end of March, followed by a gradual freshening of the water column through April–May. In the Churchill Estuary, conditions varied abruptly throughout winter–spring depending on the physical interaction among river discharge, the seasonal landfast ice, and the rubble zone along the seaward margin of the landfast ice. Until late May, the rubble zone partially impounded river discharge, influencing the surface salinity, stratification, flushing time, and distribution and abundance of nutrients in the estuary. The river discharge, in turn, advanced and enhanced sea ice ablation in the estuary by delivering sensible heat. Weak stratification, the supply of riverine nitrogen and silicate, and a relatively long flushing time (~ 6 days) in the period preceding melt may have briefly favoured phytoplankton production in the estuary when conditions were still poor in the surrounding coastal environment. However, in late May, the peak flow and breakdown of the ice-rubble zone around the estuary brought abrupt changes, including increased stratification and turbidity, reduced marine and freshwater nutrient supply, a shorter flushing time, and the release of the freshwater pool into the interior ocean. These conditions suppressed phytoplankton productivity while enhancing the inventory of particulate organic matter delivered by the river. The physical and biological changes observed in this study highlight the variability and instability of small frozen estuaries during winter–spring transition, which implies sensitivity to climate change.

Kuzyk, Z. A., R. W. Macdonald, S. C. Johannessen, G. A. Stern, 2010, Biogeochemical Controls on PCB Deposition in Hudson Bay, *Env. Sci. Tech.*, **44**(9): 3280-3285, doi:10.1021/es903832t

PCB concentrations, congener patterns, and fluxes were examined in 13 dated and organically characterized (C, N, $\delta^{13}C$, $\delta^{15}N$) marine sediment cores from Hudson Bay, Canada, to investigate the importance of organic matter (OM) supply and transport to PCB sequestration. Drawdown of PCBs, supported by marine primary production, is reflected in elevated ∑PCB concentrations and more highly chlorinated PCB signatures in surface sediments underlying eutrophic regions. Sediments in oligotrophic regions, which are dominated by "old" marine OM, have lower PCB concentrations and weathered signatures. For the surface of Hudson Bay, average atmospheric deposition appears to be very low (ca. 1.4 pg ∑PCBs cm^{-2} a^{-1}) compared to fluxes reported for nearby lakes (ca. 44 pg ∑PCBs

cm^{-2} a^{-1}). ^{210}Pb fails to provide a means to normalize the fluxes, highlighting important differences in the biocycling of ^{210}Pb and PCBs. Unlike ^{210}Pb, atmospheric PCB exchange with the water's surface is partially forced by the aquatic organic carbon cycle. The extremely low atmospheric deposition of PCBs to the surface of Hudson Bay is likely a reflection of the Bay's exceptionally low productivity and vertical carbon fluxes. If future marine production and vertical flux of carbon increase due to loss of ice cover or change in river input as consequences of global warming, PCB deposition would also increase.

Kuzyk, Z. A., R. W. Macdonald, J.-E. Tremblay, and G. A. Stern, 2010, Elemental and stable isotopic constraints on river influence and patterns of nitrogen cycling and biological productivity in Hudson Bay, *Cont. Shelf Res.*, **30**(2): 163-176, doi:10.1016/j.csr.2009.10.014

Elemental (carbon and nitrogen) ratios and stable carbon and nitrogen isotope ratios ($\delta^{13}C$ and $\delta^{15}N$) are examined in sediments and suspended particulate matter from Hudson Bay to study the influence of river inputs and autochthonous production on organic matter distribution. River-derived particulate organic matter (POM) is heterogeneous, nitrogen-poor and isotopically depleted, consistent with expectations for OM derived from terrestrial C3 vascular plant sources, and distinct from marine OM sources. Both $\delta^{13}C$ and C/N source signatures seem to be transmitted to sediments with little or no modification, therefore making good tracers for terrigenous OM in Hudson Bay. They suggest progressively larger contributions from marine sources with distance from shore and secondarily from south to north, which broadly corresponds to the distribution of river inputs to Hudson Bay. Processes other than mixing of marine and terrigenous OM influence sedimentary $\delta^{15}N$ values, including variability in the $\delta^{15}N$ of phytoplankton in the Bay's surface waters due to differences in relative nitrate utilization, and post-production processes, which bring about an apparently constant ^{15}N-enrichment between surface waters and underlying sediments. Variability in the $\delta^{15}N$ of phytoplankton in the Bay's surface waters, in contrast, seems to be organized spatially with a pattern that suggests an inshore–offshore difference in surface water nitrogen conditions (open- vs. closed-system) and hence the $\delta^{15}N$ value of phytoplankton. The $\delta^{15}N$ patterns, supported by a simple nitrate box-model budget, suggest that in inshore regions of Hudson Bay, upwelling of deep, nutrient-rich waters replenishes surface nitrate, resulting in 'open system' conditions which tend to maintain nitrate $\delta^{15}N$ at low and constant values, and these values are reflected in the sinking detritus. River inflow, which is constrained to inshore regions of Hudson Bay, appears to be a relatively minor source of nitrate compared to upwelling of deep waters. However, river inflow may contribute indirectly to enhanced inshore nutrient supply by supporting large-scale estuarine circulation and consequently entrainment and upwelling of deep water in this area. In contrast to previous proposals that Hudson Bay is oligotrophic because it receives too much fresh water (Dunbar, 1993), our results support most of the primary production being organized around the margin of the Bay, where river flow is constrained.

Lapoussiere, A., C. Michel, M. Gosselin, and M. Poulin, 2009, Spatial variability in organic material sinking export in the Hudson Bay system, Canada, during fall, *Cont. Shelf Res.*, **29**(9): 1276-1288, doi:10.1016/j.csr.2009.02.004

Spatial variations in the sinking export of organic material were assessed within the Hudson Bay system (i.e., Hudson Bay, Hudson Strait and Foxe Basin) during the second oceanographic expedition of ArcticNet, on board the CCGS *Amundsen* in early fall 2005. Sinking fluxes of particulate organic material were measured using short-term free-drifting particle interceptor traps deployed at 50, 100 and 150 m for 8–20 h at eight stations. Measurements of chlorophyll *a* (chl *a*), pheopigments (pheo), particulate organic carbon (POC), biogenic silica (BioSi), protists, fecal pellets and bacteria were performed on the collected material. In parallel, sea surface salinity and temperature were determined at 121 stations in the Hudson Bay system. Three hydrographic regions presenting different sedimentation patterns were identified based on average surface salinity and temperature. Hudson Strait was characterized by a marine signature, with high salinity (average=32.3) and low temperature (average=2.1 °C). Eastern Hudson Bay was strongly influenced by river runoff and showed the lowest average salinity (26.6) and highest average temperature (7.6 °C) of the three regions. Western Hudson Bay showed intermediate salinity (average=29.4) and temperature (average=4.4 °C). Sinking fluxes of total pigments (chl *a*+pheo: 3.37 mg m^{-2} d^{-1}), diatom-associated carbon (19.8 mg m^{-2} d^{-1}) and BioSi (50.2 mg m^{-2} d^{-1}) at 50 m were highest in Hudson Strait. Eastern Hudson Bay showed higher sinking fluxes of total pigments (0.52 mg m^{-2} d^{-1}), diatom-associated carbon (3.29 mg m^{-2} d^{-1}) and BioSi (36.6 mg m^{-2} d^{-1}) compared to western Hudson Bay (0.19, 0.05 and 7.76 mg m^{-2} d^{-1}, respectively). POC sinking fluxes at 50 m were low and relatively uniform throughout the Hudson Bay system (50.0–76.8 mg C m^{-2} d^{-1}), but spatial variations in the composition of the sinking organic material were observed. A large part (37–78%) of the total sinking POC was unidentifiable by microscopic observation and was qualified as amorphous detritus. Considering only the identifiable material, the major contributors to the POC sinking flux were intact protist cells in Hudson Strait (28%), fecal pellets in eastern Hudson Bay (52%) and bacteria in western Hudson Bay (17%). A significant depth-related attenuation of the POC sinking fluxes (average loss between 50 and 150 m=32%) and a significant increase in the BioSi:POC ratio (average increase between 50 and 150 m=76%) were observed in Hudson Strait and eastern Hudson Bay. For all other sinking fluxes and composition ratios, we found no statistically significant difference with depth. These results show that during fall, the sinking export of total POC from the euphotic zone remained fairly constant throughout the Hudson Bay system, whereas other components of the organic sinking material (e.g., chl *a*, BioSi, fecal pellets, protist cells) showed strong spatial variations.

Li, S. S. and R. G. Ingram, 2007, Isopycnal deepening of an under-ice river plume in coastal waters: Field observations and modeling, *J. Geophys. Res.*, **112**, C07010, doi:10.1029/2006JC003883

The Great Whale River, located on the southeast coast of Hudson Bay in Canada, forms a large river plume under complete landfast ice during early spring. Short-term fluctuations of plume depth have motivated the present numerical study of an under-ice river plume subject to tidal motion and friction. We introduce a simple two-layer model for predicting the vertical penetration of the under-ice river plume as it propagates over a deepening topography. The topography is idealized but representative. Friction on the bottom surface of the ice cover, on the seabed, and at the plume interface is parameterized using the quadratic friction law. The extent of the vertical penetration is controlled by dimensionless parameters related to tidal motion and river outflow. Model predictions are shown to compare favorably with under-ice plume measurements from the river mouth. This study illustrates that isopycnal deepening occurs when the ice-cover vertical motion creates a reduced flow cross-section during the ebbing tide. This results in supercritical flow and triggers the downward plume penetration in the offshore. For a given river discharge, the freshwater source over a tidal cycle is unsteady in terms of discharge velocity because of the variation in the effective cross-sectional area at the river mouth, through which freshwater flows.

Mundy, C. J., M. Gosselin, M. Starr, and C. Michel, 2010, Riverine export and the effects of circulation on dissolved organic carbon in the Hudson Bay system, Canada, *Limnol. Oceanogr.*, 55(1): 315-323, doi:10.4319/lo.2010.55.1.0315

The distribution of dissolved organic carbon (DOC) in Hudson Bay (HB), Foxe Basin (FB), and Hudson Strait (HS) was examined during 01–14 August 2003. The HB system displayed relatively high DOC concentrations with medians of 109, 90, and 100 mmol L^{-1} for measurements made in HB, FB, and HS, respectively. Waters were significantly modified as they circulated through the HB system. An influence of marine-derived DOC was inferred for waters entering the system from northern HS and FB. The presence of a cold-water layer and elevated DOC concentrations observed in HB along the western coast and at depth was explained through either brine rejection and export of surface DOC to depth during sea ice formation or the decomposition of a settling algal bloom. As waters circulated in HB, an input of terrigenous DOC was the dominant modifying factor. In particular, DOC-laden rivers in southern HB increased the DOC concentration and then displayed a conservative behavior as water exited the bay along the southern coast of HS. Additionally, the late stages of ice melt observed during this study showed a significant dilution effect on surface DOC concentrations within eastern HB. Input and export of riverine DOC in the HB system was estimated at ~5.5 Tg C yr^{-1}, which is approximately 23% of the annual DOC input from rivers draining directly into the central Arctic Ocean and therefore represents an important contribution of terrigenous carbon to northern seas.

2.14 Tidal Processes and Studies

Arbic, B.K., P. St-Laurent, G. Sutherland, and C. Garrett, 2007, On the resonance and influence of the tides in Ungava Bay and Hudson Strait, *Geophys. Res. Lett.*, **34**, L17606, doi:10.1029/2007GL030845.2007

The tides of Leaf Basin in Ungava Bay may be the world's highest. An analysis of the frequency dependence of the response to outside forcing, a normal mode analysis, and a study of the damped oscillation of an initial disturbance, suggest that the Ungava Bay/Hudson Strait region has a natural period of about 12.7 hours and so is close to resonance with the tidal forcing. The implications for regional and global tides in the present, past, and future are explored.

Cummins, P. F., R. H. Karsten, and B. K. Arbic, 2010, The Semi-Diurnal Tide in Hudson Strait as a Resonant Channel Oscillation, *Atmos-Ocean.*, **48**(3): 163–176 doi:10.3137/OC307.2010

Tidal studies have shown that there exists a resonance of the semi-diurnal tide in the Hudson Bay- Hudson Strait system. The resonant response is particularly strong within Hudson Strait and Ungava Bay. It is shown here that the semi-diurnal tide in Hudson Strait has characteristics that are similar to those of a half-wavelength open channel resonance. A simple analytical model is developed to account for the salient aspects of the semi-diurnal response in the strait. Non-dimensional parameters that govern the response are identified and evaluated based on the physical dimensions of the region and results from a numerical tidal model. Taking account of the mechanical impedance presented to the channel by Hudson Bay, the results suggest that a channel mode is resonant near semi-diurnal periodicities, in general agreement with observations and more complex tidal models of the region. The possibility that Ungava Bay may have a separate quarter-wavelength resonance driven at the entrance to the continental shelf is also briefly explored.

Griffiths, S. D. and W. R. Peltier, 2008, Megatides in the Arctic Ocean under glacial conditions, *Geophys. Res. Lett.*, **35**, L08605, doi:10.1029/2008GL033263

Over the history of the Earth, changes in ocean depth and coastal configuration have led to considerable variations in the pattern and amplitude of ocean tides. Here we perform global simulations of ocean tides for the Last Glacial Maximum, using new data sets for both ocean depth and density stratification. We show how the configuration of the Arctic Ocean, which was almost entirely enclosed by continents at that time, leads to the near-resonant excitation of large semi-diurnal tides. Under certain conditions, this previously unidentified Arctic tide is massively amplified in the Canadian Archipelago. Such tides may have played a role in destabilizing the coastal margins of North American ice sheets, with implications for rapid changes in the Earth's climate and ocean circulation.

Hannah, C. G., F. Dupont, and M. Dunphy, 2009, Polynyas and Tidal Currents in the Canadian Arctic Archipelago, *Arctic*, 62: 83-95

A tidal model of the Canadian Arctic Archipelago was used to map the strength of the tidal currents, tidal mixing (h/U^3), and the vertical excursion associated with the tidal currents that drive water upslope and downslope. The hot spots in these quantities correspond to the location of many of the small polynyas in the archipelago, supporting the idea that the tidal currents make an important contribution to the dynamics of many of these recurring polynyas. The potential

link with tidal mixing means that these locations may have enhanced plankton production in the summer.

St-Laurent, P., F. J. Saucier, and J.-F. Dumais, 2008, On the modification of tides in a seasonally ice-covered sea, *J. Geophys. Res.*, **113**, C11014, doi:10.1029/2007JC004614

New observations from eight moorings located in Foxe Basin, Hudson Strait, and Hudson Bay are used to study the seasonal variability of the M_2 tide. Significant seasonal variations of the M_2 surface elevation are found in all these regions and at all seasons. The largest variations occur during winter while both elevation increase (Hudson Strait) and decrease (Hudson Bay, Foxe Basin) are observed. These variations are found recurrent at the stations where multiyear observations are available. Observations from a velocity profiler are consistent with a seasonal damping of the tides because of friction under ice. Numerical simulations with a sea ice-ocean coupled model and realistic forcing qualitatively reproduce most of the features of the observed variability. The simulations show that the winter M_2 variations are essentially caused by the under-ice friction, albeit with strong regional differences. Under-ice friction mostly occurs in a limited region (Foxe Basin) and can account for both increased and decreased M_2 elevations during winter.

2.15 Contaminants Transport

Bidleman, T. F., H. Kylin, L. M. Jantunen, P. A. Helm, and R. W. Macdonald, 2007, Hexachlorocycloheexanes in the Canadian Archipelago. 1. Spatial Distribution and Pathways of HCHs in Surface Water, *Env. Sci. & Tech.,* **41**(8): 2688-2695, doi:10.1021/es062375b

Hexachlorocyclohexanes (HCHs) in the surface water of the Canadian Archipelago and south Beaufort Sea were measured in summer, 1999. Overall concentrations of HCH isomers were in order of abundance: α-HCH (3.5 ± 1.2 ng L^{-1}) > γ-HCH (0.31 ± 0.07 ng L^{-1}) > β-HCH (0.10 ± 0.03 ng L^{-1}). Concentrations and ratios of α-HCH/γ-HCH decreased significantly ($p < 0.001$ to 0.003) from west to east, but there was no significant variation in α-HCH/ β-HCH. The (+) enantiomer of α-HCH was preferentially degraded, with enantiomer fractions (EFs) ranging from 0.432−0.463 and increasing significantly ($p < 0.001$) from west to east. Concentrations also varied latitudinally for α-HCH and γ-HCH ($p < 0.002$) but not for β-HCH. Principal component analysis with variables α-HCH and γ-HCH concentrations, EF, latitude, and longitude accounted for 71% (PC 1) and 16% (PC 2) of the variance. Mixing in the eastern Archipelago was modeled by assuming three end members with characteristic concentrations of α-HCH and γ-HCH. The model accounted for the observed concentrations and higher EFs of α-HCH at the eastern stations.

2.16 Biophysical Processes

Azetsu-Scott, K., A. Clarke, K. Falkner, J. Hamilton, E. P. Jones, C. Lee, B. Petrie, S. Prinsenberg, M. Starr, and P. Yeats, 2010, Calcium carbonate saturation states in the

waters of the Canadian Arctic Archipelago and the Labrador Sea, *J. Geophys. Res.*, **115**, C11021, doi:10.1029/2009JC005917

Ocean acidification is predicted to occur first in polar oceans. We investigated the saturation state of waters with respect to calcite (Ω_{cal}) and aragonite (Ω_{arg}) in six sections along an Arctic outflow pathway through the Canadian Arctic Archipelago (CAA) and into the northwestern Atlantic using dissolved inorganic carbon and total alkalinity measurements from 2003 to 2005. The study area, a key region connecting the Arctic and the North Atlantic, includes Smith Sound, Barrow Strait, Baffin Bay, Davis Strait, Hudson Strait, and the Labrador Sea. The average Ω_{arg} in the Arctic outflow was 1.18 ± 0.17 in Barrow Strait and 1.31 ± 0.14 in Smith Sound, with areas where $\Omega_{arg} < 1$. The Arctic outflow through the CAA has a high content of Pacific waters, which have a low saturation state. These waters can be traced along the western Baffin Bay to Davis Strait. South of Davis Strait, this outflow is modified by mixing with slope and offshore waters of Atlantic origin and with the outflow from Hudson Strait. Despite the mixing, low saturation state water can still be identified on the southern Labrador Shelf. The aragonite saturation horizon is found at ~150 m in Barrow Strait; at 200 m in Baffin Bay, Davis Strait, and Hudson Strait; and at 2300 m in the Labrador Sea. This study provides baseline data of the saturation states for the waters of the CAA and the northwest Atlantic. It also illustrates the downstream evolution of low saturation state Arctic outflow in the northwest Atlantic.

Benoit, D., Y. Simard, and L. Fortier, 2008, Hydroacoustic detection of large winter aggregations of Arctic cod (*Boreogadus saida*) at depth in ice-covered Franklin Bay (Beaufort Sea), *J. Geophys. Res.*, **113**, C06S90, doi:10.1029/2007JC004276

In the Canadian Arctic, the large biomass of Arctic cod that must exist to explain consumption by predators has eluded detection. From December 2003 to May 2004, acoustic estimates of Arctic cod biomass at a 225-m-deep station in central Franklin Bay (southeastern Beaufort Sea) increased progressively by 2 orders of magnitude, reaching maximum values of 2.7 and 55 kg m^{-2} in April. During accumulation in Franklin Bay, the fish occupied the lower part of the Pacific halocline (140 m to bottom), where the temperature-salinity signature (−1.4 to 0.3°C; 33 to 34.8 practical salinity units) corresponded to slope waters. Currents at 200 m along the western slope of Amundsen Gulf headed SSE in early winter, suggesting the passive advection of Arctic cod from Amundsen Gulf into Franklin Bay. Retention in Franklin Bay against the general circulation resulted from the fish keeping at depth to reduce predation by diving seals and/or to benefit from relatively warm temperatures in the lower halocline. Extrapolating a standing biomass of 11.23 kg m^{-2} at the station in April to the whole of Franklin Bay, the availability of polar cod would amply satisfy the requirements of predators. Dense accumulations of Arctic cod in embayments in winter likely play an important role in structuring the ecosystem of the Beaufort Sea. Understanding how climate change and the reduction of the sea ice cover will affect the stability of the oceanographic/behavioral accumulation process requires further research and modeling.

Forest, A., M. Sampei, R. Makabe, H. Sasaki, D. G. Barber, Y. Gratton, P. Wassmann, and L. Fortier, 2008, The annual cycle of particulate organic carbon export in Franklin Bay (Canadian Arctic): Environmental control and food web implications, *J. Geophys. Res.*, **113**, C03S05, doi:10.1029/2007JC004262

As part of the Canadian Arctic Shelf Exchange Study (CASES), we assessed the importance of new production and resuspension in determining the nature and magnitude of the deep (210 m) particulate organic carbon (POC) flux from October 2003 to September 2004 in central Franklin Bay. In spring and summer, phytoplankton production was nutrient-limited in the stratified surface layer and the initial spring bloom evolved into a subsurface chlorophyll maximum (SCM) at the nutricline. Large herbivorous calanoid copepods intercepted little of the initial bloom but grazed intensely on the SCM. The phytoplankton and fecal pellet fluxes culminated simultaneously in July–August (24 and 23 mg C m^{-2} d^{-1}, respectively). The detrital POC flux peaked in September (52 mg C m^{-2} d^{-1}), coincident with wind-induced resuspension of recently settled POC. In the fall, detrital POC fluxes increased again to 22 mg C m^{-2} d^{-1}, following the off-shelf transport of terrigenous POC carried by the Mackenzie River plume and POC resuspended by wind on the shelf. In winter, the relatively weak POC fluxes (2–7 mg C m^{-2} d^{-1}, detrital at 90%) resulted from the settling down of resuspended sediments. We propose a conceptual model in which the ecosystem of Franklin Bay shifts from an algal to a detrital mode according to seasonal changes in the relative importance of fresh and old POC supplies. On the basis of this model, the ecosystem of southeastern Beaufort Sea could evolve toward a less productive equilibrium dominated by sediment resuspension in response to the ongoing reduction of the ice cover.

Garneau, M.-È., S. Roy, C. Lovejoy, Y. Gratton, and W. F. Vincent, 2008, Seasonal dynamics of bacterial biomass and production in a coastal arctic ecosystem: Franklin Bay, western Canadian Arctic, *J. Geophys. Res.*, **113**, C07S91, doi:10.1029/2007JC004281

The Canadian Arctic Shelf Exchange Study (CASES) included the overwintering deployment of a research platform in Franklin Bay (70°N, 126°W) and provided a unique seasonal record of bacterial dynamics in a coastal region of the Arctic Ocean. Our objectives were (1) to relate seasonal bacterial abundance (BA) and production (BP) to physico-chemical characteristics and (2) to quantify the annual bacterial carbon flux. BA was estimated by epifluorescence microscopy and BP was estimated from ^{3}H-leucine and ^{3}H-thymidine assays. Mean BA values for the water column ranged from 1.0 (December) to 6.8×10^5 cells mL^{-1} (July). Integral BP varied from 1 (February) to 80 mg C m^{-2} d^{-1} (July). During winter-spring, BP was uncorrelated with chlorophyll *a* (Chl *a*), but these variables were significantly correlated during summer-autumn ($r_s = 0.68$, $p < 0.001$, $N = 38$), suggesting that BP was subject to bottom-up control by carbon supply. Integrated BP data showed three distinct periods: fall-winter, late winter–late spring, and summer. A baseline level of BB and BP was maintained throughout late winter–late spring despite the persistent cold and darkness, with irregular fluctuations that may be related to hydrodynamic events. During this period, BP rates were correlated with

colored dissolved organic matter (CDOM) but not Chl *a* ($r_{s\,BP.CDOM|Chl\,a} = 0.20$, $p < 0.05$, $N = 176$). Annual BP was estimated as 6 g C m^{-2} a^{-1}, implying a total BP of 4.8×10^{10} g C a^{-1} for the Franklin Bay region. These results show that bacterial processes continue throughout all seasons and make a large contribution to the total biological carbon flux in this coastal arctic ecosystem.

Lalande, C., A. Forest, D. G. Barber, Y. Gratton, and L. Fortier, 2009, Variability in the annual cycle of vertical particulate organic carbon export on Arctic shelves: Contrasting the Laptev Sea, Northern Baffin Bay and the Beaufort Sea, *Cont. Shelf Res.*, **29**(17): 2157-2165, doi:10.1016/j.csr.2009.08.009

The ongoing regression of sea ice cover is expected to significantly affect the fate of organic carbon over the Arctic continental shelves. Long-term moored sediment traps were deployed in 2005–2006 in the Beaufort Sea, Northern Baffin Bay and the Laptev Sea to compare the annual variability of POC fluxes and to evaluate the factors regulating the annual cycle of carbon export over these continental shelves. Annual POC fluxes at 200 m ranged from 1.6 to 5.9 g C m^{-2} yr^{-1} with the highest export in Northern Baffin Bay and the lowest export over the Mackenzie Shelf in the Beaufort Sea. Each annual cycle exhibited an increase in POC export a few weeks before, during, or immediately following sea ice melt, but showed different patterns over the remainder of the cycle. Enhanced primary production, discharge of the Lena River, and resuspension events contributed to periods of elevated POC export over the Laptev Sea slope. High POC fluxes in Northern Baffin Bay reflected periods of elevated primary production in the North Water polynya. In the Beaufort Sea sediment resuspension contributed to most of the large export events. Our results suggest that the outer shelf of the Laptev Sea will likely sustain the largest increase in POC export in the next few years due to the large reduction in ice cover and the possible increase in the Lena River discharge. The large differences in forcing among the regions investigated reinforce the importance of monitoring POC fluxes in the different oceanographic regimes that characterize the Arctic shelves to assess the response of the Arctic Ocean carbon cycle to interannual variability and climate change.

Lalande, C., S. Bélanger, and L. Fortier, 2009, Impact of a decreasing sea ice cover on the vertical export of particulate organic carbon in the northern Laptev Sea, Siberian Arctic Ocean, *Geophys. Res. Lett.*, **36**, L21604, doi:10.1029/2009GL040570

Long-term sediment traps were deployed from September 2005 to August 2007 in the northern Laptev Sea to assess the annual variability in vertical export of particulate organic carbon (POC). The second year of deployment coincided with the record low in Arctic summer ice extent reached in 2007 that resulted in an increase in marine primary production over the Siberian shelves. POC export fluxes increased during ice melt in 2007, leading to a ~2-fold increase in annual POC export relative to 2005–2006 over the continental slope of the Laptev Sea. These results suggest that the continuous decrease of sea ice extent could sustain increased POC export in the northern Laptev Sea and adjacent seas, potentially altering marine ecosystem structure in the Siberian Arctic.

Lavoie, D., K. L. Denman, and R. W. Mac donald, 2010, Effects of future climate change on primary productivity and export fluxes in the Beaufort Sea, *J. Geophys. Res.*, **115**, C04018, doi:10.1029/2009JC005493

We present projections of future prim ary production for the Canadian Beaufort Shelf of the Arctic Oce an, using simulations of future clim ate change from the Canadian Global Climate Model (CGCM2) to force a co upled sea ice-ocean-biological one-dimensional model. We compare three 18 year sim ulations, 1975–1992, 2042–2059, and 2082–2099, to describe the im pacts of a reduction in sea ice cover duration and thickness and an increase in surface freshwater flux es. Our results show an increase in average annual primary production of 6% between the period 1975–1992 and the period 2042–2059 and an increase of 9% between 1975–1992 and 2082–2099. The relative contribution of the ice algal and spring phytoplankton blooms to the annual prim ary production is reduced in the future runs owing to a reduction in the length of the ice algal grow th season (resulting from earlier snow and ice melt) and to a reduction in the replenishment of nutrient to the m ixed layer in winter. The duration of the summ er subsurface phytoplankton bloom increases, which fa vors the developm ent of t he main copepod species and leads to an increas e in export production (16% between 1975–1992 and 2082–2099) that is greater than the increase in prim ary production.

Li, W. K. W., F. A. McLaughlin, C. Love joy, and E. C. C armack, 2009, Smallest Algae Thrive As the Arctic O cean Freshens, *Science*, **326**(5952): 539, doi:10.1126/science.1179798

As climate changes and the upper Arctic Ocean receiv es more heat and fresh water, it be comes more dif ficult for mixing processes to deliver nutrients from depth to th e surface for phytoplankton growth. Com petitive advantage will presumably accrue to s mall cells b ecause they are m ore effective in acquiring nutrients and less susceptible to gravitational settling than large cells. Since 2004, we have dis cerned an increas e in the sm allest algae and b acteria along with a concomitant decrease in somewhat larger algae. If this trend toward a community of smaller cells is sustained, it may lead to reduced biological production at higher trophic levels.

McLaughlin, F. A. and E. C. Carmack, 2010, Deepening of the nutricline and chlorophyll maximum in the Canada Basin interior, 2003–2009, *Geophys. Res. Lett.*, **37**, L24602, doi:10.1029/2010GL045459

Physical and chem ical data collected in the C anada Basin interior from 2003–2009 show that recent increases in both Ekman convergence and freshwater input, associated with sea ice retreat and m elt, have affected the structure and dynam ics of the upper ocean, and such changes accelerated from 2007–2009 when salt-stratification below the seasonal m ixed layer increased about 25%. This increased stratification further constrains vertical heat flux and the winter renewal of nutrients into the euphotic zone. O ne consequence of increased convergence is that both the depth of the nutricline (i.e. the depth wh ere nitrate con centrations

begin to increase from zero) and the depth of the chlorophyll maximum (which occurs slightly below the depth of the nutricline as here both nitrate and light are sufficient to allow primary production) have increased. Nitrate concentrations at the chlorophyll maximum depth have also recently decreased which suggests that the availability of light may play a progressively greater role in determining the depth at which primary production occurs. If these trends continue, assuming that the depth of the winter mixed layer does not deepen, such changes will negatively affect primary productivity as long as the Arctic Oscillation remains anticyclonic and freshwater continues to be stored in the Beaufort Gyre. These findings show that, under such conditions, the response of sea ice retreat in the basin interior is distinct and opposite to the response on adjacent continental shelves where shelf-break upwelling will increase, bringing nitrate into the euphotic zone and enhancing production.

Mundy, C. J., M. Gosselin, J. Ehn, Y. Gratton, A. Rossnagel, D. G. Barber, J. Martin, J.-É. Tremblay, M. Palmer, K. R. Arrigo, G. Darnis, L. Fortier, B. Else, and T. Papakyriakou, 2009, Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea, *Geophys. Res. Lett.*, **36**, L17601, doi:10.1029/2009GL038837

The Canadian Beaufort Sea has been categorized as an oligotrophic system with the potential for enhanced production due to a nutrient-rich intermediate layer of Pacific-origin waters. Using under-ice hydrographic data collected near the ice-edge of a shallow Arctic bay, we documented an ice-edge upwelling event that brought nutrient-rich waters to the surface during June 2008. The event resulted in a 3-week long phytoplankton bloom that produced an estimated 31 g C m^{-2} of new production. This value was approximately twice that of previous estimates for annual production in the region, demonstrating the importance of ice-edge upwelling to the local marine ecosystem. Under-ice primary production estimates of up to 0.31 g C m^{-2} d^{-1} showed that this production was not negligible, contributing up to 22% of the daily averaged production of the ice-edge bloom. It is suggested that under-ice blooms are a widespread yet under-documented phenomenon in polar regions, which could increase in importance with the Arctic's thinning ice cover and subsequent increase in transmitted irradiance to the under-ice environment.

Schell, T. M., T. J. Moss, D. B. Scott, and A. Rochon, 2008, Paleo–sea ice conditions of the Amundsen Gulf, Canadian Arctic Archipelago: Implications from the foraminiferal record of the last 200 years, *J. Geophys. Res.*, **113**, C03S02, doi:10.1029/2007JC004202

Four boxcores were collected as part of the Canadian Arctic Exchange Shelf Study (CASES) in the Amundsen Gulf at water depths of 59 m to 600 m. Data from these cores help to develop a record of changes in the oceanographic history of the area over the last 200 years, with particular reference to the indication of paleo–sea ice formation, a key element of the Arctic ecosystem. The four sites cover a range of water depths and environments to provide a basis for comparison. The benthic foraminifera of sites CA-06 (253 m water depth) and CA-18 (600 m water depth) show an increase in Arctic Surface Water associated

agglutinated foraminifera over the last ~100 years (uppermost 8 to 16 cm). These are indicating a decrease in sea ice cover and in cold saline Arctic Bottom Water influence; these are similar to Canadian Arctic Archipelago postglacial faunas. This contrasts with abundant planktic foraminifera at the same stations, suggesting strong, oceanic Arctic surface influence (little freshwater) in the central Gulf. The foraminifera of sites 403B (59 m water depth) and 415B (56 m water depth), at the outermost edges of Amundsen Gulf, indicate that the present-day location of the winter flaw lead has been in place for at least the last 100 years, with foraminiferal faunas similar to those of the Beaufort Shelf. Additionally, station 415 is on an earlier Holocene shoreline that is covered with cobbles.

Tremblay, J.-É., K. Simpson, J. Martin, L. Miller, Y. Gratton, D. Barber, and N. M. Price, 2008, Vertical stability and the annual dynamics of nutrients and chlorophyll fluorescence in the coastal, southeast Beaufort Sea, *J. Geophys. Res.*, **113**, C07S90, doi:10.1029/2007JC004547

The first quasi-annual time series of nutrients and chlorophyll fluorescence in the southeast Beaufort Sea showed that mixing, whether driven by wind, local convection, or brine rejection, and the ensuing replenishment of nutrients at the surface were minimal during autumn and winter. Anomalously high inventories of nutrients were observed briefly in late December, coinciding with the passage of an eddy generated offshore. The concentrations of NO_3^- in the upper mixed layer were otherwise low and increased slowly from January to April. The coincident decline of NO_2^- suggested nitrification near the surface. The vernal drawdown of NO_3^- in 2004 began at the ice-water interface during May, leaving as little as 0.9 μM of NO_3^- when the ice broke up. A subsurface chlorophyll maximum (SCM) developed promptly and deepened with the nitracline until early August. The diatom-dominated SCM possibly mediated half of the seasonal NO_3^- consumption while generating the primary NO_2^- maximum. Dissolved inorganic carbon and soluble reactive phosphorus above the SCM continued to decline after NO_3^- was depleted, indicating that net community production (NCP) exceeded NO_3^--based new production. These dynamics contrast with those of productive Arctic waters where nutrient replenishment in the upper euphotic zone is extensive and NCP is fueled primarily by allochthonous NO_3^-. The projected increase in the supply of heat and freshwater to the Arctic should bolster vertical stability, further reduce NO_3^--based new production, and increase the relative contribution of the SCM. This trend might be reversed locally or regionally by the physical forcing events that episodically deliver nutrients to the upper euphotic zone.

2.17 Carbon Cycle and Ecosystems

Berreville, O. F., A. F. Vézina, K. R. Thompson, and B. Klein, 2008, Exploratory data analysis of the interactions among physics, food web structure, and function in two Arctic polynyas, *Can. J. Fish. Aquat. Sci.*, **65**(6): 1036-1046, doi:10.1139/F08-016

Polynyas are areas of open water in ice-covered seas, characterized by high biological productivity. The NEW (Northeast Water) and NOW (North Water)

polynyas, located off the east and west coasts of Greenland, were extensively sampled in 1993 and 1998, respectively. We used principal component analysis to explore the seasonal covariations among physical, chemical, and ecological characteristics in these polynyas. In both polynyas, the most explanatory eigenvector revealed the expected seasonal development of the bloom (nutrient consumption and biomass increases) associated with declining ice cover, warming, and mixed-layer shallowing. This seasonal pattern, however, was much weaker in NEW than in NOW. No connections between the structure of the food web and recycling processes were apparent in either polynya. The analysis points to much stronger and richer interactions between the mesoplankton (i.e., diatoms-zooplankton) and microbial food webs in NOW than in NEW. The differences between the polynyas may be explained in part by differences in their longevity, with the longer-lived NOW polynya having more time to develop complex trophic interactions. The results also indicate that the connections between food web structure and ecosystem function (i.e., new production versus recycling), at least at the seasonal scale, are weaker than expected.

Else, B. G. T., T. N. Papakyriakou, M. A. Granskog, and J. J. Yackel, 2008, Observations of sea surface fCO_2 distributions and estimated air-sea CO_2 fluxes in the Hudson Bay region (Canada) during the open water season, *J. Geophys. Res.*, **113**, C08026, doi:10.1029/2007JC004389

The lack of baseline estimates of air-sea CO_2 exchange in Arctic and sub-Arctic regions represents a major shortfall in our ability to understand how climate change may affect CO_2 fluxes at high latitudes. The 2005 ArcticNet cruise of Hudson Bay (Canada) provided a rare comprehensive oceanographic survey of one such region. Ship-based observations of sea-surface fugacity of CO_2 (fCO_{2sw}) were made at 56 locations between 15 September and 26 October and were found to range from 259 μatm in Hudson Strait to 425 μatm at the entrance to James Bay. Strong relationships between fCO_{2sw} and river discharge were identified, with coastal waters observed to be supersaturated with respect to the atmosphere, while offshore waters were undersaturated. High correlations of fCO_{2sw} with salinity, sea surface temperature, and colored dissolved organic matter suggest that thermodynamic effects and the oxidation of riverine carbon are driving supersaturation in the coastal zone. Calculated instantaneous fluxes of CO_2 ranged from +16.5 mmol m^{-2} d^{-1} in James Bay to −19.6 mmol m^{-2} d^{-1} in Foxe Channel. Using National Centers for Environmental Prediction wind speed climatologies, a net sink in Hudson Bay of −0.73 (±0.4) mmol m^{-2} d^{-1} was estimated for study period, substantially lower compared to many other Arctic shelf environments. This initial study provides a preliminary examination of fCO_{2sw} dynamics in Hudson Bay; future analyses and field measurements will be necessary to properly constrain CO_2 fluxes in this season and over an annual cycle.

Galand, P. E., C. Lovejoy, A. K. Hamilton, R. G. Ingram, E. Pedneault, and E. C. Carmack, 2009, Archaeal diversity and biogeochemical function are coupled to oceanic circulation, *Environ Microbiol.*, **11**(4): 971–980, doi:10.1111/j.1462-2920.2008.01822.x

Evidence of microbial zonation in the open ocean is rapidly accumulating, but while the distribution of communities is often described according to depth, the other physical factors structuring microbial diversity and function remain poorly understood. Here we identify three different water masses in the North Water (eastern Canadian Arctic), defined by distinct temperature and salinity characteristics, and show that they contained distinct archaeal communities. Moreover, we found that one of the water masses contained an increased abundance of the archaeal alpha-subunit of the ammonia monooxygenase gene (*amoA*) and accounted for 70% of the *amoA* gene detected overall. This indicates likely differences in putative biogeochemical capacities among different water masses. The ensemble of our results strongly suggest that the widely accepted view of depth stratification did not explain microbial diversity, but rather that parent water masses provide the framework for predicting communities and potential microbial function in an Arctic marine system. Our results emphasize that microbial distributions are strongly influenced by oceanic circulation, implying that shifting currents and water mass boundaries resulting from climate change may well impact patterns of microbial diversity by displacing whole biomes from their historic distributions. This relocation could have the potential to establish a substantially different geography of microbial-driven biogeochemical processes and associated oceanic production.

Guo, L., C. Ping, and R.W. Macdonald, 2007, Mobilization pathways of organic carbon from permafrost to arctic rivers in a changing climate, *Geophys. Res. Lett.,* **34**, L13603, doi:1029/2007GL030689

Arctic warming may cause the release of vast amounts of soil organic carbon (SOC) from permafrost, which will manifest itself in the fluxes and composition of organic carbon in northern rivers and Arctic coastal regions. To elucidate the transport pathways of SOC, radiocarbon composition was measured for dissolved organic carbon (DOC), particulate organic carbon (POC), sediments and SOC from the Mackenzie, Sagavanirktok, and Yukon river basins, and soil leaching experiments were conducted. The radiocarbon ages of riverine suspended POC and sediments ranged from 4430 to ~ 7970 yr BP, while DOC was much younger (390–1440 yr BP) except samples from the Sag River. Soil leaching experiments released <1% of SOC as DOC. The decoupling in age and partitioning between POC and DOC indicates that POC in these rivers is dominated by old SOC derived from permafrost thawing and river-bank erosion in contrast to DOC, which is more readily influenced by modern terrestrial biomass, especially in large river basins which also drain subarctic regions. These observations imply that melting of permafrost will be manifest in the age and amounts of POC in arctic rivers whereas change in DOC will reflect altered plant ecology.

Jutterström, S., E. Jeansson, L. G. Anderson, R. Bellerby, E. P. Jones, W. M. Smethie, Jr., and J. H. Swift, 2008, Evaluation of anthropogenic carbon in the Nordic Seas using observed relationships of N, P and C versus CFCs, *Prog. Oceanogr.*, **78**(1): 78-86, doi:10.1016/j.pocean.2007.06.001

Several methods to compute the anthropogenic component of total dissolved inorganic carbon (C_T^{anthro}) in the ocean have been reported, all in some way deducing (a) the effect by the natural processes, and (b) the background concentration in the pre-industrial scenario. In this work we present a method of calculating C_T^{anthro} using nutrient and CFC data, which takes advantage of the linear relationships found between nitrate (N), phosphate (P) and CFC-11 in the Nordic Seas sub-surface waters. The basis of the method is that older water has lower CFC-11 concentration and also has been exposed to more sinking organic matter that has decayed, resulting in the slopes of P versus CFC-11 and N versus CFC-11 being close to the classic Redfield ratio of 1:16. Combining this with the slope in total alkalinity (A_T) versus CFC-11 to correct for the dissolution of metal carbonates gives us the possibility to deduce the concentration of anthropogenic C_T in the Nordic Seas. This further allowed us to compute the inventory of anthropogenic C_T below 250 m in the Nordic Seas in spring 2002, to ~1.2 Gt C.

McGuire, A. D., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. Macdonald, and N. Roulet, 2009, Sensitivity of the carbon cycle in the Arctic to climate change, *Ecological Monographs*, **79**:523–555, doi:10.1890/08-2025.1

The recent warming in the Arctic is affecting a broad spectrum of physical, ecological, and human/cultural systems that may be irreversible on century time scales and have the potential to cause rapid changes in the earth system. The response of the carbon cycle of the Arctic to changes in climate is a major issue of global concern, yet there has not been a comprehensive review of the status of the contemporary carbon cycle of the Arctic and its response to climate change. This review is designed to clarify key uncertainties and vulnerabilities in the response of the carbon cycle of the Arctic to ongoing climatic change. While it is clear that there are substantial stocks of carbon in the Arctic, there are also significant uncertainties associated with the magnitude of organic matter stocks contained in permafrost and the storage of methane hydrates beneath both subterranean and submerged permafrost of the Arctic. In the context of the global carbon cycle, this review demonstrates that the Arctic plays an important role in the global dynamics of both CO_2 and CH_4. Studies suggest that the Arctic has been a sink for atmospheric CO_2 of between 0 and 0.8 Pg C/yr in recent decades, which is between 0% and 25% of the global net land/ocean flux during the 1990s. The Arctic is a substantial source of CH_4 to the atmosphere (between 32 and 112 Tg CH_4/yr), primarily because of the large area of wetlands throughout the region. Analyses to date indicate that the sensitivity of the carbon cycle of the Arctic during the remainder of the 21st century is highly uncertain. To improve the capability to assess the sensitivity of the carbon cycle of the Arctic to projected climate change, we recommend that (1) integrated regional studies be conducted to link observations of carbon dynamics to the processes that are likely to influence those dynamics, and (2) the understanding gained from these integrated studies be incorporated into both uncoupled and fully coupled carbon–climate modeling efforts.

Mucci, A., B. Lansard, L. A. Miller, and T. N. Papakyriakou, 2010, CO_2 fluxes across the air-sea interface in the southeastern Beaufort Sea: Ice-free period, *J. Geophys. Res.*, **115**, C04003, doi:10.1029/2009JC005330

Surface mixed layer CO_2 fugacities (fCO_2-sw) calculated from carbonate system parameters in the southeastern Beaufort Sea during the ice-free period ranged from 240 to 350 μatm in fall 2003 and from 175 to 515 μatm in summer 2004. The surface mixed layer remains mostly undersaturated with respect to atmospheric CO_2 (378 μatm) and, therefore, acts as a potential CO_2 sink throughout this period. Air-sea CO_2 fluxes (FCO_2) were first computed assuming ice-free conditions and ranged from −32.4 to +8.6 mmol m^{-2} d^{-1} in fall 2003 and summer 2004, respectively. Then we included a reduction factor to account for ice cover (ic) and we computed the resulting fluxes (FCO_2-ic). In fall 2003, FCO_2-ic ranged from −4.7 mmol m^{-2} d^{-1} in the relatively open water of the Cape Bathurst Polynya to −0.1 mmol m^{-2} d^{-1} in the southeastern Beaufort Sea, limited by the presence of the multiyear sea ice. In summer 2004, FCO_2-ic ranged from −13.1 mmol m^{-2} d^{-1} on the western Mackenzie Shelf to +8.6 mmol m^{-2} d^{-1} at Cape Bathurst; the variability being ascribed to competing effects of vertical mixing, temperature variations, and possibly biological production. On average, a net sink of −2.3 ± 3.5 mmol m^{-2} d^{-1} was estimated for the ice-free period over the study area. Nevertheless, the FCO_2 displays strong variability due to ice coverage, freshwater input, and upwelling events. The potential responses (direction and intensity of potential feedbacks) of the carbon cycle in the study area to a changing Arctic climate are discussed.

Shadwick, E. H., T. Papakyriakou, A. E. F. Prowe, D. Leong, D., S. A. Moore, and H. Thomas, H, 2009, Carbon cycling in the Arctic Archipelago: the export of Pacific carbon to the North Atlantic, *Biogeosciences Discuss.*, **6**: 971-994, doi:10.5194/bgd-6-971-2009

The Arctic Ocean is expected to be disproportionately sensitive to climatic changes, and is thought to be an area where such changes might be detected. The Arctic hydrological cycle is influenced by: runoff and precipitation, sea ice formation/melting, and the inflow of saline waters from Bering and Fram Straits and the Barents Sea Shelf. Pacific water is recognizable as intermediate salinity water, with high concentrations of dissolved inorganic carbon (DIC), flowing from the Arctic Ocean to the North Atlantic via the Canadian Arctic Archipelago. We present DIC data from an east-west section through the Archipelago, as part of the Canadian International Polar Year initiatives. The fractions of Pacific and Arctic Ocean waters leaving the Archipelago and entering Baffin Bay, and subsequently the North Atlantic, are computed. The eastward transport of carbon from the Pacific, via the Arctic, to the North Atlantic is estimated.

Steiner, N. and K. L. Denman, 2008, Parameter sensitivities in a 1-D model for DMS and sulphur cycling in the upper ocean, *Deep-Sea Research I*, **55**: 847-865, doi:10.1016/j.dsr.2008.02.010

We have developed a marine DMS (dimethylsulfide) module and implemented it in a 1-D coupled atmosphere-ocean-biogeochemical model. In developing the marine sulphur model we have found that several parameters used in the model

are not known to even an order of magnitude. Our approach is used to test the model's sensitivity to these parameters. A parameter change of ±25% is applied to test the respective range of changes in the DMS fluxes. The model is run for a 3-year time period as well as for the time period of the Subarctic Ecosystem Response to Iron Enrichment Study (SERIES) in July 2002. The simulated seasonal cycle is in agreement with available observations: Near surface DMS concentrations vary from 1.5 nmol L^{-1} in winter to in summer. Simulated DMS production is found to be most sensitive to variations of the S:N ratio and the bacterial consumption rate of DMS. Implementing light or UV limited bacterial activity shows a negligible effect in winter and increases DMS concentrations by 0.2–in summer. Similarly a yield increase under UV stress increases summer values by 1–. The simulated diel cycle in surface DMS concentration is no more than, even when light-dependent changes in bacterial activity are considered. Simulating the DMS response to iron fertilization with the standard run leads to overestimation during an initial bloom of small phytoplankton. While implementing light-dependent bacterial activity has a minor effect, the implementation of yields that depend on nutrient availability significantly improves the results. The model confirms earlier results showing the importance of including atmospheric DMS concentrations in gas flux calculations when there are high surface concentrations and small atmospheric boundary layer heights. Simulated summer concentrations in the upper layer can be underestimated by or more if the atmospheric concentration is set to zero. Our study shows that inclusion of mechanistic DMS modules in comprehensive climate models requires better knowledge of the variation of key parameters in the marine sulphur cycle. Even though there are still open questions, the model reasonably reproduces the mean annual cycle; and including variable DMS yield improves the simulation of the DMS response to iron fertilization during SERIES.

Tanhua, T., E. P. Jones, E. Jeansson, S. Jutterström, W. M. Smethie Jr., D. W. R. Wallace, and L. G. Anderson, 2009, Ventilation of the Arctic Ocean: Mean ages and inventories of anthropogenic CO_2 and CFC-11, *J. Geophys. Res.*, **114**, C01002, doi:10.1029/2008JC004868

The Arctic Ocean constitutes a large body of water that is still relatively poorly surveyed because of logistical difficulties, although the importance of the Arctic Ocean for global circulation and climate is widely recognized. For instance, the concentration and inventory of anthropogenic CO_2 (C_{ant}) in the Arctic Ocean are not properly known despite its relatively large volume of well-ventilated waters. In this work, we have synthesized available transient tracer measurements (e.g., CFCs and SF_6) made during more than two decades by the authors. The tracer data are used to estimate the ventilation of the Arctic Ocean, to infer deep-water pathways, and to estimate the Arctic Ocean inventory of C_{ant}. For these calculations, we used the transit time distribution (TTD) concept that makes tracer measurements collected over several decades comparable with each other. The bottom water in the Arctic Ocean has CFC values close to the detection limit, with somewhat higher values in the Eurasian Basin. The ventilation time for the intermediate water column is shorter in the Eurasian Basin (~200 years) than in

the Canadian Basin (~300 years). We calculate the Arctic Ocean C_{ant} inventory range to be 2.5 to 3.3 Pg-C, normalized to 2005, i.e., ~2% of the global ocean C_{ant} inventory despite being composed of only ~1% of the global ocean volume. In a similar fashion, we use the TTD field to calculate the Arctic Ocean inventory of CFC-11 to be $26.2 \pm 2.6 \times 10^{6}$ moles for year 1994, which is ~5% of the global ocean CFC-11 inventory.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, and K. Shimada, 2009, Aragonite Undersaturation in the Arctic Ocean: Effects of Ocean Acidification and Sea Ice Melt, *Science*, **326**(5956): 1098, doi:10.1126/science.1174190

The increase in anthropogenic carbon dioxide emissions and attendant increase in ocean acidification and sea ice melt act together to decrease the saturation state of calcium carbonate in the Canada Basin of the Arctic Ocean. In 2008, surface waters were undersaturated with respect to aragonite, a relatively soluble form of calcium carbonate found in plankton and invertebrates. Undersaturation was found to be a direct consequence of the recent extensive melting of sea ice in the Canada Basin. In addition, the retreat of the ice edge well past the shelf-break has produced conditions favorable to enhanced upwelling of subsurface, aragonite-undersaturated water onto the Arctic continental shelf. Undersaturation will affect both planktonic and benthic calcifying biota and therefore the composition of the Arctic ecosystem.

3 Pacific Ocean

3.1 North Pacific

Ito, T., C. Deutsch, S. Emerson, and R. C. Hamme, 2007, Impact of diapycnal mixing on the saturation state of argon in the subtropical North Pacific, *Geophys. Res. Lett.*, **34**, L09602, doi:10.1029/2006GL029209

Diapycnal mixing plays an important role in both physical and biogeochemical processes in the oceans, yet the rate of tracer mixing has not been adequately quantified. A theoretical analysis predicts that diapycnal mixing should raise the saturation state of noble gases in the thermocline, at a rate proportional to diapycnal diffusivity. We apply this theory to existing measurements of argon in the ventilated thermocline, where the increase in the saturation state should be proportional to the integrated effect of diapycnal mixing. Combining argon observations from time-series stations in the North Pacific with freon ventilation age, we tentatively estimate the regional diapycnal diffusivity at $0.35 \pm 0.21\ 10^{-4}$ m^2s^{-1}. Major sources of uncertainty include spatial and temporal variability and sparse sampling. These uncertainties could be significantly reduced using measurements of several noble gases in a transect from the isopycnal outcrop to the interior gyre.

Thomson, R. E., and M. V. Krassovski, 2010, Poleward reach of the California Undercurrent extension, *J. Geophys. Res.*, **115**, C09027, doi:10.1029/2010JC006280

The California Undercurrent is known to transport relatively warm, high-salinity, nutrient-rich water from the equatorial Pacific to Vancouver Island along the western continental slope of North America. This transport helps maintain the high productivity of the eastern boundary California Current system. In this study, we use several decades of water property survey data for the coasts of Oregon, Washington, British Columbia, and Alaska to show that equatorial Pacific water carried poleward by the undercurrent can eventually reach the Aleutian Islands, roughly 11,000 km from the source region. Long-term current meter records confirm the undercurrent as far north as Vancouver Island, where the current is found to be weakest in spring but then to strengthen through the summer and fall before merging with the wind-forced, poleward flowing Davidson Current in winter. The core depth of the equatorial water increases from 150 m ± 25 m off northwest Washington (near the northern end of the western North America coastal upwelling domain) to 225 m ± 25 m off southeast Alaska (near the southern end of the Gulf of Alaska coastal downwelling domain).

3.2 Northeast Pacific Ocean

Batten, S. D. and H. J. Freeland, 2007, Plankton populations at the bifurcation of the North Pacific Current, *Fish. Oceanogr.*, **16**(6): 536-546, doi:10.1111/j.1365-2419.2007.00448.x

As the eastward-flowing North Pacific Current approaches the North American continent it bifurcates into the southward-flowing California Current and the northward-flowing Alaska Current. This bifurcation occurs in the south-eastern Gulf of Alaska and can vary in position. Dynamic height data from Project Argo floats have recently enabled the creation of surface circulation maps which show the likely position of the bifurcation; during 2002 it was relatively far north at ~53°N then, during early 2003, it moved southwards to a more normal position at ~45°N. Two ship-of-opportunity transects collecting plankton samples with a Continuous Plankton Recorder across the Gulf of Alaska were sampled seasonally during 2002 and 2003. Their position was dependent on the commercial ship's operations; however, most transects sampled across the bifurcation. We show that the oceanic plankton differed in community composition according to the current system they occurred in during spring and fall of 2002 and 2003, although winter populations were more mixed. Displacement of the plankton communities could have impacts on the plankton's reproduction and development if they use cues such as day length, and also on foraging of higher trophic-level organisms that use particular regions of the ocean if the nutritional value of the communities is different. Although we identify some indicator taxa for the Alaska and California currents, functional differences in the plankton communities on either side of the bifurcation need to be better established to determine the impacts of bifurcation movement on the ecosystems of the north-east Pacific.

Chhak, K. C., E. Di Lorenzo, P. F. Cummins, and N. Schneider, 2009, Forcing of low-frequency ocean variability in the Northeast Pacific, *J. of Clim.*, **22(5)**: 1255, doi:10.1175/2008JCLI2639.1

An ocean model is used to examine and compare the forcing mechanisms and underlying ocean dynamics of two dominant modes of ocean variability in the northeast Pacific (NEP). The first mode is identified with the Pacific decadal oscillation (PDO) and accounts for the most variance in model sea surface temperatures (SSTs) and sea surface heights (SSHs). It is characterized by a monopole structure with a strong coherent signature along the coast. The second mode of variability is termed the North Pacific Gyre Oscillation (NPGO). This mode accounts for the most variance in sea surface salinities (SSSs) in the model and in long-term observations. While the NPGO is related to the second EOF of the North Pacific SST anomalies (the Victoria mode), it is defined here in terms of SSH anomalies. The NPGO is characterized by a pronounced dipole structure corresponding to variations in the strengths of the eastern and central branches of the subpolar and subtropical gyres in the North Pacific. It is found that the PDO and NPGO modes are each tied to a specific atmospheric forcing pattern. The PDO is related to the overlying Aleutian low, while the NPGO is forced by the North Pacific Oscillation. The above-mentioned climate modes captured in the model hindcast are reflected in satellite altimeter data.

A budget reconstruction is used to study how the atmospheric forcing drives the SST and SSH anomalies. Results show that the basinwide SST and SSS anomaly patterns associated with each mode are shaped primarily by anomalous horizontal advection of mean surface temperature and salinity gradients (T and S) via anomalous surface Ekman currents. This suggests a direct link of these modes with atmospheric forcing and the mean ocean circulation. Smaller-scale patterns in various locations along the coast and in the Gulf of Alaska are, however, not resolved with the budget reconstructions. Vertical profiles of the PDO and NPGO indicate that the modes are strongest mainly in the upper ocean down to 250 m. The shallowness of the modes, the depth of the mean mixed layer, and wintertime temperature profile inversions contribute to the sensitivity of the budget analysis in the regions of reduced reconstruction skill.

Foreman, M. G. G., W. R. Crawford, J. Y. Cherniawsky, and J. Galbraith, 2008, Dynamic ocean topography for the northeast Pacific and its continental margins, *Geophys. Res. Lett.*, **35**, L22606, doi:10.1029/2008GL035152

Estimates of dynamic ocean (or sea surface) topography based on satellite altimetry and gravity observations generally become degraded as they approach land. In this study, dynamic ocean topography for the northeast Pacific Ocean is computed independently of satellite observations using a high resolution model and seasonal climatologies of temperature, salinity, and wind stress. Comparisons with estimates based on satellite gravity and altimetry measurements show reasonable agreement in the deep ocean but are poor on continental margins where the ocean model estimates not only reveal significant seasonal differences, but are also shown to be reasonably accurate when compared with satellite altimetry and coastal tide gauge measurements. The dynamic ocean topography estimates provided here will permit more accurate calculations of the geoid and satellite altimeter absolute heights and currents.

Freeland, H. J., 2007, A Short History of Ocean Station Papa and Line-P, *Prog. Oceanogr.*, **75**(2): 120-125, doi:10.1016/j.pocean.2007.08.005

This short article summarises the origins of observations at Ocean Station Papa, the evolution into Line P and the subsequent history of observations along that line.

Hamme, R. C., et al., 2010, Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific, *Geophys. Res. Lett.*, **37**, L19604, doi:10.1029/2010GL044629

about 20 authors!!!!

Using multiple lines of evidence, we demonstrate that volcanic ash deposition in August 2008 initiated one of the largest phytoplankton blooms observed in the subarctic North Pacific. Unusually widespread transport from a volcanic eruption in the Aleutian Islands, Alaska deposited ash over much of the subarctic NE Pacific, followed by large increases in satellite chlorophyll. Surface ocean pCO_2, pH, and fluorescence reveal that the bloom started a few days after ashfall. Ship-based measurements showed increased dominance by diatoms. This evidence points toward fertilization of this normally iron-limited region by ash, a relatively new mechanism proposed for iron supply to the ocean. The observations do not support other possible mechanisms. Extrapolation of the pCO_2 data to the area of the bloom suggests a modest ~0.01 Pg carbon export from this event, implying that even large-scale iron fertilization at an optimum time of year is not very efficient at sequestering atmospheric CO_2.

Inoue, R. and C. Garrett, 2007, Fourier representation of quadratic friction, *J. Phys. Oceanogr.*, **37**, 593-610, doi:10.1175/JPO2999.1

If a current is composed of a number of constituents with different frequencies, then quadratic friction may be analyzed at the same frequencies. The ratios of the constituents of the friction differ from the ratios for the current itself, with a classic result being that for unidirectional flow a very weak current constituent experiences proportionately 50% more friction than a strong constituent. Here, exact results for the magnitude of the friction constituents are derived and confirmed numerically. The results are applied to the tidal currents in Juan de Fuca Strait and the Strait of Georgia, showing that minor constituents experience proportionately more friction than the main constituent by an amount that varies spatially but is typically less than the classic result of 50%. For two-dimensional currents it is shown that, if there are two current constituents with the same ellipticity and major axis direction, the friction coefficients are separable functions of the current constituent ratio and the ellipticity. Some results are derived for two constituents with different ellipticity and major axis direction. For the case of two constituents with rectilinear but misaligned currents, each constituent experiences friction inclined at an angle to its current. Last, the effect of a tidal current on the bottom friction experienced by a steady flow is investigated for arbitrary relative magnitudes and directions of the tide and steady flow. In particular, the inclination of the mean friction to the mean flow is quantified.

Ivanochko, T. S., S. E. Calvert, R. E. Thomson, and T. F. Pedersen, 2008, Geochemical reconstruction of Pacific decadal variability from the eastern North Pacific during the Holocene, *Can. J. Earth Sci.*, **45**: 1317-1329, doi:10.1139/E08-037

Determining climate variations over the Holocene requires high-resolution records with well-developed age models. A 40m long marine sediment core raised from Effingham Inlet, an anoxic fjord on the west coast of Vancouver Island, British Columbia, Canada, yields such a record. Forty six ^{14}C accelerator mass spectrometry (AMS) dates determined from terrestrial plant material form the age model. Downcore sampling at both 5cm (20year) and 1.5cm (7year) resolution indicates that high-frequency oceanographic variability has prevailed at this site over the last 10000years. Spectral analysis of wt.% opal, a proxy for diatom productivity in the basin, reveals the bidecadal and pentadecadal periods of the Pacific decadal oscillation (PDO)- North Pacific index (NPI) that are related to changes in the strength of the Aleutian Low. Coherence analysis between the Effingham Inlet data and $\delta^{18}O$ records from Jellybean Lake (a high elevation site in southwest Yukon) indicates regional coherence at periods of 45, 70, and 510years between productivity in Effingham Inlet and changes in the Aleutian Low strength. Over the entire Holocene, the strength of decadal variability has changed. Both 20- and 50-year periods are present to some degree in the early Holocene, and only the 50year period is evident in the late Holocene. These data imply that regime shifts would have been more frequent in the early Holocene relative to the last several thousand years.

Ivanochko, T. S., S. E. Calvert, J. R. Southon, R. J. Enkin, J. Baker, A. Dallimore, and T. F. Pedersen, 2008, Determining the post-glacial evolution of a northeast Pacific coastal fjord using a multiproxy geochemical approach. *Can. J. Earth Sci.*, **45**(11): 1331-1344, doi:10.1139/E08-030

A 40.32m piston core recovered from Effingham Inlet, on the west coast of Vancouver Island, provides the basis for a high-resolution geochemical study of the last deglaciation and the Holocene. Glacial retreat, basin isolation, sea-level rise, and productivity variations are determined using proxies for sediment composition (K/Al, Fe/Al, Mg/Al), grain size (Ti/Al, Zr/Al), sedimentary redox conditions (Mo/Al, U/Al), and productivity (wt.% organic carbon, wt.% opal). As local ice retreated and marine waters inundated the basin, coarse-grained glacimarine sediments were replaced by finer grained, laminated, opal-rich sediments. During meltwater pulse-1a, the dominance of local crustal rise over eustatic sea-level rise resulted in the progressive restriction of ocean circulation in Effingham Inlet and the formation of a temporary freshwater lake. The transition into stable Holocene conditions was initiated at ~12 700 BP, which corresponds to the onset of the Younger Dryas, as identified by the Greenland Ice core Project (GRIP) ice core $\delta^{18}O$ record and was completed by 10 700 BP, ~800years after the GRIP ice core record stabilized. Holocene Mo/Al and U/Al ratios range between 12-35 ($\times 10^{4}$) and 1-3.4 ($\times 10^{4}$), respectively, indicating that although large-amplitude, high-frequency fluctuations occur, the sediments of Effingham Inlet inner basin have remained organic rich and oxygen depleted for the entire

Holocene period. The combination of anoxic bottom waters and a Holocene sedimentation rate of 217cm /ka have preserved a high-resolution record of environmental change in the northeast Pacific over the last 11 000 years.

Jackson, J. M., P. G. Myers, and D. Ianson, 2009, An Examination of Mixed Layer Sensitivity in the Northeast Pacific Ocean from July 2001 - July 2005 Using the General Ocean Turbulence Model and Argo Data, *Atmos.-Ocean*, **47**(2): 139–153, doi:10.3137/OC308.2009

The mixed layer depth (MLD) at Ocean Station Papa (OSP) in the northeast Pacific Ocean has been shoaling for the past 50 years, with the shallowest maximum MLDs ever recorded occurring in the winters of 2002–03 and 2003–04. We use the General Ocean Turbulence Model (GOTM) to estimate the MLD and to determine how various atmospheric forcings from 2001–05 at four stations in the northeast Pacific affect the MLD. Three of the stations are in the Alaskan Gyre: OSP (50°N, 145° W) in the south; S 16 (49°17′N, 134°40′W) at the southeastern edge; CAG (55°N, 145° W) in the centre; and one, NSG (40°N, 145°W), is south of the Alaskan Gyre. Interpolated Argo temperature and salinity, for both initial conditions and restoring, and atmospheric inputs (heat fluxes and wind stress) from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis were used. Experiments showed that in the winter, the MLD was most sensitive to increased winds at all stations and also to decreased heat fluxes everywhere except at OSP. In summer, MLD was most sensitive to changes in the shortwave radiation. A combination of effects from the 2002–03 El Niño (i.e., decreased outgoing heat fluxes, cloud cover and wind speeds) and a strong stratification created by a subsurface cold water anomaly caused the MLD to be shallow in the Gulf of Alaska during the winter of 2002–03. Finally, our results show that for the modelled period (2001–05), the MLD at OSP behaved differently than at other stations in the Gulf of Alaska and therefore OSP may not be the best location to represent the region.

Ladd, C., W. R. Crawford, C. E. Harpold, W. K. Johnson, N. B. Kachel, P. Stabeno, and F. A.Whitney, 2009, A synoptic survey of young mesoscale eddies in the Eastern Gulf of Alaska, *Deep-Sea Research II*, **56**(24): 2460-2473, doi:10.1016/j.dsr2.2009.02.007

Eddies in the Gulf of Alaska are important sources of coastal water and associated nutrients, iron, and biota to the high-nutrient, low-chlorophyll central Gulf of Alaska. Three primary eddy formation regions along the eastern boundary of the gulf have been identified, (from south to north, Haida, Sitka, and Yakutat). In the spring of 2005, three eddies (one of each type) were sampled soon after their formation. The subsurface eddy core water in all three eddies was defined by high iron concentrations and low dissolved oxygen compared with surrounding basin water. The Sitka and Yakutat core waters also exhibited a subsurface temperature maximum (mesothermal water) coincident in depth with the iron maximum, suggesting that eddies may play a role in the formation of temperature inversions observed throughout the Gulf of Alaska. The data suggest different formation

regions, with the Yakutat eddy forming in shallow shelf water with riverine input, while the Sitka and Haida eddies appear to form in deeper water.

Pospelova, V., A. de Vernal and T. F. Pedersen, 2008, Distribution of dinoflagellate cysts in surface sediments from the northeastern Pacific Ocean (43-35 N) in relation to sea-surface temperature, productivity and coastal upwelling, *Marine Micropaleontology*, **68**, 21-48, doi:10.1016/j.marmicro.2008.01.008

Fifty-six surface sediment samples from the northeastern Pacific (43–25°N) were investigated in order to examine the spatial distribution of modern organic-walled dinoflagellate cysts in relation to hydrological conditions and marine productivity. The analyzed dinoflagellate cyst assemblages are diverse, and include over 60 taxa. Multivariate statistical analysis (CCA) of dinoflagellate cysts and environmental variables identifies annual productivity and sea-surface temperature as main factors affecting dinoflagellate cyst distribution in the region. In the studied area, marine productivity is greatly influenced by the strength of the coastal upwelling. Cyst assemblages from the coastal sites associated with active upwelling are characterized by the dominance of heterotrophic taxa, particularly Brigantedinium spp., Echinidinium spp. and cysts of Protoperidinium americanum. Taxa associated with low productivity offshore sites are Impagidinium spp., Nematosphaeropsis labyrinthus, Pyxidinopsis reticulata and Operculodinium centrocarpum. Dinoflagellate cyst species associated with warmer waters are Lingulodinium machaerophorum, Spiniferites mirabilis, S. ramosus, S. delicatus/bulloideus, Bitectatodinium spongium and Polykrikos cf. kofoidii, while those from cooler environments include Selenopemphix nephroides, Trinovantedinium variable and cysts of Pentapharsodinium dalei. Combining the present cyst dataset with other published cyst data from the Northeastern Pacific, we have compiled a "NE Pacific 188" database. This database can be used as a basis for the quantitative reconstructions of (paleo)temperature and productivity in the Northeastern Pacific.

Rogachev, K., N. Shlyk and E. Carmack, 2007, The shedding of mesoscale anticyclonic eddies from the Alaskan Stream and westward transport of warm water, *Deep-Sea Res. II*, **54**(23-26): 2643-2656 doi:10.1016/j.dsr2.2007.08.017

The south-flowing waters of the Kamchatka and Oyashio Currents and west-flowing waters of the Alaskan Stream are key components of the western sub-Arctic Pacific circulation. We use CTD data, Argo buoys, WOCE surface drifters, and satellite-derived sea-level observations to investigate the structure and interannual changes in this system that arise from interactions among anticyclonic eddies and the mean flow. Variability in the temperature of the upstream Oyashio and Kamchatka Currents is evident by warming in mesothermal layer in 1994–2005 compared to 1990–1991. A major fraction of the water in these currents is derived directly from the Alaskan Stream. The stream also sheds large anticyclonic (Aleutian) eddies, averaging approximately 300 km in diameter with a volume transport significant in comparison with that of the Kamchatka Current itself. These eddies enclose pools of relatively warm and saline water whose temperature is typically 4 °C warmer and salinity is 0.4 greater than that of cold-

core Kamchatka eddies in the same density range. Aleutian eddies drift at approximately 1.2 km d^{-1} and retain their distinctive warm and salty characteristics for at least 2 years. Selected westward pathways during 1990–2004 are identified. If the shorter northern route is followed, Aleutian eddies remain close to the stream and persist sufficiently long to carry warm and saline water directly to the Kamchatka Current. This was observed during 1994–1997 with substantial warming of the waters in the Kamchatka Current and upstream Oyashio. If the eddies take a more southern route they detach from the stream but can still contribute significant quantities of warm and saline water to the upstream Oyashio, as in 2004–2005. However, the eddies following this southern route may dissipate before reaching the western boundary current region.

Steiner, N., S. Vagle, K. L. Denman, and C. McNeil, 2007, Oxygen and nitrogen cycling in the northeast Pacific-Simulations and observations at Station Papa in 2003/2004, *J. Mar. Res.*, **65**(3): 441-469

A long-term air-sea exchange mooring has been maintained in the North Pacific near Ocean Station Papa (OSP, 145W, 50N) since September 2002 as part of the Canadian Surface Ocean Lower Atmosphere Study (C-SOLAS). The mooring provides a new long-term data set for gas measurements. In addition to Conductivity, Temperature and Depth (CTD) recorders at two depths, the mooring is equipped with ProOceanus Gas Tension Devices (GTDs) measuring the total gas pressure at four different depths, two oxygen sensors, two fluorometers for chlorophyll estimates, and an upward-looking 200 kHz echo-sounder for bubble measurements. Chlorophyll data have been added using SeaWiFS imagery and occasional bottle casts. Data collected from June 2003 to June 2004 are compared with simulations from a 1-D coupled atmosphere-ocean-biogeochemical model. The coupled model consists of an atmospheric Single Column Model (SCM), based on the CCCma AGCM (Canadian Centre for Climate Modelling and Analysis-Atmospheric General Circulation Model), the General Ocean Turbulence Model (GOTM) and a 7-component ecosystem model embedded in GOTM. The ecosystem model also includes oxygen, nitrogen, carbon, and silica cycling. The study focuses on simulated and observed N_2 and O_2 variability. The comparison of these gases allows for separation of physical and biological processes; which can then be evaluated in more detail with the aid of model simulations. The model also tests different parameterizations for saturation and gas exchange, including a formulation for gas injection via bubbles, which affects gas concentrations within the whole mixed layer. For most of the time the model shows good agreement with observations. However, in summer 2003 the observations reveal a strong oxygen and chlorophyll event, which is not reproduced in the standard model run. A weaker signal is seen in May 2004. OSP is a High Nutrient Low Chlorophyll (HNLC) region, limited by the micronutrient iron. Increases in usually low chlorophyll values occur occasionally due to natural iron enrichment (dust deposition, eddy transport, below surface layer transport). Although limitations of 1-D modeling become apparent here, an assumed input of iron in the model explains the differences between simulated and observed oxygen and chlorophyll maxima. The model

provides information on the strength and duration of potential iron contribution. No obvious dust events or eddy traverses to supply iron were recorded during this time period. An alternative explanation is entrainment from deeper waters, where occasional iron enrichment is known to occur due to off-shelf transport via eddies or recirculation from the Alaskan shelf.

Shore, J., M. W. Stacey, D. G. Wright, 2008, Sources of Eddy Energy Simulated by a Model of the Northeast Pacific Ocean, *J. Phys. Oceanogr.*, **38**: 2283–2293, doi:10.1175/2008JPO3800.1

This paper examines the energy sources for eddy variability in the Gulf of Alaska using a numerical model and a novel form of data assimilation referred to as spectral nudging. Spectral nudging is distinguished from conventional nudging by its ability to operate only on specified frequency and wavenumber bands; in the present case, only the subannual variability is nudged, and only on spatial scales of 100 km or more. By using this approach, the broad-brush aspects of the model's mean state are constrained to remain near the mean climatological conditions, while the simulated eddy field is determined by the model dynamics. Simulations of the North Pacific Ocean with a 0.25° horizontal resolution and spectral nudging have been previously shown to produce eddy fields that are significantly more energetic and more realistic than those produced by prognostic (i.e., not nudged) simulations. The analysis of the spectrally nudged model results undertaken here reveals the tendency of the circulation to be both baroclinically and barotropically unstable in different regions and to differing degrees. Along the north coast of the Gulf of Alaska, the simulation suggests that barotropic instability is more important overall as an energy source for eddies than is baroclinic instability. Along the east coast of the Gulf of Alaska, the simulation suggests that both baroclinic and barotropic instabilities are important. Although the overall energy transfer is from the mean state to the eddy field, there are regions of the model, particularly along the north coast of the Gulf of Alaska, where the transfer of energy is from the eddy field to the mean flow.

Subbotina, M. M., R. E. Thomson, and M. V.Anisimov, 2008, Numerical simulation of a hydrophysical structure near the seafloor in a hydrothermal venting region. Translated from Doklady Akademii Nauk. 423(3–6), *Oceanology*, **423A**(9): 1423-1426, doi:10.1134/S1028334X08090213

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OCEANOLOGY

Numerical Simulation of a Hydrophysical Structure near the Seafloor in a Hydrothermal Venting Region¶

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The present study provides numerical simulations of the near-bottom circulation at the Endeavor segment of Juan de Fuca Ridge (ER) in the northeast Pacific that arises from the effect of hydrothermal vent sources. Numerical experiments have shown that the near-bottom current to the northeast along the ridge axial valley is generated solely by the hydrothermal venting. A near-steady background flow across the ridge does not create any significant near-bottom flow in the valley. However, model results show that the background current in the deep ocean does have an important influence on the direction and intensity of hydrothermal plume evolution above the axial valley. Additional investigations show that the model best captures the observed plume parameters and plume drift to the west when the external background flow has a westward velocity component.

Studies of hydrothermal vent fields associated with the rift crests of mid-ocean ridges are important not only for understanding the biological activity of these regions but also for determining the impact of the hydrothermal input on near-bottom ocean circulation. Several major hydrothermal vent fields are situated within the rift valley between two crests of the Endeavor segment of the mid–Pacific Ocean Juan de Fuca Ridge. The 100 m wide valley extends from the southwest to the northeast over a distance of about 10 km (Fig. 1), gradually shoaling by about 50 m to the northeast.

The model domain of the ER region is marked by a square dotted line in Fig. 1. After that left and right peripheries of the model domain were smoothed to avoid hydrophysical noise, caused on the one hand by steep boundary conditions for both incoming and outgoing background flow and on the other hand by rough topographic relief along the left and right boundaries. Below and above the ER, nonleaking boundary conditions were set. Hydrothermal venting in the axial valley consists mainly of focused hydrothermal source fields separated from each other by 2–3 km and lying 100 m below the ridge crests (white circles in Fig. 1). Each of the hydrothermal vents has a source temperature of about 340°C.

A constant near-bottom current directed to the northeast is observed in the ER valley, i.e., in the direction of the ER valley orientation. Above the ridge crests, relatively warm hydrothermal plumes of neutral buoyancy are observed to move to the west. Thomson et. al. [1] hypothesized that the hydrothermal vents [2] are the reason for the steady mean current along the valley axes. To check this hypothesis we conducted numerical simulations with several different idealized ER regions [3]. These simulations confirm the hypothesis that the current inside the valley is generated by the hydrothermal vents. In these experiments, we have also observed relatively warm, neutrally buoyant plumes whose temperature anomalies and spatial distributions closely resembled those of observed plumes.

The mid-ocean Pacific Ridge being studied is subjected to tidal, inertial, and near-steady background currents. In [4], the authors assume that a near-steady background current flowing across the ridge may penetrate inside the valley and cause the along-axis current in the ER valley. To check this assumption, we conducted numerical simulation with a near-steady external current in the absence of hydrothermal forcing. We note that almost nothing is known about the magnitude of possible near-steady currents in the ER region. So the magnitude of the background current for our simulations was taken from the model results of the 1/8 degree resolution General Circulation Ocean Model of the Institute of Numerical Mathematics, Russian Academy of Sciences (GCOM of INM), for the Pacific region (kindly provided by N.A. Diansky). Although the topographic relief used in the GCOM of INM is

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Thomson, R. E., M. M. Subbotina, and M. V. Anisimov, 2009, Numerical simulation of mean currents and water property anomalies at Endeavour Ridge: Hydrothermal versus topographic forcing, *J. Geophys. Res.*, **114**, C09020, doi:10.1029/2008JC005249

Numerical simulations based on realistic seafloor topography are used to examine near-bottom currents in the region of the Endeavour segment of Juan de Fuca Ridge (Endeavour Ridge) in the northeast Pacific. Results support earlier findings that hydrothermal venting within the ~ 2200-m deep axial valley, rather than topographically modified, basin-scale cross-ridge geostrophic flow, is responsible

for the near-steady northward currents observed within the confines of the valley. Although it does not generate deep flow within the valley, the basin-scale circulation determines the horizontal redistribution of the hydrothermal plumes once they rise above the ridge crest. Simulations of the near-bottom temperature and salinity fields reveal that model runs that incorporate a deep westward background flow most closely reproduce the observed plume anomaly distributions above the ridge, indicating that bottom currents in the region are predominantly westward, counter to the prevailing southeasterly flow of the wind-driven California Current in the upper half of the water column.

Thomson, R. E. and I. V. Fine, 2009, A diagnostic model for mixed layer depth estimation with application to Ocean Station "P" in the northeast Pacific, *J. Phys. Oceanogr.*, **39**(6): 1399–1415, doi:10.1175/2008JPO3984.1

This paper presents a simple diagnostic model for estimating mixed layer depth based solely on the one-dimensional heat balance equation, the surface heat flux, and the sea surface temperature. The surface fluxes drive heating or cooling of the upper layer whereas the surface temperature acts as a "thermostat" that regulates the vertical extent of the layer. Daily mixed layer depth estimates from the diagnostic model (and two standard bulk mixed layer models) are compared with depths obtained from oceanic profiles collected during the 1956–80 Canadian Weathership program at Station P and more recent (2001–07) profiles from the vicinity of this station from Argo drifters. Summer mixed layer depths from the diagnostic model agree more closely with observed depths and are less sensitive to heat flux errors than those from bulk models. For the Weathership monitoring period, the root-mean-square difference between modeled and observed monthly mean mixed layer depths is 6 m for the diagnostic model and 10 m for the bulk models. The diagnostic model is simpler to apply than bulk models and sidesteps the need for wind data and turbulence parameterization required by these models. Mixed layer depths obtained from the diagnostic model using NCEP–NCAR reanalysis data reveal that—contrary to reports for late winter—there has been no significant trend in the summer mixed layer depth in the central northeast Pacific over the past 52 yr.

Ueno, H., K. Sato, H. J. Freeland, W. R. Crawford, H. Onishi, E. Oka, and T. Suga, 2009, Anticyclonic Eddies in the Alaskan Stream. *J. Phys. Oceanogr.*, **39**, 934–951, doi:10.1175/2008JPO3948.1

Anticyclonic eddies propagating southwestward in the Alaskan Stream (AS) were investigated through analysis of altimetry data from satellite observations during 1992–2006 and hydrographic data from profiling float observations during 2001–06. Fifteen long-lived eddies were identified and categorized based on their area of first appearance. Three eddies were present at the beginning of the satellite observations; another three formed in the eastern Gulf of Alaska off Sitka, Alaska; and four were first detected at the head of the Gulf of Alaska near Yakutat, Alaska. The other five eddies formed along the AS between 157° and 169°W, and were named AS eddies. While the eddies that formed in the Gulf of Alaska mainly decayed before exiting the Gulf of Alaska, the AS eddies mostly

crossed the 180° meridian and reached the western subarctic gyre. Four of five AS eddies formed under negative or weakly positive wind stress curls, which possibly caused AS separation from the coast. Comparison of eddy propagation speeds in the AS with the bottom slope showed that eddies propagated faster over steeper slopes, although eddy speeds were slower than those predicted by the topographic planetary wave dispersion relation. An AS eddy was observed by profiling floats in the western subarctic gyre after it detached from the AS. Intermediate-layer water near the eddy center had low potential vorticity compared with the surrounding water, suggesting that AS eddies provided the western subarctic gyre with water just south of the Aleutian Islands.

Ueno, H., W. R. Crawford, and H. Onishi, 2010, Impact of Alaskan Stream eddies on chlorophyll distribution in the North Pacific. *J. of Oceanogr.*, **66**:(3), 319-328, doi:10.1007/s10872-010-0028-6

The impact of the Alaskan Stream (AS) eddies on the chlorophyll a (chl-a) distribution in the central subarctic North Pacific was investigated through analysis of chl-a and altimetry data from satellite observations. Altimetry observations provided the locations of mesoscale eddies in time and space within the maps of chlorophyll distributions. The climatological chl-a distributions averaged in the area and time showing presence of AS eddies suggested that AS eddies contributed significantly to the chl-a distribution in the deep-sea region of the subarctic North Pacific. The chl-a distribution was closely related to the AS eddies regardless of whether the eddy was located in or detached from the AS. A combination of two or three AS eddies sometimes formed high chl-a concentration belts that injected chlorophyll and coastal nutrient-rich waters southward from the Aleutian Islands far into the deep-sea region of the subarctic North Pacific. These results indicate that chl-a distribution in the central subarctic North Pacific was strongly impacted by AS eddies.

3.2.1 Subarctic Pacific

Crawford, W. R. and M. Robert, 2007, Recent trends in waters of the subarctic northeast Pacific, *PICES Press*, **14**(2): 24-25

no abstract; first paragraph

Near-surface waters of the northeast Pacific Ocean have been unusually warm since the summer of 2004. Figure 1 reveals this warming through a sequence of plots of temperature anomalies for the summers of 2004 and 2005, plus winter 2005. The summer temperatures have warmed significantly since 2001, with almost no observations of colder-than-normal temperatures in 2004 and 2005.

Crawford, W. R. and P. Chandler, 2007, Recent trends in waters of the subarctic NE Pacific, Cooler and fresher in summer of 2006, *PICES Press*, **15**(1): 22-23

no abstract; first paragraph

Ocean temperatures at 10 m depth in the eastern Gulf of Alaska cooled by several degrees from winter 2006 to winter 2007, with coastal waters of the NE gulf cooling the most. This decline followed a period of extremely high temperatures in the region in the summers of 2004 and 2005. Above-normal temperatures

appeared to persist into 2007 only in the Strait of Georgia in the SE region of Temperatures there often lag those in oceanic waters by several months to a year. Much of the cooling from Oregon to British Columbia might be attributed to major storms and southerly storm tracks of late 2006 that cooled oceanic surface waters. Cooling earlier in 2006 is believed to be associated with a shift in atmospheric circulation patterns. Impacts of continuing cooling in late 2006 and into 2007 are pointed out in a recent overview (DFO Ocean Status Report 2007/001; http://sci.info.pac.dfo.ca/PSARC/ OSR's/OSR.htm). It notes that cooling in the last half of 2006 along the West Coast was accompanied by more boreal copepods on the Oregon continental shelf. Dr. William Peterson of the U.S. National Marine Fisheries Service reports that preliminary indications from samples collected in the winter and early spring of 2007 are that the copepod community is dominated by cool water species, *Pseudocalanus mimus* and *Calanus marshallae*. *Neocalanus plumchrus/flemingerii* also appeared to be unusually abundant in the spring of 2007.

Crawford, W. R. and P. F. Cummins, 2007, Recent trends in waters of the subarctic NE pacific: Cooling of 2006 continues into 2007, *PICES Press*, **15**(2): 26-27

no abstract: first paragraph

Ocean temperatures at 10 m depth in the eastern Gulf of Alaska cooled by several degrees from winter 2006 to winter 2007, with coastal waters of the NE gulf cooling the most. This decline followed a period of extremely high temperatures in the region in the summers of 2004 and 2005. Above-normal temperatures appeared to persist into 2007 only in the Strait of Georgia in the SE region of Temperatures there often lag those in oceanic waters by several months to a year. Much of the cooling from Oregon to British Columbia might be attributed to major storms and southerly storm tracks of late 2006 that cooled oceanic surface waters. Cooling earlier in 2006 is believed to be associated with a shift in atmospheric circulation patterns. Impacts of continuing cooling in late 2006 and into 2007 are pointed out in a recent overview (DFO Ocean Status Report 2007/001; http://sci.info.pac.dfo.ca/PSARC/ OSR's/OSR.htm). It notes that cooling in the last half of 2006 along the West Coast was accompanied by more boreal copepods on the Oregon continental shelf. Dr. William Peterson of the U.S. National Marine Fisheries Service reports that preliminary indications from samples collected in the winter and early spring of 2007 are that the copepod community is dominated by cool water species, *Pseudocalanus mimus* and *Calanus marshallae*. *Neocalanus plumchrus/flemingerii* also appeared to be unusually abundant in the spring of 2007.

Crawford, W. R., J. Galbraith, and N. Bolingbroke, 2007, Line P ocean temperature and salinity, 1956-2005, *Prog. Oceanogr.*, **75**(2): 161-178, doi:10.1016/j.pocean.2007.08.017

Vertical profiles of temperature and salinity have been measured for 50 years along Line P between the North American west coast and mid Gulf of Alaska. These measurements extend 1425 km into the gulf at 13 or more sampling stations. The 10–50-m deep layer of Line P increased in temperature by 0.9 °C from 1958 to 2005, but is significant only at the 90% level due to large

interannual variability. Most of this increase in temperature accompanies the 1977 shift in wind patterns. Temperature changes at 100–150 m and salinity changes in both layers are not statistically significant. Much of the variance in temperature is in the upper 50 m of Line P, and temperature changes tend to be uniform along Line P except for waters on the continental margin. Salinity changes are dominated by variability in the halocline between 100 and 150 m depth and are less uniform along Line P. Largest oscillations in temperature and salinity are between 1993 and 2003. These events can be understood by considering changes in eastward wind speed and wind patterns that are revealed in the first two modes of the Pacific Decadal Oscillation. Changes in these patterns are indicators for both Ekman surface forcing (Surface ocean currents flow to the right of the wind direction) and Ekman pumping (Surface waters diverge away from regions of positive wind stress curl, leading to upwelling of colder saltier water). Changes in temperature along the nearshore part of Line P suggest Ekman surface forcing is the stronger of the two processes in the upper layer. The change in salinity anomalies in the halocline along the seaward end of Line P, following the wind shift in 1977, is in agreement with enhanced upwelling caused by stronger Ekman pumping in this region.

Crawford, W. R., P. J. Brickley, and A. C. Thomas, 2007, Mesoscale eddies dominate phytoplankton distribution in northern Gulf of Alaska, *Prog. Oceanogr.*, **75**(2): 287-303, doi:10.1016/j.pocean.2007.08.016

The HNLC waters of the Gulf of Alaska normally receive too little iron for primary productivity to draw down silicate and nitrate in surface waters, even in spring and summer. Our observations of chlorophyll sensed by SeaWiFS north of 54°N in pelagic waters (>500 m depth) of the gulf found that, on average, more than half of all surface chlorophyll was inside the 4 cm contours of anticyclonic mesoscale eddies (the ratio approaches 80% in spring months), yet these contours enclosed only 10% of the total surface area of pelagic waters in the gulf. Therefore, eddies dominate the chlorophyll and phytoplankton distribution in surface pelagic waters. We outline several eddy processes that enhance primary productivity. Eddies near the continental margin entrain nutrient – (and Fe) – rich and chlorophyll-rich coastal waters into their outer rings, advecting these waters into the basin interior to directly increase phytoplankton populations there. In addition, eddies carry excess nutrients and iron in their core waters into pelagic regions as they propagate away from the continental margin. As these anticyclonic eddies decay, their depressed isopycnals relax upward, injecting nutrients up toward the surface layer. We propose that this transport brings iron and macro-nutrients toward the surface mixed layer, where they are available for wind-forced mixing to bring them to surface. These mesoscale eddies decay slowly, but steadily, perhaps providing a relatively regular upward supply of macro-nutrients and iron toward euphotic layers. They might behave as isolated oases of enhanced marine productivity in an otherwise iron-poor basin. We note that much of this productivity might be near or just below the base of the surface mixed layer, and therefore poorly sampled by colour-sensing satellites. It is

possible, then, that eddies enrich phytoplankton populations to a greater extent than noted from satellite surface observations only.

Cullen, J. T., M. Chong, and D. Ianson, 2009, British Columbian continental shelf as a source of dissolved iron to the subarctic northeast Pacific Ocean, *Global Biogeochem. Cycles*, **23**, GB4012, doi:10.1029/2008GB003326

The distribution of dissolved (<0.4 μm) iron (Fe) across the continental shelf and slope of Queen Charlotte Sound on the west coast of Canada was examined to estimate the potential of these waters as a source of Fe to the Fe-limited waters of the subarctic northeast Pacific. Iron profiles obtained in shelf, slope, and offshore waters demonstrate decreasing concentrations of Fe with distance from the continent. Within 50 m of the shelf sediments dissolved Fe concentrations were 5.3 ± 0.3 nM. This signal was detected, although attenuated by 80%, along the isopycnal surface at offshore stations 40–50 km seaward of the shelf break, strongly suggesting cross-shelf transport of an Fe-rich plume originating in low dissolved oxygen (<3 ml L^{-1}, <130 μmol kg^{-1}) waters in subsurface water over the continental shelf. Several physical mechanisms that may cause these Fe-enriched waters to advect offshore in this region (i.e., tidal currents and Ekman transport in the bottom boundary layer, coastal downwelling/relaxation from upwelling, and the formation of anticyclonic, westward-propagating, coastal eddies) are discussed. We suggest that strong tidal currents over broad continental shelves may play a key role in Fe supply to ocean basins.

Cummins, P. F. and H. J. Freeland, 2007, Variability of the N. Pacific Current and its bifurcation, *Prog. Oceanogr.*, **75**(2): 253-265, doi:10.1016/j.pocean.2007.08.006

The North Pacific Current (NPC) bifurcates approaching the west coast of North America into a subpolar branch that forms the Alaska Current, and a subtropical branch that includes the California Current. The variability of this current system is discussed using numerical results from a wind-driven, reduced-gravity model. Indices of the strength of the subpolar and subtropical components of the NPC are examined based on output from multi-decadal simulations with the numerical model. This shows periods of both correlated and anti-correlated variability of the subpolar and subtropical gyres. A decomposition of the gyre transport time series indicates that the dominant mode of variability is a "breathing" mode in which the subpolar and subtropical gyres co-vary in response to fluctuations in the strength of the NPC. This finding is consistent with an analysis of dynamic height data of limited duration from the array of Argo drifting floats. The variability of the NPC is also examined using sea surface height (SSH) data from satellite altimetry over the period 1993–2005. The leading mode of SSH over the northeast Pacific dominates the variability of the NPC and is shown to be associated with in-phase variations in the transport of the subtropical and subpolar gyres. A strong correlation is found between time-dependent fluctuations in SSH across the NPC and variations in the strength of the transport of the NPC in the model. This agreement provides evidence for variability of the NPC occuring in direct response to large-scale atmospheric forcing.

Galbraith, E. D., M. Kienast, S. L. Jaccard, T. F. Pedersen, B. G. Brunelle, D. M. Sigman, and T. Kiefer, 2008, Consistent relationship between global climate and surface nitrate utilization in the western subarctic Pacific throughout the last 500 ka, *Paleoceanography*, **23**, PA2212, doi:10.1029/2007PA001518

The open subarctic Pacific is, at present, a high nitrate low chlorophyll (HNLC) region, where nitrate is perennially abundant at the surface. Theoretically, the HNLC status of this region is subject to modification by ocean circulation and/or micronutrient supply, with implications for the effectiveness of the biological pump and hence carbon sequestration in the ocean interior. Records of biogenic detritus in sediments from throughout the subarctic Pacific indicate that export production was generally lower during glacial maxima, while nitrogen isotope measurements from the Bering Sea have shown that nitrate consumption there was more complete during the last glacial period than it is today. Here, nitrogen isotopic analyses of bulk sediments ($\delta^{15}N_{bulk}$) from three deep water sites in the open subarctic Pacific are evaluated in terms of regional nitrate isotopic composition and local relative nitrate utilization. The eastern subarctic Pacific $\delta^{15}N_{bulk}$ record bears great similarity to $\delta^{15}N_{bulk}$ records from the western margin of North America over the last glacial cycle, suggesting that variability in the isotopic composition of subeuphotic zone nitrate, the growth substrate, is reasonably coherent throughout the northeast Pacific and dominates at these sites. However, the two western subarctic Pacific records, which lie at the heart of the HNLC region, display a different pattern, implying that significant changes in local relative nitrate utilization overlie the regional background variability. After a novel correction intended to remove the background signal associated with denitrification in the eastern tropical North Pacific, these nitrate utilization records are correlated with a benthic oxygen isotope stack reflecting global deep ocean temperature and ice volume ($r^2 = 0.65$). The correlation implies a strong link between global climate and subarctic Pacific nitrate utilization, with nearly complete nitrate consumption during glacial periods when export production was low.

Halfar, J., R. Steneck, B. Schöne, G. W. K. Moore, M. Joachimski, A. Kronz, J. Fietzke, and J. Estes, 2007, Coralline alga reveals first marine record of subarctic North Pacific climate change, *Geophys. Res. Lett.*, **34**, L07702, doi:10.1029/2006GL028811

While recent changes in subarctic North Pacific climate had dramatic effects on ecosystems and fishery yields, past climate dynamics and teleconnection patterns are poorly understood due to the absence of century-long high-resolution marine records. We present the first 117-year long annually resolved marine climate history from the western Bering Sea/Aleutian Island region using information contained in the calcitic skeleton of the long-lived crustose coralline red alga *Clathromorphum nereostratum*, a previously unused climate archive. The skeletal $\delta^{18}O$-time series indicates significant warming and/or freshening of surface waters after the middle of the 20th century. Furthermore, the time series is spatiotemporally correlated with Pacific Decadal Oscillation (PDO) and tropical El Niño-Southern Oscillation (ENSO) indices. Even though the western Bering Sea/Aleutian Island region is believed to be outside the area of significant marine

response to ENSO, we propose that an ENSO signal is transmitted via the Alaskan Stream from the Eastern North Pacific, a region of known ENSO teleconnections.

Jaccard, S. L., E. D. Galbraith, D. M. Sigman, G. H. Haug, R. Francois, T. F. Pedersen, P. Dulski, and H. R. Thierstein, 2009, Subarctic Pacific evidence for a glacial deepening of the oceanic respired carbon pool, *Earth and Planetary Science Letters*, **277**: 156-165, doi:10.1016/j.epsl.2008.10.017

Measurements of benthic foraminiferal cadmium:calcium (Cd/Ca) have indicated that the glacial–interglacial change in deep North Pacific phosphate (PO_4) concentration was minimal, which has been taken by some workers as a sign that the biological pump did not store more carbon in the deep glacial ocean. Here we present sedimentary redox-sensitive trace metal records from Ocean Drilling Program (ODP) Site 882 (NW subarctic Pacific, water depth 3244 m) to make inferences about changes in deep North Pacific oxygenation – and thus respired carbon storage – over the past 150,000 yr. These observations are complemented with biogenic barium and opal measurements as indicators for past organic carbon export to separate the influences of deep-water oxygen concentration and sedimentary organic carbon respiration on the redox state of the sediment. Our results suggest that the deep subarctic Pacific water mass was depleted in oxygen during glacial maxima, though it was not anoxic. We reconcile our results with the existing benthic foraminiferal Cd/Ca by invoking a decrease in the fraction of the deep ocean nutrient inventory that was preformed, rather than remineralized. This change would have corresponded to an increase in the deep Pacific storage of respired carbon, which would have lowered atmospheric carbon dioxide (CO_2) by sequestering CO_2 away from the atmosphere and by increasing ocean alkalinity through a transient dissolution event in the deep sea. The magnitude of change in preformed nutrients suggested by the North Pacific data would have accounted for a majority of the observed decrease in glacial atmospheric pCO_2.

McKinnell, S. M. and W. R. Crawford, 2007, The 18.6-year lunar nodal cycle and surface temperature variability in the northeast Pacific, *J. Geophys. Res.*. **112**, C02002, doi:10.1016/j.dsr.2008.06.003

The 18.6-year lunar nodal cycle (LNC) is a significant feature of winter (January) air and sea temperatures along the North American west coast over a 400-year period. Yet much of the recent temperature variation can also be explained by wind patterns associated with the PNA teleconnection. At Sitka, Alaska, (57°N) and nearby stations in northern British Columbia, the January PNA index accounts for over 70% of average January air temperatures in lengthy meteorological records. It appears that the LNC signal in January air temperatures in this region is not independent of the PNA, but is a component of it. The Sitka air temperature record, along with SSTs along the British Columbia coast and the PNA index have significant cross-correlations with the LNC that appear at a 2-year lag, LNC leading. The influence of the PNA pattern declines in winter with decreasing latitude but the LNC component does not. It appears as a significant feature of long-term SST variation at Scripps Pier and the California Current

System. The LNC also appears over centennial-scales in proxy temperatures along western North America. The linkage of LNC-moderated surface temperatures to processes involving basin-scale teleconnections expands the possibility that the proximate mechanism may be located remotely from its expression in the northeast Pacific. Some of the largest potential sources of a diurnal tidal signal in the atmosphere are located in the western Pacific; the Sea of Okhotsk and the Indonesian archipelago.

Pena, A. and D. E. Varela, 2007, Seasonal and interannual variability in phytoplankton and nutrient dynamics along Line P in the NE subarctic Pacific, *Prog. Ocean.*, **75**(2): 200-222, doi:10.1016/j.pocean.2007.08.009

We analysed mixed-layer seasonal and interannual variability in phytoplankton biomass and macronutrient (NO_3 and $Si(OH)_4$) concentrations from three decades of observations, and nitrogen uptake rates from the 1990s along Line P in the NE subarctic Pacific. Chlorophyll *a* concentrations near 0.35 mg m^{-3} were observed year-round along Line P except at the nearshore station (P4) where chlorophyll *a* concentrations in spring were on average 2.4 times the winter values. In contrast, the temporal variability in carbon-to-chlorophyll ratios at the two main end members of Line P (P4 and OSP) was high. Large seasonal and interannual variability in NO_3 and $Si(OH)_4$ concentration were observed along Line P. Highest upper mixed-layer (top 15 m) nutrient concentrations occurred on the continental shelf in late summer and early fall due to seasonal coastal upwelling. Beyond the shelf, maximum nutrient concentrations increased gradually offshore, and were highest in late winter and early spring due to mixing by winter storms. Interannual variations in upper mixed-layer nutrient concentrations beyond the shelf (>128°W) were correlated with E–W winds and the PDO since 1988 but were not correlated with either climate index between 1973 and 1981. Despite differences in nutrient concentration, nutrient utilization (ΔNO_3 and $\Delta Si(OH)_4$) during the growing season were about 7.5 μM at all offshore stations. Variations in ΔNO_3 were correlated with those of $\Delta Si(OH)_4$. The annual cycle of absolute NO_3 uptake (ρNO_3) and NH_4 uptake (ρNH_4) rates by phytoplankton in the upper mixed-layer showed a weak increasing trend from winter to spring/summer for the period 1992–1997. Rates were more variable at the nearshore station (P4). Rates of ρNO_3 were low along the entire line despite abundant NO_3 and low iron (Fe), at the offshore portion of Line P and sufficient Fe at the nearshore station (P4). As a result, new production contributed on average to only 32 ± 15% of the total nitrogen (N) uptake along Line P. NO_3 utilization in the NE subarctic Pacific is probably controlled by a combination of environmental variables, including Fe, light and ambient NH_4 levels. Elevated ambient NH_4 concentrations seem to decrease the rates of new production (and *f*-ratios) in surface waters of the oceanic subarctic NE Pacific. Contrary to expectation, phytoplankton biomass, nutrient utilization (ΔNO_3 and $\Delta Si(OH)_4$), and nitrogen uptake ($\rho NO_3 + \rho NH_4$) varied relatively little along Line P, despite significant differences in the factors controlling phytoplankton composition assemblages and production. Future studies would benefit from including other variables, especially light limitation, to

improve our understanding of the seasonal and interannual variability in phytoplankton biomass and nutrients in this region.

Pena, A. and S. J. Bograd, 2007, Time series of the northeast Pacific, *Prog. Ocean.*, **75**(2): 115-119, doi:10.1016/j.pocean.2007.308.008

In July 2006, the North Pacific Marine Science Organization (PICES) and Fisheries & Oceans Canada sponsored the symposium "Time Series of the Northeast Pacific: A symposium to mark the 50th anniversary of Line P". The symposium, which celebrated 50 years of oceanography along Line P and at Ocean Station Papa (OSP), explored the scientific value of the Line P and other long oceanographic time series of the northeast Pacific (NEP). Overviews of the principal NEP time-series were presented, which facilitated regional comparisons and promoted interaction and exchange of information among investigators working in the NEP. More than 80 scientists from 8 countries attended the symposium. This introductory essay is a brief overview of the symposium and the 10 papers that were selected for this special issue of Progress in Oceanography.

Pickart, R. S., A. M. Macdonald, G. W. K. Moore, I. A. Renfrew, J. E. Walsh, and William S. Kessler, 2009, Seasonal Evolution of Aleutian Low Pressure Systems: Implications for the North Pacific Subpolar Circulation, *J. Phys. Oceanogr.*, **39**(6): 1317–1339, doi:10.1175/2008JPO3891.1

The seasonal change in the development of Aleutian low pressure systems from early fall to early winter is analyzed using a combination of meteorological reanalysis fields, satellite sea surface temperature (SST) data, and satellite wind data. The time period of the study is September–December 2002, although results are shown to be representative of the long-term climatology. Characteristics of the storms were documented as they progressed across the North Pacific, including their path, central pressure, deepening rate, and speed of translation. Clear patterns emerged. Storms tended to deepen in two distinct geographical locations—the Gulf of Alaska in early fall and the western North Pacific in late fall. In the Gulf of Alaska, a quasi-permanent "notch" in the SST distribution is argued to be of significance. The signature of the notch is imprinted in the atmosphere, resulting in a region of enhanced cyclonic potential vorticity in the lower troposphere that is conducive for storm development. Later in the season, as winter approaches and the Sea of Okhotsk becomes partially ice covered and cold, the air emanating from the Asian continent leads to enhanced baroclinicity in the region south of Kamchatka. This corresponds to enhanced storm cyclogenesis in that region. Consequently, there is a seasonal westward migration of the dominant lobe of the Aleutian low. The impact of the wind stress curl pattern resulting from these two regions of storm development on the oceanic circulation is investigated using historical hydrography. It is argued that the seasonal bimodal input of cyclonic vorticity from the wind may be partly responsible for the two distinct North Pacific subarctic gyres.

Schallenberg, C., M. R. Lewis, D. E. Kelley, and J. J. Cullen, 2008, Inferred influence of nutrient availability on the relationship between Sun-induced chlorophyll fluorescence

and incident irradiance in the Bering Sea, *J. Geophys. Res.*, **113**, C07046, doi:10.1029/2007JC004355

This study examines variability in the relationship between Sun-induced chlorophyll fluorescence and incident solar irradiance as a potential diagnostic of the nutritional status of phytoplankton. The study site is the Bering Sea, where two optical drifters were caught for more than 100 days in an anticyclonic eddy, while two others provided data from adjacent waters. Estimates of fluorescence emission normalized to the absorption of light by pigments were analyzed as a function of irradiance to describe variability of the quantum yield of fluorescence. Yields in bright sunlight and under lower light varied by a factor of 5 or more on the scale of days to weeks. For the one drifter that remained in the high-velocity region of the eddy, there was a lagged correlation between the eddy rotation period and fluorescence parameters, with higher fluorescence yields in both low and high irradiance associated with slower rotation. Since nutrient input to the photic zone may increase with increasing shear of the eddy flow, this is consistent with the established suggestion that Sun-induced fluorescence increases with nutrient stress in phytoplankton. Independent measurements of variable fluorescence (*Fv*/*Fm*, an indicator of photosynthetic efficiency) further support this interpretation. However, modeling shows that the established hypothesis of competition between photosynthesis and fluorescence for absorbed photons (i.e., photochemical quenching), with high fluorescence yields reflecting photosynthetic debility, does not apply near the sea surface, where photosynthesis is saturated, and dissipation of excess absorbed radiation by nonphotochemical quenching is the dominant influence on fluorescence yield.

Whitney, F. A., H. J. Freeland and M. Robert, 2007, Decreasing oxygen levels in the interior waters of the subarctic Pacific, *Prog. Oceanogr.* **75**(2): 179-199, doi:10.1016/j.pocean.2007.08.007

Fifty years of measurements at Ocean Station Papa (OSP, 50°N, 145° W) show trends in the interior waters of the subarctic Pacific that are both impacted by short term (few years to bi-decadal) atmospheric or ocean circulation oscillations and by persistent climate trends. Between 1956 and 2006, waters below the ocean mixed layer to a depth of at least 1000 m have been warming and losing oxygen. On density surfaces found in the depth range 100–400 m (σ_θ = 26.3–27.0), the ocean is warming at 0.005–0.012 °C y^{-1}, whereas oxygen is declining at 0.39–0.70 µmol kg^{-1} y^{-1} or at an integrated rate of 123 mmol m^{-2} y^{-1} (decrease of 22% over 50 years). During this time, the hypoxic boundary (defined as 60 µmol O_2 kg^{-1}) has shoaled from ~400 to 300 m. In the Alaska Gyre, the 26.2 isopycnal occasionally ventilates, whereas at OSP 26.0 σ_θ has not been seen at the ocean surface since 1971 as the upper ocean continues to stratify. To interpret the 50 year record at OSP, the isopycnal transport of oxygenated waters within the interior of the subarctic Pacific is assessed by using a slightly modified "NO" parameter [Broecker, W., 1974. "NO" a conservative water-mass tracer. Earth and Planetary Science Letters 23, 100–107]. The highest nitrate–oxygen signature in interior waters of the North Pacific is found in the Bering Sea Gyre, Western Subarctic Gyre and East Kamchatka Current region as a consequence of winter

mixing to the ~26.6 isopycnal. By mixing with low NO waters found in the subtropics and Okhotsk Sea, this signature is diluted as waters flow eastward across the Pacific. Evidence of low NO waters flowing north from California is seen along the coasts of British Columbia and SE Alaska. Oxygen in the subsurface waters of the Alaskan Gyre was supplied ~60% by subarctic and 40% by subtropical waters during WOCE surveys, whereas such estimates are shown to periodically vary by 20% at OSP. Other features discernable in the OSP data include periods of increased ventilation of deeper isopycnals on an ~18 year cycle and strong, short term (few month) variability caused by passing mesoscale eddies. The potential impacts of declining oxygen on coastal ecosystems are discussed.

Wong, C. S., L. Xie and W. W. Hsieh, 2007, Variation in nutrients, carbon and other hydrographic parameters related to the 1976/77 and 1988/89 regime shifts in the sub-arctic Northeast Pacific, *Prog. Oceanogr.*, **75**(2): 326-342, doi:10.1016/j.pocean.2007.08.002

For time series at Station P (50°N, 145° W) and stations along Line P, long term changes in eight oceanographic and chemical parameters (sea surface temperature (SST), salinity, oxygen, phosphate (PO_4), silicate (SiO_4), nitrate (NO_3), dissolved inorganic carbon (DIC), and apparent oxygen utilisation (AOU)) were influenced by climate regime shifts with a "step change" of anomalies for nutrients and carbon in the sub-arctic Pacific during the 1976/77 and 1988/89 regime shifts. The presence of regime shifts in the data in the late 1970s and the late 1980s was supported by the statistical test of [Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters 31, L09204, doi:10.1029/2004GL019448], based on the Student *t*-test. The response of nutrients and carbon to the regime shifts was more intensive in 1976/77 than in 1988/89. Salinity, PO_4, SiO_4, NO_3, oxygen and DIC showed positive anomalies during 1950–1975 and negative ones during 1976–1995. The effect of La Niña on nutrients and carbon was larger than that of El Niño. Strong La Niña events (e.g. 1988/89) caused a sudden increase in nutrients and carbon. Two regime shifts (1976/77 and 1988/89) occurred just after two strong La Niña events in 1976/77 and 1988/89. At Station P, upwelling of nutrient-poor subsurface water tended to decrease the nutrients at the surface.

Wong, C. S., J. R. Christian, S.-K. Emmy Wong, J. Page, L. Xie, and S. Johannessen, 2010, Carbon dioxide in surface seawater of the eastern North Pacific Ocean (Line P), 1973–2005, *Deep Sea Research Part I*, **57**(5): 687-695, doi:10.1016/j.dsr.2010.02.003

Partial pressure of CO_2 (pCO_2) in surface seawater has been measured in the northeastern Pacific Ocean at Station P and along Line P since 1973. These data have been divided into 'oceanic' and 'coastal/transition' zones, and the seasonal and interannual variability and the long-term trends for each zone have been examined. The oceanic zone shows little seasonality in surface seawater pCO_2, with undersaturation throughout the year. A strong, biologically-driven seasonal cycle is offset by variation in temperature-dependent solubility of CO_2. The

coastal/transition zone shows a decline in pCO_2 from winter–spring through summer and fall that is likely the result of seasonal stratification and convection rather than coastal upwelling. Interannual variability all along Line P is correlated with the multivariate ENSO index (MEI), with lower seawater pCO_2 associated with El Niño conditions. Correlations with the Pacific Decadal Oscillation Index are similar but weaker, in part because there are few data prior to the 1976 regime shift. The long-term trend in seawater pCO_2 in the oceanic zone is $+1.36 \pm 0.16$ µatm year^{-1}, indistinguishable from the atmospheric growth rate, and varies little among the seasons. In the coastal/transition zone a slow increase in the pCO_2 of surface seawater relative to that of the atmosphere has led to increasing undersaturation, particularly in spring. Aliasing of the seasonal and interannual variability due to sampling frequency may explain part of the observed trend in the coastal/transition zone, but real changes in physical or biological processes are also possible and require more detailed study.

3.3 Modelling

Deng, Z., Y. Tang, and G. Wang, 2010, Assimilation of Argo temperature and salinity profiles using a bias-aware localized EnKF system for the Pacific Ocean, *Ocean Modelling*, **35**(3): 187-205, doi:10.1016/j.ocemod.2010.07.007

In this study, Argo profiles of temperature and salinity for the period from January 2005 to December 2007 are assimilated into a primitive equation model of the Pacific Ocean using a bias-aware localized ensemble Kalman filter (EnKF) with a sequence of 5-day assimilation cycles. Some other in situ observations, including XBT, TAO/TRITON and CTD profiles, used to supplement, are also assimilated into the model. To improve the assimilation performance, several strategies addressing the computational expense and model error statistics are incorporated into the assimilation scheme. Validation is performed by comparing the analyzed ocean states with independent data, including withheld Argo profiles, satellite remote sensing sea level height anomalies (SLA) and the NCEP ocean state re-analysis products. The results show that the assimilation system is capable of significantly reducing the bias and RMSE of ocean temperature and salinity compared with the control run. It can also improve the simulation of zonal currents and SLAs along the equator, especially during strong ENSO events. In addition, a hybrid coupled ENSO prediction model initialized by the assimilation analysis improves the ENSO prediction skill compared against that initialized by the control run without data assimilation.

3.4 Tropical Pacific

Aguilar-Martinez, S. and W. W. Hsieh, 2009, Forecasts of Tropical Pacific Sea Surface Temperatures by Neural Networks and Support Vector Regression, *Int. J. Oceanogr.*, **2009**, doi:10.1155/2009/167239

Two nonlinear regression methods, Bayesian neural network (BNN) and support vector regression (SVR), and linear regression (LR), were used to forecast the tropical Pacific sea surface temperature (SST) anomalies at lead times ranging from 3 to 15 months, using sea level pressure (SLP) and SST as predictors.

Datasets for 1950–2005 and 1980–2005 were studied, with the latter period having the warm water volume (WWV) above the 20 ◦C isotherm integrated across the equatorial Pacific available as an extra predictor.

The forecasts indicated that the nonlinear structure is mainly present in the second PCA (principal component analysis) mode of the SST field. Overall, improvements in forecast skills by the nonlinear models over LR were modest. Although SVR has two structural advantages over neural network models, namely (a) no multiple minima in the optimization process and (b) an error norm robust to outliers in the data, it did not give better overall forecasts than BNN. Addition of WWV as an extra predictor generally increased the forecast skills slightly; however, the influence of WWV on SST anomalies in the tropical Pacific appears to be linear.

Cannon, A. J. and W. W. Hsieh, Robust nonlinear canonical correlation analysis: application to seasonal climate forecasting, *Nonlin. Processes Geophys.*, **15:** 221-232, doi:10.5194/npg-15-221-2008

Robust variants of nonlinear canonical correlation analysis (NLCCA) are introduced to improve performance on datasets with low signal-to-noise ratios, for example those encountered when making seasonal climate forecasts. The neural network model architecture of standard NLCCA is kept intact, but the cost functions used to set the model parameters are replaced with more robust variants. The Pearson product-moment correlation in the double-barreled network is replaced by the biweight midcorrelation, and the mean squared error (mse) in the inverse mapping networks can be replaced by the mean absolute error (mae). Robust variants of NLCCA are demonstrated on a synthetic dataset and are used to forecast sea surface temperatures in the tropical Pacific Ocean based on the sea level pressure field. Results suggest that adoption of the biweight midcorrelation can lead to improved performance, especially when a strong, common event exists in both predictor/predictand datasets. Replacing the mse by the mae leads to improved performance on the synthetic dataset, but not on the climate dataset except at the longest lead time, which suggests that the appropriate cost function for the inverse mapping networks is more problem dependent.

Choi, J., S.-I. An, B. Dewitte, and W.W. Hsieh, 2009, Interactive feedback between the tropical Pacific Decadel Oscillation and ENSO in a coupled general circulation model, *J. Clim.*, **22**: 6597-6611, doi:10.1175/2009JCLI2782.1

The output from a coupled general circulation model (CGCM) is used to develop evidence showing that the tropical Pacific decadal oscillation can be driven by an interaction between the El Niño–Southern Oscillation (ENSO) and the slowly varying mean background climate state. The analysis verifies that the decadal changes in the mean states are attributed largely to decadal changes in ENSO statistics through nonlinear rectification. This is seen because the time evolutions of the first principal component analysis (PCA) mode of the decadal-varying tropical Pacific SST and the thermocline depth anomalies are significantly correlated to the decadal variations of the ENSO amplitude (also skewness). Its

spatial pattern resembles the residuals of the SST and thermocline depth anomalies after there is uneven compensation from El Niño and La Niña events. In addition, the stability analysis of a linearized intermediate ocean–atmosphere coupled system, for which the background mean states are specified, provides qualitatively consistent results compared to the CGCM in terms of the relationship between changes in the background mean states and the characteristics of ENSO. It is also shown from the stability analysis as well as the time integration of a nonlinear version of the intermediate coupled model that the mean SST for the high-variability ENSO decades acts to intensify the ENSO variability, while the mean thermocline depth for the same decades acts to suppress the ENSO activity. Thus, there may be an interactive feedback consisting of a positive feedback between the ENSO activity and the mean state of the SST and a negative feedback between the ENSO activity and the mean state of the thermocline depth. This feedback may lead to the tropical decadal oscillation, without the need to invoke any external mechanisms.

Christian, J. R., R. A. Feely, M. Ishii, R. Murtugudde, and X. Wang, 2008, Testing an ocean carbon model with observed sea surface pCO2 and DIC in the tropical Pacific Ocean, *J. Geophys. Res.*, **113**, C07047, doi:10.1029/2007JC004428

A basin-scale carbon model for the tropical Pacific has been tested against in situ observations of CO_2 partial pressure (pCO_2) and dissolved inorganic carbon. Best agreement between model and observations occurs when gas exchange is enhanced at low wind speeds and when frictional smoothing as a parameterization of mesoscale eddy stirring/mixing is minimal. However, different realizations of the biological pump are not equally sensitive to the friction parameters, and it is not possible to completely isolate the effects of physics and biology. The model ocean shows substantial interannual variability in pCO_2 and CO_2 flux which is strongly correlated with the Multivariate ENSO Index. Interannual variability is similar to other models and suggests a relatively small role for the ocean in interannual variability of atmospheric CO_2 growth. There are significant areas where CO_2 remained supersaturated throughout the 1997–1998 El Niño and there was net outgassing from the "Wyrtki Box" at all times, but the net flux from the full model domain was near zero at the peak of the event. Testing the model against ship-based observations produces a credible four-dimensional field of the tropical ocean carbon system. Sampling this field with methods analogous to those used in empirical reconstructions of CO_2 flux suggests that those methods can underestimate the interannual variability by up to a factor of ~2.5 depending on the grid resolution used. Models and observations are not currently adequate to state with confidence that undersampled mesoscale variability does not affect the variability of the regional aggregate flux.

Deng, Z. and Y. Tang, 2009, Reconstructing the Past Wind Stresses over the Tropical Pacific Ocean from 1875 to 1947, *J. Appl. Meteor. Climatol.*, **48**(6): 1181–1198, doi:10.1175/2008JAMC2049.1

An important step in understanding the climate system is simulating and studying the past climate variability, using oceanic models, atmospheric models, or both.

Toward this goal, long-term wind stress data, as the forcing of oceanic or climate models, are often required. In this study, the possibility of reconstructing the past winds of the tropical Pacific Ocean using historical sea surface temperature (SST) and sea level pressure (SLP) datasets was explored. Four statistical models, based on principal component (PC) regression and singular vector decomposition (SVD), were developed for reconstructing monthly pseudo wind stress over the tropical Pacific for the period 1875–1947. The high-frequency noise was removed from the raw data prior to the reconstruction. These models are SST-based PC regression (model 1), SLP-based PC regression (model 2), SST-based SVD (model 3), and SLP-based SVD (model 4). The results show that reconstructed wind stresses from all models can account for more than one-half of the total variances. In general, the SLP is better than SST as a predictor and the SVD method is superior to the PC regression. Forced by these reconstructed wind stresses, an oceanic general circulation model can simulate realistic interannual variability of the tropical Pacific SST. However, the wind stress reconstructed by SST-based models leads to better simulation skill in comparison with that from SLP-based models. Last, a long-term wind stress dataset was constructed for the period from 1875 to 1947 by the SST-based SVD model, which provides a useful tool for studying the past climate variability over the tropical Pacific, especially for El Niño–Southern Oscillation.

Kienast, M., M. Lehmann, A. Timmermann, E. Galbraith, T. Bolliet, A. Holbourn, C. Normandeau, and C. Laj, 2008, A mid-Holocene transition in the nitrogen dynamics of the western equatorial Pacific: Evidence of a deepening thermocline? *Geophys. Res. Lett.*, **35**, L23610, doi:10.1029/2008GL035464

Sedimentary $\delta^{15}N$ records from the oligotrophic western equatorial Pacific (WEP) off Mindanao show that late Holocene sedimentary $\delta^{15}N$ is substantially lower than that of the early Holocene, following a gradual >3 ‰ decrease that occurred between 7 and 3 kyrs ago. Analyses of modern day nitrate isotope profiles from the same region indicate the sensitivity of the WEP N pools towards (1) the advection of ^{15}N-enriched nitrate from the Eastern Equatorial Pacific (EEP) by the North Equatorial Current (NEC) and the Mindanao Current in subsurface waters and, (2) at shallow depths, the input of new and ^{15}N-depleted nitrate through N_2 fixation. We suggest that the Holocene decrease in sedimentary $\delta^{15}N$ reflects a diminished relative input of ^{15}N-enriched nitrate to the surface biota, either through an increase of regional nitrogen fixation, a change in nitrate consumption along the advective path of nitrate supply, or a decrease in the vertical supply of ^{15}N-enriched nitrate from the NEC. The latter mechanism is consistent with a Holocene deepening of the WEP nitracline/thermocline.

Kissel, C., C. Laj, M. Kienast, T. Bollet, A. Holbourn, P. Hill, W. Kuhnt, and P. Braconnot, 2010, Monsoon variability and deep oceanic circulation in the western equatorial Pacific over the last climatic cycle: Insights from sedimentary magnetic properties and sortable silt, *Paleoceanography*, **25**, PA3215, doi:10.1029/2010PA001980

Magnetic and grain size properties of a sediment core located in the western equatorial Pacific, off the southeastern tip of the Philippine island of Mindanao,

are presented in an effort to reconstruct past changes in the East Asian Monsoon and deep ocean circulation during the last 160 kyrs. The sedimentary concentration of magnetic particles, interpreted to reflect past changes in runoff from Mindanao, varies almost in antiphase with Northern Hemisphere insolation. This suggests that precipitation was lower in the western equatorial Pacific region during boreal insolation maxima and thus corroborates model results showing opposing trends in precipitation between land and the marine realm there. Variations in the grain size distribution of the inorganic sediment fraction, as recorded by both the sortable silt mean size and the magnetic grain size, provide a monitor of changes in sediment reworking by bottom currents. The close correlation of this proxy of bottom current strength and the benthic d18O record from the same site implies a tight coupling between deep water flow, most likely Antarctic Intermediate Water (AAIW), and global climate.

Tang, Y. and Z. Deng, 2010a, Tropical Pacific upper ocean heat content variations and ENSO predictability during the period from 1881-2000, *Advance in Geosciences*, 18: 87-108

In this study, a long-term analysis of the tropical Pacific upper ocean heat content (HC) was obtained for the period from 1881–2000, by assimilating historic sea surface temperature dataset into an oceanic general circulation model (OGCM) with Ensemble Kalman filter. The validation against the NCEP (National Center of Environmental Prediction) HC and the observed HC indicates that the analyzed HC captures very well the large-scale observed features of HC. There exists a striking interannual variability in the tropical Pacific upper ocean HC anomalies (HCA). Like ENSO (El Ni˜no and the Southern Oscillation), the HCA interannual variability also has a significant interdecadal variation. The interdecadal variation in the HCA causes the interdecadal variation in the lagged correlation between the HCA of the equatorial western Pacific ocean and the SSTA (sea surface temperature anomalies) of the equatorial eastern Pacific, which in turn affects ENSO prediction skill (Ni˜no3.4 SSTA). The long-term retrospective ENSO prediction from 1881–2000 by the model supported the above conclusion.

Turk, D., C. J. Zappa, C. S. Meinen, J. R. Christian, D. T. Ho, A. G. Dickson, and W. R. McGillis, 2010, Rain impacts on CO_2 exchange in the western equatorial Pacific Ocean, *Geophys. Res. Lett.*, **37**, L23610, doi:10.1029/2010GL045520

The ocean plays a major role in the global carbon cycle through the atmosphere-ocean partitioning of atmospheric carbon dioxide. Rain alters the physics and carbon chemistry at the ocean surface to increase the amount of CO_2 taken up by the ocean. This paper presents the results of a preliminary study wherein rain measurements in the western equatorial Pacific are used to determine the enhanced transfer, chemical dilution and deposition effects of rain on air-sea CO_2 exchange. Including these processes, the western equatorial Pacific CO_2 flux is modified from an ocean source of +0.019 mol CO_2 m^{-2} yr^{-1} to an ocean sink of −0.078 mol CO_2 m^{-2} yr^{-1}. This new understanding of rain effects changes the ocean's role in the global carbon budget, particularly in regions with low winds and high precipitation.

Ye, Z. and W. W. Hsieh, 2008a, Enhancing predictability by increasing nonlinearity in ENSO and Lorenz systems, *Nonlin. Processes Geophys.*, **15**: 793-801, doi:10.5194/npg-15-793-2008

The presence of nonlinear terms in the governing equations of a dynamical system usually leads to the loss of predictability, e.g. in numerical weather prediction. However, for the El Niño-Southern Oscillation (ENSO) phenomenon, in an intermediate coupled equatorial Pacific model run under the 1961–1975 and the 1981–1995 climatologies, the latter climatology led to longer-period oscillations, thus greater predictability. In the Lorenz (1963) 3-component chaos system, by adjusting the model parameters to increase the nonlinearity of the system, a similar increase in predictability was found. Thus in the ENSO and Lorenz systems, enhanced nonlinearity from changes in the governing equations could produce longer period oscillations with increased predictability.

Ye, Z. and W. W. Hsieh, 2008b, ENSO and associated overturning circulations from enhanced greenhouse gases, *J. Clim.*, 21:5745-5763

With data from 12 coupled models in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), climate under year 2000 greenhouse gas (GHG) + aerosol forcing was compared with climate under preindustrial conditions. In the tropical Pacific, the warming in the mean sea surface temperatures (SST) was found to have an El Niño–like pattern, while both the equatorial zonal overturning circulation and the meridional overturning circulation weakened under increased GHG forcing.

For the El Niño–Southern Oscillation (ENSO), the asymmetry in the SST anomalies between El Niño and La Niña was found to be enhanced under increased GHG, for both the ensemble model data and the observed data (1900–99). Enhanced asymmetry between El Niño and La Niña was also manifested in the anomalies of the zonal wind stress, the equatorial undercurrent, and the meridional overturning circulation in the increased GHG simulations. The enhanced asymmetry in the model SST anomalies was mainly caused by the greatly intensified vertical nonlinear dynamic heating (NDH) anomaly (i.e., product of the vertical velocity anomaly and the negative vertical temperature gradient anomaly) during El Niño (but not during La Niña). Under increased GHG, the enhanced positive NDH anomalies during El Niño, when time averaged over the whole record, would change the SST mean state by an El Niño–like pattern.

Zhang, X., Y. Lu, and K. R. Thompson, 2009, Sea level variations in the tropical Pacific Ocean and the Madden-Julian Oscillation, *J. Phys. Oceanogr.*, **39**(8): 1984-1992, doi:10.1029/2009JC005734

A global ocean circulation model is used to examine the dynamical response of the tropical Pacific Ocean to forcing associated with the Madden-Julian Oscillation (MJO). Model sensitivity experiments first reveal that MJO-related changes in sea level are caused primarily by changes in wind stress. Further, the

MJO-related changes in sea surface temperature (SST) are mainly caused by buoyancy (heat) flux in the Indian Ocean, by wind stress in the central tropical Pacific, and by both buoyancy flux and wind stress in the eastern tropical Pacific. Additional model sensitivity studies quantify the tropical Pacific Ocean response to MJO wind forcing. The simulations reveal that the subsurface temperature variations associated with the MJO propagate eastward along the thermocline and rise to the surface in the eastern Pacific. Zonal advection plays a dominant role in SST variation in the central Pacific; vertical advection plays an important role in the evolution of subsurface and surface temperatures in the eastern Pacific. Finally, it is shown that MJO wind forcing can rectify SST variations through nonlinear interactions of the intraseasonal variations of the zonal currents and the zonal SST gradient.

Zhang, X., Y. Lu, K. R. Thompson, J. Jiang, and H. Ritchie, 2010, Tropical Pacific Ocean and the Madden-Julian Oscillation: Role of wind and buoyancy forcing, *J. Geophys. Res.*, **115**, C05022, doi:10.1029/2009JC005734

A global ocean circulation model is used to examine the dynamical response of the tropical Pacific Ocean to forcing associated with the Madden-Julian Oscillation (MJO). Model sensitivity experiments first reveal that MJO-related changes in sea level are caused primarily by changes in wind stress. Further, the MJO-related changes in sea surface temperature (SST) are mainly caused by buoyancy (heat) flux in the Indian Ocean, by wind stress in the central tropical Pacific, and by both buoyancy flux and wind stress in the eastern tropical Pacific. Additional model sensitivity studies quantify the tropical Pacific Ocean response to MJO wind forcing. The simulations reveal that the subsurface temperature variations associated with the MJO propagate eastward along the thermocline and rise to the surface in the eastern Pacific. Zonal advection plays a dominant role in SST variation in the central Pacific; vertical advection plays an important role in the evolution of subsurface and surface temperatures in the eastern Pacific. Finally, it is shown that MJO wind forcing can rectify SST variations through nonlinear interactions of the intraseasonal variations of the zonal currents and the zonal SST gradient.

3.5 Western Pacific

Han, G. and W. Huang, 2008, Pacific Decadal Oscillation and Sea Level Variability in the Bohai, Yellow, and East China Seas, *J. Phys. Oceanogr.*, **38**(12): 2772–2783

Sea level variability off East China has been investigated based primarily on 10 years of Ocean Topography Experiment (TOPEX)/Poseidon altimetry data. The altimetric annual harmonic has a magnitude of 10 to 30 cm in amplitude and is highest in summer, agreeing well with independent tide-gauge data. After the inverse barometer effect is removed, the annual sea level cycle can be approximately accounted for by the steric height variation. Significant interannual sea level change was also observed from altimetry and tide-gauge data, with a range of ~10 cm. The interannual and longer-term sea level variability in the altimetric data are negatively correlated (significant at the 95% confidence level) with the Pacific decadal oscillation (PDO), attributed in part to steric height

change. The altimetric sea level rise rate is 0.64 cm yr^{-1} for the period from 1992 to 2002, consistent with the tide-gauge rate of 0.6 cm yr^{-1}. These values are much larger than the rate of 0.24 cm yr^{-1} observed at the same tide gauges but for the period from 1980 to 2002, implying the sensitivity to the length of data as a result of the decadal variability. The potential role of the PDO in the interannual and longer-term sea level variability is discussed in terms of regional manifestations such as the ocean temperature and salinity and the Kuroshio transport.

Han G. and W. Huang: Low-frequency sea level variability in the South China Sea and its relationship with ENSO, *Theoretical and Applied Climatology*, **97**: 41-52, doi:10.1007/s00704-008-0070-0

Sea-level variability in the South China Sea was investigated based on satellite altimetry, tide-gauge data, and temperature and salinity climatology. The altimetric sea-level results clearly reveal three distinct amphidromes associated with the annual cycle. The annual sea level is higher in fall/winter in the coast and shelf region and lower in summer/fall in the central sea, agreeing well with independent tide-gauge data. Averaged over the deep basin (bottom depth > 2,000 m), the annual cycle can be approximately accounted for by the steric height relative to 700 db. Significant interannual sea-level change is observed from altimetry and tide-gauge data. The interannual and longer-term sea-level variability in the altimetric data is negatively correlated (significant at the 95% confidence level) with the El Niño - Southern Oscillation (ENSO), attributed in part to the steric height change. The altimetric sea-level rise rate is 1.0 cm/year for the period from 1993 to 2001, which is consistent with the rate derived from coastal tide-gauge data and approximately accountable for by the steric height calculated relative to 700 db. The tide-gauge sea-level (steric height) rise rate of 1.05 (0.9) cm/year from 1993 to 2001 is much larger than that of 0.22 (0.12) cm/year for the period from 1979 to 2001, implying the sensitivity to the length of data as a result of the decadal variability. Potential roles of the ENSO in the interannual and longer-term sea-level variability are discussed in terms of regional manifestations such as the ocean temperature and salinity.

Kang, S. K., Cherniawsky, J. Y., M. G. G. Foreman, J.-K. So, and S. R. Lee, 2008, Spatial variability in annual sea level variations around the Korean peninsula, *Geophys. Res. Lett.* 35, L03603, doi:10.1029/2007GL032527

Analyses of annual sea level variations (Sa) around the Korean peninsula reveal systematic spatial patterns in the phase lags and amplitudes. Sa amplitudes in this region vary between 10 and 20 cm, with atmospheric pressure accounting for only 7.7 to 9.4 cm. These patterns are dominated by annual changes in thermosteric sea levels in the Yellow Sea (YS) and East/Japan Sea (EJS), with only minor contributions from seasonal wind-driven set up.

Rabinovich, A. B., G. V. Shevchenko, and R. E. Thomson, 2007, Sea-ice and current response to the wind: a vector regressional analysis approach, *J. Atmos. Oceanic Tech.*, **24**: 1086-1101, doi:10.1175/JTECH2015.1

The authors describe a two-dimensional (vector) regressional model for examining the anisotropic response of ice drift and ocean current velocity ("drift velocity") to surface wind forcing. Illustration of the method is limited to sea ice response. The principal mathematical and physical properties of the model are outlined, together with estimates of the "response matrices" and the corresponding "response ellipses" (drift velocity response to a unity wind velocity forcing). For each direction, φ, of the wind vector the method describes a corresponding "wind factor" $\alpha(\varphi)$ (relative drift speed) and "turning angle" $\theta(\varphi)$ (the angle between the drift velocity and wind vector). The major ellipse axis corresponds to the direction of the "effective wind" ($\varphi = \varphi_{max}$) and the minor axis to the direction of the "noneffective" wind. The eigenvectors of the response matrix define wind directions that are the same as the wind-induced drift velocity directions. Depending on the water depth and offshore distance, six analytical cases are possible, ranging from rectilinear response ellipses near the coast to purely circular response ellipses in the open ocean. The model is used to examine ice drift along the western shelf of Sakhalin Island (Sea of Okhotsk). Responses derived from the vector regression (four parameter) method are less constrained and therefore more representative of wind-induced surface motions than those derived using the traditional complex transfer function (two parameter) approach.

Rogachev, K., E. Carmack and M. Foreman, 2008, Bowhead whales feed on plankton concentrated by estuarine and tidal currents in Academy Bay, Sea of Okhotsk, *Cont. Shelf Res.*, **28**(14): 1811-1826, doi:10.1016/j.csr.2008.04.014

Academy Bay in the Sea of Okhotsk is an important summertime feeding ground for pelagic-feeding Bowhead whales (*Balaena mysticetus*) in the western subarctic North Pacific. The present work combines satellite observations with physical (CTD, currents, tides) and biological (zooplankton sampling) measurements. Data obtained aboard the *RV Lugovoe* in August–September 2003 and July–August 2004 show dense populations of zooplankton (such as copepods *Calanus glacialis*, *Pseudocalanus* sp., pteropods *Limacina helicina*, and chaetognaths *Sagitta* sp.) that are concentrated by physical mechanisms within this critically important ecosystem. We show that near-bottom, cold water intrusions from the northern Sea of Okhotsk associated with the estuarine circulation advect arctic herbivorous calanoids (*Calanus glacialis*) and mollusks *Limacina helicina* into the region.

Satellite and in situ observations that include conductivity–temperature–depth (CTD) data and measurements of tidal currents are used to study the nature of the estuarine circulation. Results show an anticyclonic circulation, associated with the effect of earth's rotation. An analytical model shows horizontally convergent flows in the lower layer toward the western coast of the bay that push water upward along the steep slope. This together with zooplankton vertical migration leads to aggregation. Thus the combination of the residual eddy formation and swimming behavior act to concentrate zooplankton near the cape and to provide the necessary densities of planktonic food supply for Bowhead whales.

Steinke, S., M. Kienast, J. Groeneveld, L. -C. Lin, M.-T. Chen, and R. Rendle-Buhring, 2008, Proxy dependence of the temporal pattern of deglacial warming in the tropical South China Sea: Toward resolving seasonality, *Quat. Sci.. Rev.*, **27**(7-8): 688 - 700, doi:10.1016/j.quascirev.2007.12.003

Sea surface temperatures (SSTs), reconstructed from two *Globigerinoides ruber* (white) morphotypes (*G. ruber* sensu stricto, (s.s.); *G. ruber* sensu lato, (s.l.)) Mg/Ca and alkenones ($U^{K'}_{37}$) from core MD01-2390 from the tropical South China Sea (SCS) during the last deglaciation reveal a proxy-dependent discrepancy in the temporal pattern of the deglacial warming. Alkenone data suggest that the deglacial warming is punctuated by a decrease in temperature between ~17 and 15 ka BP, corroborating previously published alkenone $U^{K'}_{37}$ SST records from the southern SCS. Within dating uncertainties, this cooling is coeval with the Heinrich Event 1 (H1) time interval in the North Atlantic region, underscoring the imprints of northern hemisphere forcing on tropical SCS ocean temperatures. The deglacial $U^{K'}_{37}$ SST minimum is also paralleled by a maximum in *G. ruber* morphotype-specific $\delta^{18}O$. *G. ruber* Mg/Ca SST estimates suggest a morphotype-specific record of SSTs during the time interval of H1. Whereas *G. ruber* s.s. imply a continuous warming starting around 18 ka BP without any marked response to H1, *G. ruber* s.l.-based Mg/Ca SST estimates reveal a cooling around ~17–15 ka BP similar to the H1 interval cooling seen in the alkenone SST record. Similar proxy-dependent differences in deglacial surface water warming have been recorded in the eastern equatorial Pacific, implying a common pattern on both sides of the tropical Pacific Ocean. We submit that this discrepancy could be due to differences in seasonality of planktonic foraminifera *G. ruber* morphotypes and alkenone-producing algae.

Yamazaki, H., I. Iwamatsu, D. Hasegawa, and T. Nagai, 2009, Chlorophyll Patches Observed during Summer in the Main Stream of the Kuroshio, *Atmos.-Ocean*, **47**(4): 299–307, doi:10.3137/OC306.2009

Two transects through the Oyashio-Kuroshio frontal region were made off the coast of Japan using a towed CTD-fluorometer (Aquashuttle). These show numerous patches of elevated chlorophyll concentration adjacent to the Kuroshio front. In particular, a few patches are found in the main stream of the Kuroshio. Making use of the Temperature and Salinity (T-S) properties of the identified patches, the origin of the patches is inferred. It is confirmed that the patches appearing in the Kuroshio are not from the adjacent coastal waters. Their T-S properties are similar to those in the upstream portion of the Kuroshio. These facts suggest that the elevated level of chlorophyll in the patches arise because of mixing that occurs while the Kuroshio passes over the Izu Ridge. The patches found in the main stream of the Kuroshio are transported to the Kuroshio extension, which is the nursery ground for many pelagic larval fish. These patches, if they appear during the spawning season, may provide food for these larval fish. Thus mixing due to bottom topography and islands of the Izu Ridge may play an important role for the survival of larval fish downstream, in the region of the Kuroshio extension.

3.6 Biophysical Processes

Fennel, K., 2008, Widespread implementation of controlled upwelling in the North Pacific Subtropical Gyre would counteract diazotrophic N2 fixation, *Mar. Ecol. Prog. Ser.*, **371**: 301-303, doi:10.3354/meps07772

Karl & Letelier (2008; Mar Ecol Prog Ser 364:257–268) examined the stimulation of diazotrophic N_2 fixation by controlled upwelling of deep-water nutrients as a potential carbon sequestration strategy in low-nutrient, low-chlorophyll regions such as the North Pacific Subtropical Gyre. They did not examine the effect of buoyancy on vertical stratification. Since seawater upwelled from depth is colder and saltier, and therefore denser than surface water, it would have to be diluted sufficiently to prevent its convective sinking. This dilution would lead to a decrease in vertical stratification, which could counteract N_2 fixation, as diazotrophs bloom only under well-stratified conditions. A back-of-the-envelope calculation of the effect of large-scale controlled upwelling on upper ocean stratification shows that controlled upwelling is unlikely to scale up and serve as a climate stabilization wedge as defined by Pacala & Socolow (2004; Science 305:968–972), i.e. it would not sequester 1 Gt C yr^{-1} over 30 yr.

Harris, S. L., D. E. Varela, F. W. Whitney, and P. J. Harrison, 2009, Nutrient and phytoplankton dynamics off the west coast of Vancouver Island during the 1997/98 ENSO event, *Deep Sea Res. Part II*, **56**(24): 2487-2502, doi:10.1016/j.dsr2.2009.02.009

Six research cruises were conducted off the west coast of Vancouver Island between April and October of 1997 and 1998 as part of the Canadian GLOBEC project to compare nutrient and phytoplankton dynamics between ENSO (1997) and non-ENSO (1998) years. Limited sampling also was conducted during three cruises in 1999. During the 1997 ENSO period, there was a shallow thermocline (~10 m) that resulted in a shallower mixed layer, lower salinity and density, and stronger summer stratification. In general on the shelf, the 1997 growing season was characterized by higher nitrate (7.5 μM) and silicic acid (17 μM) concentrations, lower total chlorophyll (~76 mg m^{-2}), lower phytoplankton carbon biomass (0.2 mg C L^{-1}), and lower diatom abundance and biomass than in 1998. Phytoplankton assemblages were dominated by nanoplankton in 1997 and by diatoms in 1998. These results suggest that the 1997 ENSO was responsible for a reduction in the growth and biomass of larger phytoplankton cells. In mid-1998, the hydrographic characteristics off the west coast of Vancouver Island changed suddenly. The 1997 poleward transport of warm water reversed to an equatorward transport of coastal water in July 1998, which was accompanied by normal summer upwelling. During 1998, a large diatom bloom (mainly dominated by *Chaetoceros debilis*, *Leptocylindrus danicus* and to a lesser extent by *Skeletomema* and *Pseudo-nitzschia* sp.) was observed in July over the continental shelf. This large bloom resulted in chlorophyll concentrations of up to 400 mg m^{-2}, primary productivity of up to 11 g C m^{-2} d^{-1}, and near undetectable dissolved nitrogen concentrations at some of the shelf stations in 1998. In contrast, during 1997, the sub-tropical waters that were advected over the slope, resulted in low chlorophyll *a* and primary productivity (generally <1 g C m^{-2} d^{-1}).

Therefore, there was a sharp contrast between the very high primary productivity on the shelf in July 1998, due to normal nutrient replenishment from summer upwelling and outflow from the Strait of Juan de Fuca, and the lower primary productivity during the 1997 ENSO year. During 1998, non-ENSO conditions resulted in phytoplankton biomass that was twice as high on the shelf as that measured in regions beyond the continental shelf of the west coast of Vancouver Island.

Ryan, J. P., J. F. R. Gower, S. A. King, W. P. Bissett, A. M. Fischer, R. M. Kudela, Z. Kolber, F. Mazzillo, E. V. Rienecker, and F. P. Chavez, 2008, A coastal ocean extreme bloom incubator, *Geophys. Res. Lett.*, **35**, L12602, doi:10.1029/2008GL034081

Novel remote sensing methods and in situ observations reveal that intense dinoflagellate blooms occur frequently in Monterey Bay, California. Blooms can contain surface chlorophyll concentrations exceeding 500 μg l^{-1} and occupy ~5 to 80 km^2. They occur primarily during August through November and can persist for > 1 month. Maximum bloom frequency and mean intensity are in a shallow (< 25 m depth) area of the northeastern bay, in coincidence with the warmest surface water, low wind stress, and retentive circulation. These conditions favor dinoflagellates, which can vertically migrate to acquire nutrients in the thermocline and aggregate as "red tide" near the surface. Bloom incubation areas, also indicated in other coastal upwelling systems, may disproportionately influence regional bloom ecology.

Ryan, J. P., A. M. Fischer, R. M. Kudela, J. F. R. Gower, S. A. King, R. Marin III, and F. P. Chavez, 2009, Influences of upwelling and downwelling winds on red tide bloom dynamics in Monterey Bay, California, *Cont. Shelf Res.*, **29**(5-6): 785-795, doi:10.1016/j.csr.2008.11.006

It has recently been shown that inner shelf waters of NE Monterey Bay, California function as an "extreme bloom incubator", frequently developing dense "red tide" blooms that can rapidly spread. Located within the California Current upwelling system, this open bay is strongly influenced by oceanographic dynamics resulting from cycles of upwelling favorable winds and their relaxation and/or reversal. Different wind forcing causes influx of different water types that originate outside the bay: cold nutrient-rich waters during upwelling and warm nutrient-poor waters during relaxation. In this study, we examine how the bay's bloom incubation area can interact with highly variable circulation to cause red tide spreading, dispersal and retention. This examination of processes is supported by satellite, airborne and in situ observations of a major dinoflagellate bloom during August and September of 2004. Remote sensing of high spatial, temporal and spectral resolution shows that the bloom originated in the NE bay, where it was highly concentrated in a narrow band along a thermal front. Upwelling circulation rapidly spread part of the bloom, mixing cool waters of an upwelling filament with warm bloom source waters as they spread. Vertical migration of the dinoflagellate populations was mapped by autonomous underwater vehicle surveys through the spreading bloom. Following bloom expansion, a two-day wind reversal forced intrusion of warm offshore waters that dispersed much of the

bloom. Upwelling winds then resumed, and the bloom was further dispersed by an influx of cold water. Throughout these oceanographic responses to changing winds, an intense bloom persisted in sheltered waters of the NE bay, where extreme blooms are most frequent and intense. Microscopic examination of surface phytoplankton samples from the central bay showed that spreading of the bloom from the NE bay and mixing with regional water masses resulted in significantly increased abundance of dinoflagellates and decreased abundance of diatoms. Similar dinoflagellate bloom incubation sites are indicated in other areas of the California Current system and other coastal upwelling systems. Through frequent bloom development and along-coast transports, relatively small incubation sites may significantly influence larger regions of the coastal marine ecosystems in which they reside.

3.7 Abyssal Flows

Thomson, R. E., E. E. Davis, M. Heesemann, and H. Villinger, 2010, Observations of long-duration episodic bottom currents in the Middle America Trench: Evidence for tidally initiated turbidity flows, *J. Geophys. Res.*, **115**, C10020, doi:10.1029/2010JC006166

Benthic flow in the Middle America Trench off the Pacific coast of Costa Rica is examined using time series from a single-point acoustic current meter moored 21 m above bottom at 4386 m depth at the southern end of the trench from November 2005 to April 2007. In addition to significant (~0.1 m s^{-1}) tidal currents, the instrument recorded a series of 12 episodic northwestward along-trench flow events of roughly monthly duration. Event velocities often exceeded 0.25 m s^{-1} and were contemporary with enhanced acoustic backscatter intensity. Events ended with a rapid (<1 day) reversal to southeastward flow and reduced backscatter. Seafloor temperature records from two nearby Ocean Drilling Program (ODP) borehole observatory sites reveal that the flow events were accompanied by a steady rise in bottom water temperature. Temperatures dropped abruptly to background values at the end of each event. The event timing generally tracked the envelope of the tidal current modulation. On the basis of the November 2002 to February 2009 borehole observatory temperature records, the events had a mean duration of 40(±20) days and were separated by a between-event interlude of 30(±25) days. Findings indicate that the episodic flows were likely rotationally modified, autosuspending turbidity currents initiated by tidal current resuspension of sediments above the shoaling trench floor to the southeast of the mooring site. Suspended particles in the turbidity currents are estimated to range from 0.0003% to 0.006% of the current by volume. Results suggest that tidally induced turbidity currents may be common to steep, well-mixed regions of the deep ocean adjacent to sediment rich continental margins.

3.8 Atmosphere-Ocean

Merryfield, W. J., B. Pal, and M. G. G. Foreman (2009), Projected future changes in surface marine winds off the west coast of Canada, *J. Geophys. Res.*, **114**, C06008, doi:10.1029/2008JC005123

Projected future changes in the seasonal climatology of surface marine winds at locations off the west coast of Canada having long records of buoy wind observations are evaluated, drawing on output from 18 climate models. The ensemble mean modeled wind climatology for a late 20th century control period 1976–1995 is found to reproduce that of the buoy observations reasonably well, except where local orographic influences not resolved by the models are strong. Over the 21st century, ensemble mean summertime upwelling favorable winds increase in speed by 5–10% and rotate clockwise by ≈5°, statistically significant changes. By contrast, 21st century changes in ensemble mean wintertime downwelling favorable winds are not statistically significant. These trends are too weak to be detectable in the 20th century buoy observations.

Vagle, S., C. McNeil, and N. Steiner, 2010, Upper ocean bubble measurements from the NE Pacific and estimates of their role in air-sea gas transfer of the weakly soluble gases nitrogen and oxygen, *J. Geophys. Res.*, **115**, C12054, doi:10.1029/2009JC005990

Simultaneous observations of upper-ocean bubble clouds, and dissolved gaseous nitrogen (N_2) and oxygen (O_2) from three winter storms are presented and analyzed. The data were collected on the Canadian Surface Ocean Lower Atmosphere Study (C-SOLAS) mooring located near Ocean Station Papa (OSP) at 50°N, 145°W in the NE Pacific during winter of 2003/2004. The bubble field was measured using an upward looking 200 kHz echosounder. Direct estimates of bubble mediated gas fluxes were made using assumed bubble size spectra and the upward looking echosounder data. A one-dimensional biogeochemical model was used to help compare data and various existing models of bubble mediated air-sea gas exchange. The direct bubble flux calculations show an approximate quadratic/cubic dependence on mean bubble penetration depth. After scaling from N_2/O_2 to carbon dioxide, near surface, nonsupersaturating, air-sea transfer rates, K_T, for $U_{10} > 12$ m s^{-1} fall between quadratic and cubic relationships. Estimates of the subsurface bubble induced air injection flux, V_T, show an approximate quadratic/cubic dependence on mean bubble penetration depth. Both K_T and V_T are much higher than those measured during Hurricane Frances over the wind speed range $12 < U_{10} < 23$ m s^{-1}. This result implies that over the open ocean and this wind speed range, older and more developed seas which occur during winter storms are more effective in exchanging gases between the atmosphere and ocean than younger less developed seas which occur during the rapid passage of a hurricane.

3.9 Waves

Huang, Y., B. Yin, and W. Perrie, 2008, Responses of summertime extreme wave heights to local climate variations in the East China Sea, *J. Geophys. Res.*, **113**, C09031. doi:10.1029/2008JC004732

We detected the responses of summertime extreme wave heights (H_{top10}, average of the highest 10% of significant wave heights in June, July and August) to local climate variations in the East China Sea by applying an empirical orthogonal function analysis to H_{top10} derived from the WAVEWATCH-III wave model driven by 6 hourly sea surface wind fields from ERA-40 reanalysis over the

period 1958–2002. Decreases in H_{top10} in the northern East China Sea (Yellow Sea) correspond to attenuation of the East Asian Summer Monsoon, while increases in the south are primarily due to enhancement of tropical cyclone activities in the western North Pacific.

Martini, K. I., M. H. Alford, J. D. Nash, E. Kunze, and M. A. Merrifield, 2007, Diagnosing a partly standing internal wave in Mamala Bay, Oahu, *Geophys. Res. Lett.*, **34**, L17604, doi:10.1029/2007GL029749

An internal partly standing wave in Mamala Bay, Hawaii is studied using new observations and the Princeton Ocean Model (POM). Previous work suggested a convergence in the bay of east- and westbound waves emanating from Kaena Ridge and Makapuu Point, respectively. New energy flux measurements with shipboard ADCP/CTD confirm that Makapuu Point is the eastern source. After validating the POM results against observations, the model output is modally decomposed and compared with the expected theoretical patterns of kinetic and available potential energy, energy flux, and group velocity for a partly standing wave. Agreement is seen for the first baroclinic mode, which also contains most of the energy. The results confirm previous suggestions of standing wave dynamics in Mamala Bay.

3.10 Internal Waves

Alford, M. H., J. A. MacKinnon, Z. Zhao, R. Pinkel, J. Klymak, and T. Peacock, 2007, Internal waves across the Pacific, *Geophys. Res. Lett.*, **34**, L24601, doi:10.1029/2007GL031566

The long-range propagation of the semidiurnal internal tide northward from the Hawaiian ridge and its susceptibility to parametric subharmonic instability (PSI) at the "critical latitude," λ_c = 28.8°N, were examined in spring 2006 with intensive shipboard and moored observations spanning 25–37°N along a tidal beam. Velocity and shear at λ_c were dominated by intense vertically-standing, inertially-rotating bands of several hundred meters vertical wavelength. These occurred in bursts following spring tide, contrasting sharply with the downward-propagating, wind-generated features seen at other latitudes. These marginally-stable layers (which have inverse 16-meter Richardson number $Ri_{16}^{-1} = 0.7$) are interpreted as the inertial waves resulting from PSI of the internal tide. Elevated near-inertial energy and parameterized diapycnal diffusivity, and reduced asymmetry in upgoing/downgoing energy, were also observed at and equatorward of λ_c. Yet, simultaneous moored measurements of semidiurnal energy flux and 1-km-deep velocity sections measured from the ship indicate that the internal tide propagates at least to 37°N, with no detectable energy loss or phase discontinuity at λ_c. Our observations indicate that PSI occurs in the ocean with sufficient intensity to substantially alter the inertial shear field at and equatorward of λ_c, but that it does not appreciably disrupt the propagation of the tide at our location.

3.11 Continental Slope and Shelf-slope Exchanges

Nash, J. D., M. H. Alford, E. Kunze, K. Martini, and S. Kelly, 2007, Hotspots of deep ocean mixing on the Oregon continental slope, *Geophys. Res. Lett.*, **34**, L01605, doi:10.1029/2006GL028170

Two deep ocean hotspots of turbulent mixing were found over the Oregon continental slope. Thorpe˜scale analyses indicate time˜averaged turbulent energy dissipation rates of $\varepsilon > 10^{-7}$ W/kg and eddy diffusivities of $K_\rho \sim 10^{-2}$ m^2/s at both hotspots. However, the structure of turbulence and its generation mechanism at each site appear to be different. At the 2200˜m isobath, sustained >100˜m high turbulent overturns occur in stratified fluid several hundred meters above the bottom. Turbulence shows a clear 12.4˜h periodicity proposed to be driven by flow over a nearby 100˜m tall ridge. At the 1300˜m isobath, tidally˜modulated turbulence of similar intensity is confined within a stratified bottom boundary layer. Along˜slope topographic roughness at scales not resolved in global bathymetric data sets appears to be responsible for the bulk of the turbulence observed. Such topography is common to most continental slopes, providing a mechanism for turbulence generation in regions where barotropic tidal currents are nominally along-isobath.

3.12 Continental Shelf Studies

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008, Evidence for Upwelling of Corrosive 'Acidified' Water onto the Continental Shelf, *Science*, 320(5882): 1490-1492, doi:10.1126/science.155676

The absorption of atmospheric carbon dioxide (CO_2) into the ocean lowers the pH of the waters. This so-called ocean acidification could have important consequences for marine ecosystems. To better understand the extent of this ocean acidification in coastal waters, we conducted hydrographic surveys along the continental shelf of western North America from central Canada to northern Mexico. We observed seawater that is undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching depths of ~40 to 120 meters along most transect lines and all the way to the surface on one transect off northern California. Although seasonal upwelling of the undersaturated waters onto the shelf is a natural phenomenon in this region, the ocean uptake of anthropogenic CO_2 has increased the areal extent of the affected area.

Moum, J. N., J. D. Nash, and J. M. Klymak, 2008, Small scale processes in the coastal ocean, *Oceanography*, **21**(4), pp. 33

Varied observations over Oregon's continental shelf illustrate the beauty and complexity of geophysical flows in coastal waters. Rapid, creative, and sometimes fortuitous sampling from ships and moorings has allowed detailed looks at boundary layer processes, internal waves (some extremely nonlinear), and coastal currents, including how they interact. These processes drive turbulence and mixing in shallow coastal waters and encourage rapid biological responses, yet are poorly understood and parameterized. The work presented here

represents examples of efforts by many physical oceanographers to quantify small-scale, coastal-mixing processes so that their effects might be included in regional circulation models.

3.13 Inshore and Coastal Waters

Burd, B. J., P. A. G. Barnes, C. A. Wright, and R. E. Thomson, 2008, Responses of subtidal benthos of the Strait of Georgia to ambient sediment conditions and natural and anthropogenic deposition, *Mar. Env. Res.*, **66**(1): S62-S79, doi:10.1016/j.marenvres.2008.08.009

Patterns in infaunal biota in the Strait of Georgia are explored relative to water depth, substrate type, organic content of sediments and sedimentation characteristics. The analyses are based on geographically-diverse grab and core data collected over a 19-year period.

Infaunal abundance and biomass were not predictable by sediment particle size, organic content or water depth. While organic flux was a reasonable predictor of biotic factors, quality of organic material, relative proportions of organic and inorganic input and source of inputs were also important in this regard. Areas with high accumulation of sediment and high organic flux rates from terrestrial (riverine) sources supported the highest macro-infaunal abundance and biomass found to date in the Strait of Georgia, and were dominated by bivalves. Polychaetes dominated in low organic deposition conditions, and where anthropogenic organic deposition was high. However, biota were severely impoverished in sediments with high organic content from marine deposition, due to low fluxes and poor quality of organic material. Taxa number was related to percent total nitrogen and to the ratio of organic/inorganic flux, both in background conditions and where there was labile organic enrichment. Faunal communities from the Fraser River delta, which experiences considerable bottom-transported riverine material, were very different in composition from those that proliferate in habitats with high deposition and organic flux from the water column.

Dallimore, A., R. J. Enkin, R. Pienitz, J. R. Southon, J. Baker, C. A. Wright, T. F. Pedersen, S. E. Calvert, T. Ivanochko, and R. E. Thomson, 2008, Postglacial evolution of a Pacific coastal fjord in British Columbia, Canada: interactions of sea-level change, crustal response, and environmental fluctuations—results from MONA core MD02-2494, *Can. J. Earth Sci.*, **45**: 1345-1362, doi:10.1139/E08-042

The sedimentary record in a 40.9 m giant (Calypso) piston core (MD 02-2494) raised from the inner basin within Effingham Inlet, British Columbia, Canada, during the 2002 Marges Ouest Nord Américaines (MONA) campaign, spans from 14 360 ^{14}C years BP (17 300 calibrated calendar (cal.) years BP) to about nine centuries before present. The core archives changes in sedimentation and sea level immediately following deglaciation of the Late Wisconsin Fraser Glaciation, which peaked about 15 000 ^{14}C years BP. The presence of the Mazama Ash in the core anchors a detailed chronology based on 49 radiocarbon dates and seven Pleistocene paleomagnetic secular variation correlations. Diatom assemblages

identify a marine–freshwater–marine transition in the basin, which occurred 11 630 ^{14}C years BP (13 500 cal. years BP). At this time, a bedrock sill, presently at 46 m depth, was briefly exposed as sea level fell and then rose again during isostatic crustal adjustments. These data constrain a new sea-level curve for the outer coast of Vancouver Island covering the past 12 000 ^{14}C years BP (14 000 cal. years BP), providing new information on the nature of deglaciation along the west coast of Canada and informing interpretations of regional paleoceanographic records and mantle viscosity models.

Foreman, M. G. G., W. Callendar, A. MacFadyen, B. M. Hickey, R. E. Thomson, and E. Di Lorenzo, 2008, Modeling the generation of the Juan de Fuca Eddy, *J. Geophys. Res.*, **113**, C03006, doi:10.1029/2006JC004082

Numerical simulations with the Regional Ocean Modeling System are used to study the generation of the cyclonic Juan de Fuca Eddy located off the entrance of Juan de Fuca Strait in summer. An initial simulation forced with average summer upwelling favorable winds, tides, and buoyancy boundary conditions that maintain an estuarine flow in Juan de Fuca Strait produces an eddy and currents that are in reasonable agreement with observations. Sensitivity studies are then carried out to explore the importance of these three forcing mechanisms. The relative proximity of dense water in the bottom estuarine flow entering the strait is shown to lead to enhanced upwelling off Cape Flattery when either wind or tidal forcing is applied. This upwelled water then mixes with the estuarine outflow and is advected offshore. The tidal upwelling arises through three mechanisms: M_2 vertical excursions of nearly 20 m at 50 m depth west of the cape on the flood tide; strong tidally rectified vertical velocities west of the cape; and the spilling of denser bottom water over the western wall of Juan de Fuca Canyon on the ebb tide. The cyclonic eddy is a consequence of geostrophic adjustment to the doming isopycnals that arise from the upwelling. These model simulations refute an earlier hypothesis that the eddy is generated when California Undercurrent water is drawn up Tully Canyon and onto the Vancouver Island shelf, suggesting instead that these canyon dynamics play only a secondary role in maintaining the eddy once it is formed.

Johannessen, S. C., R. W. Macdonald, and B. Burd, 2008, Biogeochemical cycling in the Strait of Georgia, *Mar. Environ. Res. Special Issue*, Benthic processes, organic carbon cycling and contaminants in the Strait of Georgia, Canada, **66**(1): S1-S2, doi:10.1016/j.marenvres.2008.10.001

The papers in this special issue present the results of a five-year project to study sedimentary biogeochemical processes in the Strait of Georgia, with special emphasis on the near-field of a large municipal outfall. Included in this special issue are overviews of the sedimentology, benthic biology, status of siliceous sponge reefs and distribution of organic carbon in the water column. Other papers address the cycling of contaminants (PCBs, PBDEs) and redox metals in the sediment, a method to map the extent of the influence of municipal effluent from staining on benthic bivalves, and the relationships among geochemical conditions and benthic abundance and diversity. The latter set of papers addresses the role of

municipal effluent as a pathway of organic carbon and other contaminants into the Strait of Georgia and the effect of the effluent on benthic geochemistry and biology.

Johannessen, S. C., R. W. Macdonald, C. A. Wright, B. Burd, D. P.Shaw, and A.van Roodselaar, 2009, Joined by geochemistry, divided by history: PCBs and PBDEs in Strait of Georgia sediments, *Mar. Environ. Res. Special Issue*, Benthic processes, organic carbon cycling and contaminants in the Strait of Georgia, Canada, **66**(1): S112-S120, doi:10.1016/j.marenvres.2008.03.003

Polychlorinated biphenyls (PCBs) are relict contaminants, while polybrominated diphenyl ethers (PBDEs) are in increasing use. Using sediment cores collected in the Strait of Georgia, we demonstrate that the surface sediment concentration of PCBs is largely determined by environmental processes, such as sediment accumulation and mixing rates, while that of PBDEs is strongly influenced by proximity to source. The Iona Island wastewater outfall appears to be a primary pathway for PBDEs. As well, Vancouver Harbour is highly contaminated with both classes of chemical. BDE-209, the main component of deca-BDE, is the dominant PBDE congener. Environmental debromination is not evident. Currently, the ranges of the surface concentration of PCBs and PBDEs are similar to one another, but that will change in the future, as the concentration of PBDEs continues to rise. The experience with PCBs suggests that if PBDEs were banned today, it would take decades for inorganic sediment to bury them.

Johannessen, S. C. and R. W. Macdonald, 2009, Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada, *Clim. Res.*, **40**(1): 1-21, doi:10.3354/cr00819

Global changes manifest themselves in coastal waters depending on local oceanography and ecosystems. In this paper, we consider the Strait of Georgia as a case study. After examining physical and chemical processes and trends, we discuss consequences of change on geochemical cycling and biota. Several components of the system are vulnerable. Declines in pH and O_2 of basin waters, partly imported from the shelf and partly supported by carbon cycling within the strait, could reduce benthic and pelagic habitat. Sea level rise and storms will interact with coastal development to place critical habitat, such as low-lying estuaries, intertidal zones and mudflats, at risk. The decrease and earlier peak in zooplankton biomass may lead to changes in the food web that cascade to higher trophic levels such as fish and birds. Anadromous fish, already showing declines, are vulnerable to ocean regime shifts, increasing river temperatures, habitat destruction, harvesting and contaminants. For southern resident killer whales *Orcinus orca*, a species at risk, decline in Chinook salmon *Oncorhynchus tshawytscha* together with marine traffic and biomagnifying contaminants will lead to extirpation if no action is taken. Some stressors can be controlled only through international action to mitigate climate change. However, we have local control of fishing, habitat destruction, release of some contaminants and, to some extent, river flow and temperature. Acting to control these stressors will support resilience of biota in the face of inevitable global changes.

Laval, B. E., J. Morrison, D. J. Potts, E. Carmack, S. Vagle, C. James, F. McLaughlin, and M. Foreman, 2008, Wind-driven summertime upwelling in a fjord-type and its impact on downstream river conditions; Quesnel Lake and River, British Columbia, *J Great Lakes Res.*, **34**(1): 189-203, doi:10.3394/0380-1330(2008)34[189:WSUIAF]2.0.CO;2

Observations and modeling results are presented to explore the response of a multi-basin, fjord-type lake to episodic wind forcing. Field observations show that abrupt cooling and warming events (magnitude greater than 5°C d-1) lasting 3–6 days in a large, salmon-bearing river (Quesnel River) are due to upwelling in its upstream lake (Quesnel Lake) during the summer, stratified season. Within the lake, vertical displacement of isotherms in the vicinity of the river mouth associated with this upwelling is shown to be forced by wind events longer than one quarter of the fundamental seiche period and of sufficient magnitude that the Wedderburn number approaches one. Upwelling occurs nearly-simultaneously throughout a smaller basin adjacent to the outflow (West Basin) that is separated from the Main Basin of Quesnel Lake by a sill and contraction. Wind-driven water fluxes across the sill are estimated using a conceptual model based on volume and heat budgets. These estimates provide an upper bound for flow across the sill and suggest that exchange flow may at times be internally hydraulically controlled, with epilimnetic velocities of up to 25 cm/s. Computed fluxes suggest the West Basin hypolimnion has a residence time of 6-8 weeks during the summer stratified period with each upwelling episode irreversibly exchanging 25–30% of the hypolimnetic volume with the rest of the lake. Implications of such events are profound for salmon bearing rivers wherein the thermal habitat is critical to migration success.

Masson, D. and P. F. Cummins, 2007, Temperature trends and interannual variability in the Strait of Georgia, British Columbia, *Cont. Shelf Res.*, **27**(5): 634-649, doi:10.1016/j.csr.2006.10.009

A continuous 36 year long record of semi-monthly temperature profiles from the central Strait of Georgia, British Columbia is used to examine low frequency variability and trends through the water column. Decomposition of temperature anomalies into empirical orthogonal functions shows that the dominant mode accounts for 78% of the variance, while the principal component associated with this mode (PC1) is dominated by fluctuations on interannual time scales. To relate the variability within the Strait to that occurring over the northeast Pacific, PC1 is compared with anomalies in local air temperature, sea surface temperatures off the west coast of Vancouver Island, and upper ocean temperatures along Line-P. These comparisons suggest that much of the interannual variability observed in the Strait of Georgia occurs in response to large-scale atmospheric forcing over the northeast Pacific. However, following tropical El Niño events there are significant anomalies associated with processes occurring along the coastal oceanic wave guide. The strongest event in the entire record, the remarkable negative temperature anomaly of winter 1978/1979, appears to be associated with a deep water intrusion that was forced locally.

A warming trend is observed over the period 1970–2005 through the entire water column of the Strait of Georgia, with a depth-averaged value of . The vertical variation of the linear trend in temperature is contrasted with trends observed through the upper water column in the adjoining northeast Pacific over the same time period. Comparable trends are observed within the upper 100 m of the water column. However, at greater depths trends in the Strait of Georgia exceed those observed offshore by a factor of two. This is likely a consequence of the entrainment of near-surface waters into the deep Strait by the estuarine circulation. The results illustrate how global climatic changes may be amplified at depth in a coastal sea.

Masson, D. and A. Pena, 2009, Chlorophyll distribution in a temperate estuary: The Strait of Georgia and Juan de Fuca Strait, *Estuar. Coast. Shelf Sci.,* **82**(1): 19-28, doi:10.1016/j.ecss.2008.12.022

Data collected during 7 years of seasonal surveys are used to investigate the distribution of phytoplankton biomass within the estuarine waters of the Strait of Georgia and Juan de Fuca Strait. Variability of the chlorophyll distribution is examined in relation to the density stratification, light availability and nutrient concentration. In the Strait of Georgia, both the horizontal and vertical distribution of chlorophyll are found to be linked to the presence of a near-surface layer of increased density stratification. Despite important year-to-year variability, the seasonal cycle of chlorophyll in the Strait of Georgia is dominated every year by relatively large near-surface concentrations in the spring that are linked to the seasonal increase in solar radiation onto the stratified near-surface layer. In the vertical, a sub-surface peak is observed around 10 m depth, corresponding to the depth of maximum water column stability. Nutrients within the euphotic zone are in general abundant, with the exception of the Strait of Georgia in summer where phytoplankton growth is potentially limited by low nitrate concentration near the surface. The depth of the euphotic zone is estimated along the thalweg of the estuary from transmissometer profiles. It appears to vary relatively little within the estuary from a minimum of 20 m in spring, near the mouth of the Fraser River, to an autumnal maximum of about 30 m in the northern Strait of Georgia. Finally, the estimated self-shading contribution to light attenuation is shown to be generally significant (5–10%) in the surface waters of the Strait of Georgia, during spring and summer, reaching values as high as 35% during the spring bloom.

Moum, J. N., J. M. Klymak, J. D. Nash, A. Perlin, and W. D. Smyth, 2007, Energy Transport by Nonlinear Internal Waves, *J. Phys. Oceanogr.*, **37**(7): 1968–1988

Winter stratification on Oregon's continental shelf often produces a near-bottom layer of dense fluid that acts as an internal waveguide upon which nonlinear internal waves propagate. Shipboard profiling and bottom lander observations capture disturbances that exhibit properties of internal solitary waves, bores, and gravity currents. Wavelike pulses are highly turbulent (instantaneous bed stresses are 1 N m^{-2}), resuspending bottom sediments into the water column and raising

them 30+ m above the seafloor. The wave cross-shelf transport of fluid often counters the time-averaged Ekman transport in the bottom boundary layer. In the nonlinear internal waves that were observed, the kinetic energy is roughly equal to the available potential energy and is $O(0.1)$ megajoules per meter of coastline. The energy transported by these waves includes a nonlinear advection term $\langle uE \rangle$ that is negligible in linear internal waves. Unlike linear internal waves, the pressure–velocity energy flux $\langle up \rangle$ includes important contributions from nonhydrostatic effects and surface displacement. It is found that, statistically, $\langle uE \rangle \approx 2\langle up \rangle$. Vertical profiles through these waves of elevation indicate that $up(z)$ is more important in transporting energy near the seafloor while $uE(z)$ dominates farther from the bottom. With the wave speed c estimated from weakly nonlinear wave theory, it is verified experimentally that the total energy transported by the waves is $\langle up \rangle + \langle uE \rangle \approx c\langle E \rangle$. The high but intermittent energy flux by the waves is, in an averaged sense, $O(100)$ watts per meter of coastline. This is similar to independent estimates of the shoreward energy flux in the semidiurnal internal tide at the shelf break.

Nemcek, N., D. Ianson, and P. D. Tortell, 2008, A high-resolution survey of DMS, CO2 and O2/Ar distributions in productive coastal waters, *Global Biogeochemical Cycles,*. **22**, doi:10.1029/206GN002879

We present continuous, high-resolution measurements of surface dimethylsulfide (DMS), pCO_2, and O_2/Ar obtained in coastal waters of British Columbia, Canada, using membrane inlet mass spectrometry (MIMS). Sampled underway at a frequency of twice per minute (every ~160 m at 10 knots cruising speed), our data reveal fine-scale structure in gas variability and its covariance with a number of hydrographic parameters. All parameters exhibited large ranges (pCO_2, 200–747 ppm; DMS, <1–29 nM; chl *a*, <0.1–33 μg L^{-1}), highlighting the dynamic nature of the study area. A strong anticorrelation between pCO_2 and O_2/Ar was observed across the survey region, with the distributions of these gases influenced by biology and its interplay with physical processes. In contrast, DMS levels, which varied dramatically over short distances, showed no significant correlations with any single variable for the full, high-resolution data set. However, when measurements were binned to a much coarser spatial resolution, we found a linear relationship between surface DMS and the chlorophyll/mixed layer depth ratio. The slope of this relationship differed significantly from that previously derived from open ocean data. We used several statistical techniques to estimate the spatial variability of gases and hydrographic parameters and the inherent sampling errors associated with low-frequency sampling approaches. These analyses emphasize the importance of high-resolution sampling in coastal areas, particularly for DMS.

Pawlowicz, R., O. Riche, and M. Halverson, 2007, The Circulation and Residence Time of the Strait of Georgia Using a Simple Mixing-Box Approach, *Atmos.-Ocean*, **45**(4): 173–193, doi:10.3137/ao.450401

New observations in the Strait of Georgia, British Columbia, Canada show that temperature and dissolved oxygen have a pronounced seasonal cycle, with a

spatially varying phase. Phase lags in oscillating systems arise due to internal time scales which can be interpreted in fluid systems as residence times. Exploiting phase we construct a quantitative and internally consistent circulation scheme for this body of water after dividing it into four regions: the Fraser River plume, the surface waters down to 50 m, the intermediate waters down to 200 m, and the deep water. In this scheme the intermediate water, the largest region by volume, is continually renewed, and its characteristics change in response to continuous changes in the characteristics of source waters. The dependence of the estuarine circulation on variations in fresh inflow is weak. The deep water is volumetrically less important, but seasonal changes in the density of oceanic source waters can produce a variation in the overall circulation by driving an additional inflow which leads to both deep renewal and increased upwelling. In turn, this increased upwelling results in lower surface temperatures than might otherwise be expected. Intermediate water residence times are about 160 days. Deep water is renewed once per year in summer and is affected only by vertical diffusion during the rest of the year. Surface water residence times for the entire Strait are a few months at most, but the Fraser River plume has a freshwater residence time of approximately 1 day. In addition, we find that the residence time of oceanic source waters in the Strait is 1.7 years due to a substantial recirculation in Haro Strait. Other consequences of this scheme are consistent with independent estimates of horizontal transports, air-sea heat fluxes, subsurface oxygen (O2) utilization, and primary production. Finally, analysis of the spatial phase variations suggests that the intermediate inflow enters the Strait as a boundary current along the slopes of the Fraser delta.

Zaytsev, O., A. B. Rabinovich, R. E. Thomson, and N. Silverberg, 2010, Intense diurnal surface currents in the Bay of La Paz, Mexico, *Cont. Shelf Res.*, **30**(6): 608-619, doi:10.1016/j.csr.2009.05.003

Currents in the northern Bay of La Paz were examined using an 8-month Acoustic Doppler Current Profiler (ADCP) record collected in the upper 185 m of the water column during 2007. Flow variability was dominated by tidal motions, which accounted for 43% (33% diurnal, 10% semidiurnal) of the total kinetic energy. The tidal motions had a pronounced vertical structure dominated within a shallow (~30 m thick) surface layer by intense counterclockwise (CCW) rotary S_1 diurnal radiational currents that were highly coherent with the counterclockwise seabreeze. Motions within the semidiurnal frequency band were primarily associated with significant counterclockwise S_2 radiational tidal currents, which were also coherent with the seabreeze. Both S_1 and S_2 tidal ellipses in the upper layer were aligned perpendicular to the bay entrance with mean semi-major axes of 55 and 20 cm/s, respectively. Below the surface layer, tidal currents decayed rapidly to relatively weak, clockwise rotary barotropic motions. In contrast to those for radiational harmonics, tidal ellipses of the gravitational constituents (M_2, K_1 and O_1) were oriented cross-bay. Energy within the diurnal frequency band in the surface layer was dominated by a coherent component (barotropic, phase-locked baroclinic and radiational), which accounted for roughly 65% (59% from S_1 alone) of the total diurnal kinetic energy. Of the remaining diurnal band

energy, 18% was associated with an incoherent baroclinic component and 17% with a background noise component. Below 30 m depth, the corresponding estimates are 40%, 32% and 28%, respectively. The persistent, surface-intensified CCW rotary currents observed at the mooring site are assumed to be forced by strong CCW seabreeze winds in the presence of a "slippery" low-density surface layer. This response may be further augmented by topographic narrowing at the bay entrance and by the close proximity of the diurnal and inertial frequency bands in the region.

3.13.1 Sea Level

Mazzotti, S., A. Lambert, N. Courtier, L. Nykolaishen, and H. Dragert, 2007, Crustal uplift and sea level rise in northern Cascadia from GPS, absolute gravity, and tide gauge data, *Geophys. Res. Lett.*, **34**, L15306, doi:10.1029/2007GL030283

We combine data from nine GPS, absolute gravity, and tide gauge stations to estimate the relation between sea-level rise, vertical motion, and solid Earth processes in the Pacific Northwest. GPS vertical velocities (in ITRF2000) and absolute gravity rates are well correlated, with a gradient of 0.2 ± 0.1 μGal mm^{-1}, but show a significant offset of 0.53 ± 0.30 μGal yr^{-1} (2.2 ± 1.3 mm yr^{-1}) (95% confidence). Tide gauge and GPS data indicate a northeast Pacific regional sea-level rise of 1.7 ± 0.5 mm yr^{-1}, aligned to ITRF2000, or an unlikely regional sea-level fall of -0.5 ± 0.5 mm yr^{-1}, aligned to absolute gravity. Although we cannot rule out a bias in the GPS reference-frame alignment, our results suggest a possible absolute gravity bias by a long-period mass increase from an unknown near-surface or deep-seated source. The impact of such a mass increase on gravity, vertical motion, and sea level remains to be defined.

Mazzotti, S., C. Jones, and R. E. Thomson, 2008, Relative and Absolute Sea-Level Rise in Western Canada and North-western U.S. from a Combined Tide Gauge-GPS Analysis, *J. Geophys. Res.*, **113**, C11019, doi:10.1029/2008JC004835

Empirical studies and climate models suggest large variations of absolute sea level (ASL) changes between oceanic basins. Such potential variations raise concern on the applicability of global mean ASL predictions to specific regions and on estimates of relative sea level (RSL) hazards. We address this issue for the western Canada and northwestern United States coastline by estimating the 20th century ASL rate using a combination of 34 colocated tide gauge and Global Positioning System (GPS) stations. The tide gauge data are quality controlled and corrected for spatially and temporally correlated sea level transients in order to derive robust RSL trends and standard errors. Reference frame and other GPS-specific issues are considered as part of the error budget in absolute GPS vertical velocities. Our combined tide gauge-GPS analysis, aligned to the International Terrestrial Reference Frame 2000, indicates a northeast Pacific ASL rise of 1.8 ± 0.2 mm/a through the 20th century, which is similar to accepted rates for the global eustatic mean. For the period 1993–2003, we find a regional ASL rate of -4.4 ± 0.5 mm/a consistent with satellite altimetry. On the basis of the Intergovernment Panel on Climate Change Assessment Report 4 mean scenario and our assessment of coastal motions from GPS and tide gauge data, we derive a

map of predicted 21st century RSL rise in western Canada and the northwestern United States. Variations in coastal uplift strongly affect spatial RSL patterns. Subsidence of southern Puget Sound may significantly increase RSL rise in the Seattle-Tacoma metropolitan area. Conversely, tectonic uplift along parts of the outer west coast may reduce future RSL rise by up to 50–100%.

Mazzotti, S., A. Lambert, M. Van der Kooij, and A. Mainville, 2009, Impact of anthropogenic subsidence on relative sea-level rise in the Fraser River delta, *Geol*, **37**(9): 771-774, doi:10.1130/G25640A.1

Subsidence is a common cause of amplified relative sea-level rise, flooding, and erosion in coastal environments. In particular, subsidence due to sediment consolidation can play a significant role in relative sea-level rise in large deltas. We use a combination of InSAR (interferometric synthetic aperture radar), leveling, and global positioning system data to map absolute vertical land motion in the Fraser River delta, western Canada. We show that primary consolidation of shallow Holocene sediments is the main cause for the slow subsidence (–1 to –2 mm/a) affecting the delta lowlands. In addition, parts of the delta undergo increased anthropogenic subsidence. Rapid subsidence rates (–3 to –8 mm/a) are associated with recent artificial loads and exhibit a first-order exponential decrease with a time constant of ~20 years, consistent with the theory of consolidation. Assuming two sea-level rise scenarios of 30 or 100 cm by the end of the twenty-first century, natural subsidence will augment relative sea-level rise in the Fraser Holocene lowlands by ~50% or ~ 15%. Anthropogenic subsidence will augment relative sea-level rise by ~130% or ~40%, potentially raising it to as much as 1–2 m. In deltaic, lacustrine, and alluvial environments, anthropogenic sediment consolidation can result in significant amplification and strong spatial variations of relative sea-level rise that need to be considered in local planning.

3.13.2 Estuaries

Carpenter, J. R., N. J. Balmforth, and G. A. Lawrence, 2010, Identifying unstable modes in stratified shear layers, *Phys. Fluids*, **22**(5), doi:10.1063/1.3379845

One interpretation of the mechanism of instability in stratified shear flows is based on the idea that two independently propagating waves may interact to cause mutual growth in one another. This theory is used in the present study to develop a diagnostic that can be used to identify different types of unstable modes. We focus on stratified shear layers that are susceptible to both the Kelvin–Helmholtz (KH) and Holmboe (H) modes of instability—though the formulation is more general. The diagnostic is found to be useful in differentiating between KH and H modes in the symmetric stratified shear layer (where the center of the shear layer and the density interface coincide). The asymmetric stratified shear layer is also examined since there is no clear distinction between KH- and H-type modes in this flow. The KH mechanism of growth is predicted to extend to stronger stratifications (i.e., larger bulk Richardson numbers) than in the symmetric case, in qualitative agreement with nonlinear numerical results. However, the transition is found to be a gradual one in which the KH mechanism gives way to the H as

the bulk Richardson number is increased. In order to demonstrate the utility of the method, we apply it to instability observed in the Fraser River estuary.

Halverson, M. J. and R. Pawlowicz, 2008, Estuarine forcing of a river plume by river flow and tides, *J. Geophys. Res.*, **113**, C09033, doi:10.1029/2008JC004844

Estuarine forcing of a river plume by river discharge and tides is examined with a novel data set capable of characterizing semidiurnal to annual time scales. An instrumented ferry made high-resolution salinity measurements as it crossed the Fraser River plume, British Columbia, Canada, eight times per day over the years 2003–2006. The relative contribution of different forcing factors in controlling the river plume salinity and surface area is examined over the full range of time scales. A Lomb-Scargle periodogram of the plume salinity shows energy concentrated in the semidiurnal and diurnal tidal bands. Diurnal lines contain more energy relative to semidiurnal lines than the respective tidal constituents would suggest. At fortnightly frequencies, local maxima in plume salinity coincide with periods of maxima in daily tidal height, with no phase shift. Thus the estuary adjusts quickly to changes in forcing. The effectiveness of tides in setting the plume salinity is a function of river discharge and is greatest when the river discharge is high and minimal when the river discharge is low. Tidal effects are superimposed onto the long-period river discharge cycle. At time scales of 25 days or longer, the mean river plume salinity decreases quasi-linearly with increasing river discharge, but the change in salinity with river discharge is instantaneous to within the sampling resolution. Plume surface area increases with river discharge, from 200–500 km^2 at low river flow to 1000–1500 km^2 at high river flow. The magnitude of the surface area is predicted well by scaling the mouth deformation radius.

Tedford, E. W., J. R. Carpenter, R. Pawlowicz, R. Pieters, and G. A. Lawrence, 2009, Observation and analysis of shear instability in the Fraser River estuary, *J. Geophys. Res.*, **114**, C11006, doi:10.1029/2009JC005313

We investigate the occurrence of shear instability in the Fraser River estuary. Instabilities observed with an echo sounder are compared with a linear stability analysis based on observed velocity and density profiles. We find that each set of observed instabilities coincides with an unstable mode predicted by the Taylor-Goldstein equation. Each of these instabilities occurs in a region where the gradient Richardson number is less than the critical value of 1/4. Both the Taylor-Goldstein predictions and the echo soundings indicate the instabilities are concentrated either above or below the density interface. This "one sidedness" is in contrast to the archetypal Kelvin-Helmholtz instability. Although the dominant source of mixing in the estuary appears to be caused by shear instability, when the tide produces strong near-bed velocities, small-scale overturning due to boundary layer turbulence is apparent throughout the depth.

Thomson, R. E., S. F. Mihaly, and E. A. Kulikov, 2007, Estuarine versus transient flow regimes in Juan de Fuca Strait, *J. Geophys. Res.*, **112**, C09022, doi:10.1029/2006JC003925

Residual currents in Juan de Fuca Strait are observed to switch between two fundamental states: estuarine and transient. The estuarine regime, which prevails roughly 90% of the time in summer and 55% of the time in winter, has a fortnightly modulated, three-layer structure characterized by strong (~50 cm s^{-1}) outflow above 60 ± 15 m depth, moderate (~25 cm s^{-1}) inflow between 60 and 125 m depth, and weak (~10 cm s^{-1}) inflow below 125 ± 10 m depth. Rotation increases the upper layer depth by 40 m on the northern side of the channel and upwelling-favorable coastal winds augment inflow in the bottom layer by as much as 5 cm s^{-1}. Rotation, combined with modulation of the estuarine currents by tidal mixing in the eastern strait, leads to fortnightly variability in the along-channel velocity and cross-channel positioning of the core flow regions. Transient flows, which occur roughly 10% of the time in summer and 45% of the time in winter, are rapidly evolving, horizontally and vertically sheared "reversals" in the estuarine circulation generated during poleward wind events along the outer coast. Major events can persist for several weeks, force a net inward transport, and give rise to an O(10) km wide, surface-intensified, O(100) cm s^{-1} inflow along the southern (Olympic Peninsula) boundary of the strait. This "Olympic Peninsula Countercurrent" is typically accompanied by an abrupt decrease in salinity, indicating that it is a buoyancy flow originating with low-density water on the northern Washington shelf.

3.13.3 Tides

Blanchfield, J., C. Garrett, P. Wild, and A. Rowe, 2008, Tidal stream power resource assessment for Masset Sound, Haida Gwaii, *J. Power and Energy*, **222**: 485-492, doi:10.1243/09576509JPE585

This work presents a case study for the power potential of a tidal stream connecting a bay to the open ocean. The extractable power, averaged over the tidal cycle, from Masset Sound, located in Haida Gwaii, Canada, is estimated as 79 MW when only the dominant M2 tidal constituent is included in the analysis. The value increases to 87 MW when the three dominant constituents are included. It is shown that extracting the maximum power from Masset Sound will decrease both the maximum water surface elevation within the bay and the maximum volume flowrate through the channel to approximately 58 per cent of their undisturbed values.

Grundle, D. S., D. A. Timothy, and D. E. Varela, 2009, Variations of phytoplankton productivity and biomass over an annual cycle in Saanich Inlet, a British Columbia fjord, *Cont. Shelf Res.*, **29**(19): 2257-2269, doi:10.1016/j.csr.2009.08.013

Saanich Inlet is a highly productive temperate fjord with the capability to record inter-annual patterns of water-column primary production in undisturbed laminated sediments. We investigated spatial and temporal variations in primary productivity, total and size-fractionated phytoplankton chl *a*, dissolved nutrients, temperature and salinity at the head and mouth of Saanich Inlet from May 2005 to November 2006. New primary productivity was also measured from May to October 2006. During the growing season (spring, summer and fall), primary

productivity was 1.5 times higher at the mouth than at the head of Saanich Inlet and, averaged across stations, total productivity was 460 g C m^{-2} y^{-1}. Average new productivity was 53% and 58% of total primary productivity at the head and mouth of the inlet, respectively, and during the growing season microphytoplankton (>20 µm; mainly diatoms) was the most abundant size-class of phytoplankton. These rates of primary production are as high as or higher than those measured in other fjords, possibly because of a tidally-driven fortnightly gravity exchange that supplies nutrients to surface waters that enhance biological production when nutrients would otherwise be limiting. This exchange delivers nutrients at least as far inland as the head station, while nutrients associated with an eddy near the mouth may be the cause of even higher productivity there. We discuss the impact of these nutrient sources to Saanich Inlet on the records of paleoproduction generated from two Ocean Drilling Program cores extracted from this fjord, and suggest that the fortnightly exchange buffers variations in nutrient supply occurring on sub-decadal or decadal scales.

Sutherland, G., M. Foreman, and C. Garrett. 2007. Tidal current energy assessment for Johnstone Strait, Vancouver Island. *J. Power and Energy*, **221**, 147-157, doi:10.1243/09576509JPE338

The maximum tidal power potential of Johnstone Strait, BC, Canada is evaluated using a two-dimensional finite element model (TIDE2D) with turbines simulated in certain regions by increasing the drag. Initially, side channels are closed off so that the flow is forced through one channel to test the validity of a general analytic theory [1] with numerical results. In this case, the modelled power potential of 886 MW agrees reasonably well with the analytic estimate of 826 MW. In reality, two main channels, Discovery Passage and Cordero Channel, connect the Pacific Ocean to the Strait of Georgia. Turbines are simulated in Johnstone Strait, northwest of the two main channels, and separately for Discovery Passage and Cordero Channel. Northwestern Johnstone Strait is similar to the one channel case as the flow must go through this channel, but Discovery Passage and Cordero Channel are different as the flow can be diverted away from the channel with the turbines and into the other channel. The maximum extractable power in northwestern Johnstone Strait is found to be 1335 MW, which agrees well with the theoretical estimate of 1320 MW. In Discovery Passage and Cordero Channel, the maximum extractable power is modelled to be 401 and 277 MW, respectively, due to the flow being partly diverted into the other channel. In all cases, the current is reduced to between 57 and 58 per cent of the undisturbed flow, close to the 56 per cent predicted by the analytic theory. All power calculations are for the M2 constituent alone, as this is the largest current in the region. The total power from the eight major constituents (M2, S2, N2, K2, K1, 01, P1, and Q1) can be obtained by multiplying the power estimates for M2 by 1.12.

3.13.4 Deepwater Renewal in Fjords

Manning, C., R. C. Hamme, and A. Bourbonnais, 2010, Impact of deep-water renewal events on fixed nitrogen loss from seasonally-anoxic Saanich Inlet, *Marine Chemistry*, **122**(1-4): 1-10, doi:10.1016/j.marchem.2010.08.002

We interpreted profiles of N_2/Ar ratios, , and O_2 concentration collected in Saanich Inlet, British Columbia, Canada over an annual cycle. Our measurements and data from a regional cabled observatory indicated that four deep- or bottom-water renewal events occurred over our study period. Each event was correlated with a period of weak tidal currents, such that very low tidal mixing allowed inflowing water to retain its high density as it moved across the sill and into the deeper basin. By quantifying the concentration of excess N_2 in each month and the vertical diffusion rate, we determined that the N_2 production rate ranged from 1.7 ± 0.3 mmol N_2 m^{-2} d^{-1} in summer to 8.1 ± 2.8 mmol N_2 m^{-2} d^{-1} in winter. This depth-integrated estimate accounts for all pathways resulting in fixed (bioavailable) nitrogen loss as N_2 gas, including denitrification and anammox, and incorporates any benthic production of N_2 that diffuses into the overlying water column. In spring and summer, the maximum N_2 excess corresponded to the maximum, indicating that denitrification approached completion. In these months, the average isotopic composition of the fixed N consumed was 7.5 ± 1.2‰. Following bottom-water renewal in fall, which brought in nutrient-rich, low-N_2 water, the N_2 concentration increased and became progressively more enriched in ^{15}N. The high rates of N_2 production in Saanich Inlet likely exist in other anoxic basins that undergo periodic deep-water renewal by nitrate-rich waters.

4 Atlantic Ocean

4.1 Basin Scale Processes

Boessenkool, K. P., I. R. Hall, H. Elderfield, and I. Yashayaev, 2007, North Atlantic climate and deep-ocean flow speed changes during the last 230 years, *Geophys. Res. Lett.*, **34**, L13614, doi:10.1029/2007GL030285

Variations in the near-bottom flow speed of Iceland-Scotland Overflow Water (ISOW) are documented in a 230-year-long deep-sea sediment record from the eastern flank of Reykjanes Ridge in the subpolar North Atlantic at (sub)decadal time scales. For recent decades, the ISOW palaeocurrent reconstructions show similarities with observational hydrographic data. Furthermore, recent ISOW flow changes fall mostly within the range of its variability of the past 230 years. The record also reveals a hitherto unrecognized coupling of deep flow speeds in the subpolar North Atlantic with the North Atlantic Oscillation (NAO) index, with more (less) vigorous ISOW flow during negative (positive) phases of the NAO. Our results suggest that the changes in ISOW vigor are largely controlled by the transport and characteristics of Labrador Sea Water rather than variations in the overflow itself, with implications for the meridional overturning of the Atlantic Ocean and climate.

Chylek, P., C. K. Folland, G. Lesins, and M. K. Dubey, 2010, Twentieth century bipolar seesaw of the Arctic and Antarctic surface air temperatures, *Geophys. Res. Lett.*, **37**, L08703, doi:10.1029/2010GL042793

Understanding the phase relationship between climate changes in the Arctic and Antarctic regions is essential for our understanding of the dynamics of the Earth's climate system. In this paper we show that the 20th century de-trended Arctic and Antarctic temperatures vary in anti-phase seesaw pattern – when the Arctic warms the Antarctica cools and visa versa. This is the first time that a bi-polar seesaw pattern has been identified in the 20th century Arctic and Antarctic temperature records. The Arctic (Antarctic) de-trended temperatures are highly correlated (anti-correlated) with the Atlantic Multi-decadal Oscillation (AMO) index suggesting the Atlantic Ocean as a possible link between the climate variability of the Arctic and Antarctic regions. Recent accelerated warming of the Arctic results from a positive reinforcement of the linear warming trend (due to an increasing concentration of greenhouse gases and other possible forcings) by the warming phase of the multidecadal climate variability (due to fluctuations of the Atlantic Ocean circulation).

d'Orgeville, M. and W. R. Peltier, 2009a, Implications of Both Statistical Equilibrium and Global Warming Simulations with CCSM3. Part I: On the Decadal Variability in the North Pacific Basin, *J. Clim.*, **22**(20): 5277-5297, doi:10.1175/2009JCLI2428.1

In the low-resolution version of the Community Climate System Model, version 3 (CCSM3), the modeled North Pacific decadal variability is demonstrated to be independent of the epoch for which a statistically steady control simulation is constructed, either preindustrial or modern; however, it is demonstrated to be significantly affected by the different global warming scenarios investigated.

In the control simulations, the North Pacific basin is shown to be dominated by sea surface temperature (SST) variability with a time scale of approximately 20 yr. This mode of variability is in close accord with the observed characteristics of the Pacific decadal oscillation (PDO). A detailed analysis of the statistical equilibrium runs is performed based on other model variables as well [sea surface salinity (SSS), barotropic circulation, freshwater and heat fluxes, wind stress curl, sea ice, and snow coverage]. These analyses confirm that the underlying mechanism of the PDO involves a basin-scale mode of ocean adjustment to changes of the atmospheric forcing associated with the Aleutian low pressure system. However, they also suggest that the observed sign reversal of the PDO arises from a feedback in the northern part of the basin. In this novel hypothesis, the advection to the Bering Sea of "spice" anomalies formed in the central and western Pacific sets up a typical 10-yr time scale for the triggering of the PDO reversal.

In all of the global warming simulations described in this paper, the signal represented by the detrended SST variability in the North Pacific displays significant power at multidecadal frequencies. In these simulations, the natural North Pacific decadal variability, as characterized in the control simulations (the

PDO), remains the leading mode of variability only for moderate forcing. If the warming is too strong, then the typical 20-yr time scale of the canonical PDO can no longer be detected, except in terms of SSS variability and only prior to a significant change that occurs in the Bering Strait Throughflow.

d'Orgeville, M. and W. R. Peltier, 2009b, Implications of Both Statistical Equilibrium and Global Warming Simulations with CCSM3. Part II: On the Multidecadal Variability in the North Atlantic Basin, *J. Clim.*, **22**(20): 5298–5318, doi:10.1175/2009JCLI2775.1

The nature of the multidecadal variability in the North Atlantic basin is investigated through detailed analysis of multicentury integrations performed using the low-resolution version of the Community Climate System Model, version 3 (CCSM3), a modern atmosphere–ocean coupled general circulation model. Specifically, the results of control simulations under both preindustrial and present-day perpetual seasonal cycle conditions are compared to each other and also to the results of five simulations with increasing CO_2 concentration scenarios. In the absence of greenhouse gas–induced warming, the meridional overturning circulation (MOC) variability is shown to be dependent on the details of the simulation. In the present-day control simulation, the MOC is characterized by a broad spectrum of low frequencies, whereas, in preindustrial control simulations, MOC variability is characterized either by a well-defined periodicity of 60 yr or by a broad spectrum of low frequencies. In all the control simulations, the MOC appears to respond with a delay of 10 yr to synchronous temperature and salinity anomalies in the deep water formation sites located in the subpolar gyre, but salinity dominates the density anomalies. The explanation of the modeled MOC periodicity is therefore sought in the creation of these density anomalies. The influence of increased sea ice coverage under cold/preindustrial conditions is shown to modify the salinity variability, but it is not a sufficient condition for the support of the MOC periodicity. Instead, its source appears to be a modified subpolar gyre circulation resulting from interaction with the bottom bathymetry, which is able to sustain strong coupling between the horizontal and overturning circulations.

Based on the global warming analyses, for the simulations initialized from the cold/preindustrial statistical equilibrium run, the North Atlantic variability continues to be dominated by strong coupling between the horizontal and overturning circulations if the imposed forcing is weak. More generally, the delayed response of the MOC to surface density anomalies in the deep water formation regions is preserved under weak forcing.

Jeansson, E., S. Jutterström, B. Rudels, L. G. Anderson, K. Anders Olsson, E. P. Jones, W. M. Smethie, Jr., and J. H. Swift, 2008, Sources to the East Greenland Current and its contribution to the Denmark Strait overflow, *Prog. Oceanogr.*, **78**: 12-28, doi:10.1016/j.pocean.2007.08.031

Data from the East Greenland Current in 2002 are evaluated using optimum multiparameter analysis. The current is followed from north of Fram Strait to the Denmark Strait Sill and the contributions of different source waters, in mass

fractions, are deduced. From the results it can be concluded that, at least in spring 2002, the East Greenland Current was the main source for the waters found at the Denmark Strait Sill, contributing to the overflow into the North Atlantic. The East Greenland Current carried water masses from different source regions in the Arctic Ocean, the West Spitsbergen Current and the Greenland Sea. The results agree well with the known circulation of the western Nordic Seas but also add knowledge both to the quantification and to the mixing processes, showing the importance of the locally formed Greenland Sea Arctic Intermediate Water for the East Greenland Current and the Denmark Strait.

Pimentel, S., K. Haines, and N. K. Nichols, 2008b, Modeling the diurnal variability of sea surface temperatures, *J. Geophys. Res.*, **113**, C11004, doi:10.1029/2007JC004607

In this study a one-dimensional mixed layer ocean model is customized for the purpose of estimating the diurnal signal of temperature in the near-surface ocean layer, generically referred to as sea surface temperature (SST). The model is initially run with data from three mooring locations. It is then demonstrated how operational forecast data sets can be utilized to estimate diurnal signals over a wide area. Daily diurnal variability maps are produced for a weeklong period over the Atlantic Ocean. These maps highlight the transient nature of diurnal SST signals with day to day changes in their magnitude and spatial distribution. The resulting diurnal variability maps are evaluated using a combination of infrared and microwave satellite-derived SST observations taken over the day. These matchups result in a mean error of 0.09° C and a standard deviation of 0.54°C. Advantages of modeling the diurnal cycle as opposed to using a persistence assumption are discussed.

Sushama, L., M. Ghil, and K. Ide, 2007, Spatio-Temporal Variability in a Mid-Latitude Ocean Basin Subject to Periodic Wind Forcing, *Atmos.-Ocean*, **45**(4): 227–250, doi:10.3137/ao.450404

The mid-latitude ocean's response to time-dependent zonal wind-stress forcing is studied using a reduced-gravity, 1.5-layer, shallow-water model in two rectangular ocean basins of different sizes. The small basin is 1000 km × 2000 km and the larger one is 3000 km × 2010 km; the aspect ratio of the larger basin is quite similar to that of the North Atlantic between 20°N and 60°N. The parameter dependence of the model solutions and their spatio-temporal variability subject to time-independent wind stress forcing serve as the reference against which the results for time-dependent forcing are compared. For the time-dependent forcing case, three zonal-wind profiles that mimic the seasonal cycle are considered in this study: (1) a fixed-profile wind-stress forcing with periodically varying intensity; (2) a wind-stress profile with fixed intensity, but north–south migration of the mid-latitude westerly wind maximum; and (3) a north–south migrating profile with periodically varying intensity. Results of the small-basin simulations show the intrinsic variability found for time-independent forcing to persist when the intensity of the wind forcing varies periodically. It thus appears that the physics behind the upper ocean's variability is mainly controlled by internal dynamics, although the solutions' spatial patterns are now more complex, due to

the interaction between the external and internal modes of variability. The north–south migration of wind forcing, however, does inhibit the inertial recirculation; its suppression increases with the amplitude of north–south migration in the wind-stress forcing. Model solutions in the larger rectangular basin and at smaller viscosity exhibit more realistic recirculation gyres, with a small meridional-to-zonal aspect ratio, and an elongated eastward jet; the low-frequency variability of these solutions is dominated by periodicities of 14 and 6–7 years. Simulations performed in this setting with a wind-stress profile that involves seasonal variations of realistic amplitude in both the intensity and the position of the atmospheric jet show the seven-year periodicity in the oceanic circulation to be robust. The intrinsic variability is reinforced by the periodic variations in the jet's intensity and weakened by periodic variations in the meridional position; the two effects cancel, roughly speaking, thus preserving the overall characteristics of the seven-year mode.

Yashayaev, I. and B. Dickson, 2008, Transformation and Fate of Overflows in the Northern North Atlantic, Arctic-Subarctic Ocean Fluxes, 505-526, doi:10.1007/978-1-4020-6774-7_22

The largest full-depth changes in the modern instrumented oceanographic record have taken place in the Labrador Basin of the northwest Atlantic over the last 4 decades. The extreme amplitude of anomalous conditions there and the importance of their claimed effects for the thermohaline circulation and for climate (e.g. Bryden et al. 2005) justify attempts to identify the origin of change throughout the watercolumn of the subpolar Atlantic. At depths in the Labrador Basin greater than the limits of open-ocean deep convection (2,300 m or so), change is necessarily imported to the Basin by the two main dense water overflows that cross the Greenland–Scotland Ridge via the Denmark Strait and Faroe–Shetland Channel. Each of the constituent watermasses that form these overflows (see, for example, Rudels et al. 2002) will carry with them the imprint of time-varying climatic forcing in their source regions and of modifications *en route*, and their properties will also be subject to alteration by the processes of horizontal and vertical exchange from their spillways to the Labrador Basin. The purpose of this chapter is to identify from the hydrographic record those locations that are of primary importance for the transfer of ocean climate 'signals' into and between the two spreading overflow plumes, and if possible to trace the influence of these changes downstream to the Newfoundland Basin and beyond in the Deep Western Boundary Current

4.1.1 Freshwater Content

Yashayaev, I., 2007, Changing freshwater content: Insights from the subpolar North Atlantic and new oceanographic challenges, *Prog. Ocean.*, **73**(3-4): 203-209, doi:10.1016/j.pocean.2007.04.014

Observations and analyses of oceanic inventories of heat and freshwater have recently provided convincing evidence of systematic global-scale changes. Some recent studies aimed at observing, modelling and understanding these changes are collected together in this special issue of Progress in Oceanography. This

introductory article provides some background on the procedures used to define these changes and their importance to climate change, with special reference to the North Atlantic basin. In particular, we show that significant changes in the properties and distributions of the major intermediate and deep water masses occurred in the North Atlantic's subpolar gyre between the 1960s and 1990s. These changes are described using volumetric temperature-salinity censuses and other analyses based on compilations of observations from the warm salty 1964–1972 period and the cold fresh 1995–1997 period. This article and the others in this special issue are intended to provide an overview of recent advances in our knowledge of large-scale heat and freshwater changes in the ocean with the hope that some of the open questions will inspire future work.

4.1.2 AMOC/Thermohaline Circulation

Alexander, J. and A. H. Monahan, 2009, Nonnormal Perturbation Growth of Pure Thermohaline Circulation Using a 2D Zonally Averaged Model, *J. Phys. Oceanogr.*, **39**(2): 369–386

Generalized linear stability theory is used to calculate the optimal initial conditions that result in transient amplification of the thermohaline circulation (THC) in a zonally averaged single-basin ocean model. The eigenmodes of the tangent linear model verify that the system is asymptotically stable, but the nonnormality of the system permits the growth of perturbations for a finite period through the interference of nonorthogonal eigenmodes. It is found that the maximum amplification of the THC anomalies occurs after 6 yr with both the thermally and salinity-driven components playing major roles in the amplification process. The transient amplification of THC anomalies is due to the constructive and destructive interference of a large number of eigenmodes, and the evolution over time is determined by how the interference pattern evolves. It is found that five of the most highly nonnormal eigenmodes are critical to the initial cancellation of the salinity and temperature contributions to the THC, while 11 oscillating modes with decay time scales ranging from 2 to 6 yr are the major contributors at the time of maximum amplification. This analysis demonstrates that the different dynamics of salinity and temperature anomalies allow the dramatic growth of perturbations to the THC on relatively short (interannual to decadal) time scales.

Bersch, M., I. Yashayaev, and K. P. Koltermann, 2007, Recent changes of the thermohaline circulation in the subpolar North Atlantic, *Ocean Dyn.*, **57:** 223-235, doi:10/1007/s10236-007-0103-7

Time series of hydrographic sections in the northern North Atlantic from the period 1990 to 2004 are analyzed for changes in the characteristics and distribution of water masses that are involved in the thermohaline circulation (THC). During the 1990s, the North Atlantic Oscillation (NAO) alternates from a positive phase (strong westerlies) to a negative phase (weak westerlies). The reduced ocean heat loss confined the convection in the Labrador Sea to the upper 1,200 m, generating a new salinity minimum layer characterizing the Upper Labrador Sea Water (ULSW), and led to a warming and salinization of the older

LSW below due to lateral mixing. The Lower LSW, formed in the first half of the 1990s, spread in the subpolar gyre and reached the Newfoundland and Irminger basins after about 1 to 2 years, where the associated isopycnal doming contributed to eastward frontal shifts in the upper layer. After 5 and 6 years, it arrived in the Iceland and West European basins, respectively. The collapse of the isopycnal dome in the Labrador Sea, associated with the drainage of the Lower LSW, resulted in a slowing of the cyclonic circulation of the subpolar gyre. This was accompanied in the upper layer by a westward shift of the southeastern extension of the gyre and a northward advection of warm and saline subtropical water in its eastern part, which finally reached the Labrador Sea after about 7 years. In the upper layer of the Labrador Sea, the advection of warm and saline water dominated over the heat loss to the atmosphere and the freshwater gain from melting ice and precipitation in the NAO-low period, so that no accumulation of freshwater but an increase of the heat and salt contents were observed, as in the whole eastern part of the subpolar gyre. Within 1 to 2 years after the drop of the NAO in the winter of 1995/1996, the Subarctic (Subpolar) Front shifted northward and westward north of about 50°N, favored by the retreat of the low salinity tongue extending eastward from the southern Labrador Sea, and it shifted southward and eastward in the Newfoundland Basin. Therefore, the enhanced northward advection of subtropical waters in the northeastern North Atlantic is balanced by the enhanced southward advection of subarctic waters, including Lower LSW in the Newfoundland Basin, indicating a strong response of the gyre component of the THC.

Chylek, P., C. K. Folland, G. Lesins, M. K. Dubey, and M. Wang, 2009, Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, **36**, L14801, doi:10.1029/2009GL038777

Understanding Arctic temperature variability is essential for assessing possible future melting of the Greenland ice sheet, Arctic sea ice and Arctic permafrost. Temperature trend reversals in 1940 and 1970 separate two Arctic warming periods (1910–1940 and 1970–2008) by a significant 1940–1970 cooling period. Analyzing temperature records of the Arctic meteorological stations we find that (a) the Arctic amplification (ratio of the Arctic to global temperature trends) is not a constant but varies in time on a multi-decadal time scale, (b) the Arctic warming from 1910–1940 proceeded at a significantly faster rate than the current 1970–2008 warming, and (c) the Arctic temperature changes are highly correlated with the Atlantic Multi-decadal Oscillation (AMO) suggesting the Atlantic Ocean thermohaline circulation is linked to the Arctic temperature variability on a multi-decadal time scale.

Clark, P. U., T. L. Delworth, and A. J. Weaver, 2008, Freshwater forcing: Will history repeat itself? *Science*, **320:** 316, doi:10.1126/science.320.5874.316a

No abstract but the article was short:

IN THEIR RESEARCH ARTICLE "REDUCED North Atlantic deep water coeval with the glacial Lake Agassiz freshwater outburst" (4 January, p. 60), H. F. Kleiven *et al*. present compelling evidence for an abrupt deep-ocean response to

the release of freshwater from glacial Lake Agassiz into the northwest Atlantic about 8400 years ago. Such data are particularly important in evaluating the response in ocean models of the Atlantic Meridional Overturning Circulation (MOC) to freshwater forcing. For this event, the freshwater forcing was likely large but short; Clarke *et al*. estimate that the flood had a freshwater flux of 4 to 9 Sv released in 0.5 years. In this context, we are aware of no possible mechanism that might reproduce such a forcing in response to global warming, and all available model simulations, including those with estimates of maximum Greenland Ice Sheet (GIS) melting rates, indicate that it is very unlikely that the MOC will undergo an abrupt transition during the course of the 21st century. Multimodel ensemble averages under Special Report on Emissions Scenario (SRES) A1B suggest a best estimate of 25 to 30% reduction in the overall MOC strength. In one example, 14 coupled models simulated a 100-year 0.1-Sv freshwater perturbation to the northern North Atlantic Ocean—17 times the recently estimated melt rates from the GIS—and the MOC weakened by a multimodel mean of 30% after 100 years; none of the models simulated a shutdown. Another model simulated greenhouse gas levels that increased to four times preindustrial values and then remained fixed; the resulting GIS displayed a peak melting rate of about 0.1 Sv, with little effect on the MOC. One model simulation uses the SRES A1B scenario but adds an additional 0.09-Sv freshwater forcing as an upper-bound estimate of potential GIS melting. In this case, the MOC weakened but subsequently recovered its strength, indicating that GIS melting would not cause abrupt climate change in the 21st century (5). Accordingly, we urge caution in drawing comparisons of the abrupt change 8400 years ago to future scenarios involving, for example, the melting of the GIS and its relevance to human societies.

Meissner, K. J., 2007, Younger Dryas: A data to model comparison to constrain the strength of the overturning circulation, *Geophys. Res. Lett.*, **34**, L21705, doi:10.1029/2007GL031304

The University of Victoria Earth System Climate Model (UVic ESCM) is used to compare simulated time series of radiocarbon during the Younger Dryas (YD) with paleoceanographic records. I find that only a complete shut-down and recovery of the Atlantic Meridional Overturning Circulation (AMOC) can simulate both the rise in atmospheric CO_2 concentrations seen in ice core records and the peak and subsequent decrease in atmospheric $\Delta^{14}C$ comparable to the peak recorded in the varved sediments of the Cariaco Basin. Simulated radiocarbon profiles in the western North Atlantic match well with data from deep-sea corals at the beginning of the YD, whereas planktonic/benthic foraminifera records match best with a transient state during the rapid recovery of the AMOC. The steepness of the increase in atmospheric $\Delta^{14}C$ at ~12.9 ka cal could not be simulated with oceanic circulation changes only because the response time of the climate system is too slow.

Monahan, A. H., J. Alexander, and A. J. Weaver, 2008, Stochastic models of the meridional overturning Circulation: Timescales and patterns of variability. *Phil. Trans. Roy. Soc A*, **366**(1875): 2525-2542, doi:10.1098/rsta.2008.0045

The global meridional overturning circulation (MOC) varies over a wide range of space and time scales in response to fluctuating 'weather' perturbations that may be modelled as stochastic forcing. This study reviews model studies of the effects of climate noise on decadal to centennial MOC variability, on transitions between the MOC regimes and on the dynamics of Dansgaard–Oeschger events characteristic of glacial periods.

Peltier, W. R., 2007, Rapid climate change and Arctic Ocean freshening, *Geology*, **35**(12): 1147–1148, doi:10.1130/focus122007.1

No abstract;(there was also a "comment" and "reply" associated with this article The author discusses the effectiveness of Arctic freshwater outflow in arresting the THC in relation to rapid climate change using evidence from previous studies and NCAR climate model runs and the Younger-Dryas event as an example.

Rennermalm, A. K., E. F. Wood, A. J. Weaver, M. Eby, and S. J. Déry, 2007, Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean, *J. Geophys. Res.*, **112**, G04S48, doi:10.1029/2006JG000330

Increases in high-latitude river discharge over the 20th century and projected continued increases during the 21st century may have an impact on the Atlantic meridional overturning circulation (AMOC), which could feed back to regional and global climate. Although the general trend in high-latitude river discharge is positive, there is important geographical spread in the trends. While Eurasian rivers draining into the Arctic Ocean show positive trends over the 20th century, rivers draining into Hudson Bay show negative trends since 1964. Here the sensitivity of AMOC to changes in river discharge into Hudson Bay and the Arctic Ocean is studied with an intermediate-complexity Earth system model. It is found that ocean freshening originating from Arctic rivers is more effective in slowing down the AMOC than freshening originating from Hudson Bay rivers, given the same magnitude of freshening in both regions. The lesser impact of Hudson Bay river discharge on AMOC is the result of a buildup of freshwater anomalies in the Labrador Sea affecting the northward flow of the Gulf Stream. This work highlights that not only the freshening magnitude but the region where this freshening takes place is crucial for the AMOC response to altered river discharge climatology.

Spence, J. P., M. Eby, and A. J. Weaver, 2008, The Sensitivity of the Atlantic Meridional Overturning Circulation to Freshwater Forcing at Eddy-Permitting Resolutions. *J. Clim.*, **21**, 2697–2710. doi:10.1175/2007JCLI2103.1

The effect of increasing horizontal resolution is examined to assess the response of the Atlantic meridional overturning circulation (AMOC) to freshwater perturbations. Versions of a global climate model with horizontal resolutions ranging from 1.8° (latitude) × 3.6° (longitude) to 0.2° × 0.4° are used to determine

if the AMOC response to freshwater forcing is robust to increasing resolution. In the preindustrial equilibrium climate, the representation of western boundary currents and meridional heat transport are improved with resolution. Freshwater forcings similar to the final drainage of proglacial Lakes Agassiz and Ojibway are applied evenly over the Labrador Sea and exclusively along the western boundary. The duration and maximum amplitude of model responses to freshwater forcing showed little sensitivity to increasing resolution. An evaluation with tracers of the forcing impact on different regions of North Atlantic Deep Water formation revealed the possibility that increases in Labrador Sea deep convection at higher resolution mitigate the effect of stronger boundary currents and enhanced mixing. With increasing resolution, there is less cooling in the subpolar west Atlantic, more cooling in the subpolar east Atlantic, and greater variability in the deep ocean response to the boundary forcing. While differences exist, the coarse-resolution model response remains robust at finer horizontal resolutions.

Saenko, O. A., A. J. Weaver, D. Y. Robitaille, and G. M. Flato, 2007, Warming of the subpolar Atlantic triggered by freshwater discharge at the continental boundary, *Geophys. Res. Lett.*, **34**, L15604, doi:10.1029/2007LG030674

The traditional view is that widespread discharge of freshwater into the North Atlantic leads to a reduction of the Atlantic Meridional Overturning Circulation (AMOC), a concomitant reduction of poleward heat transport and a cooling of the climate of the North Atlantic. Here we report upon coupled atmosphere-ocean general circulation model experiments that suggest a more non-uniform response of the North Atlantic climate to large freshwater perturbations. We show that in a cold climate with extensive sea ice coverage in the Labrador Sea, a massive discharge of freshwater along coastal boundaries leads to an anomalous warming in the western North Atlantic. The warming persist despite a significant weakening of the AMOC and its associated heat transport. It is maintained by major reorganizations of the large-scale wind field, oceanic circulation and convection in the subpolar Atlantic.

Stastna, M. and W. R. Peltier, 2007, On box models of the North Atlantic thermohaline circulation: Intrinsic and extrinsic millennial timescale variability in response to deterministic and stochastic forcing, *J. Geophys. Res.*, **112**, C10023, doi:10.1029/2006JC003938

Millennial timescale variability in the North Atlantic Ocean circulation is often discussed in terms of concepts that are rooted in the dynamics of simple, low-dimensional box models. In this study we discuss possible explanatory mechanisms for the millennial timescale oscillations of the North Atlantic Thermohaline Circulation that have been revealed by the Greenland ice core record for the late glacial period. We subject three qualitatively different low-order models to stochastic and sinusoidal perturbations: (1) a bistable model, (2) a model with a single stable equilibrium point and a single stable periodic orbit (limit cycle) corresponding to a collapse-flush cycle in the North Atlantic circulation, and (3) a model with a single globally stable equilibrium point which

nevertheless exhibits complex behavior when perturbed. We discuss both the physical nature of the model response and its parameter dependence. We conclude that the traditional definition of stochastic resonance should be expanded and that the temporal characteristics of the noise terms should be considered an integral part of model construction, as they profoundly affect the efficacy of a given explanatory mechanism.

Weaver, A. J., M. Eby, M. Kienast, and O. A. Saenko, 2007, Response of the Atlantic meridional overturning circulation to increasing atmospheric CO2: Sensitivity to mean climate state, *Geophys. Res. Lett.*, **34**, L05708, doi:10.1029/2006GL028756

The dependence on the mean climate state of the response of the Atlantic meridional overturning circulation (AMOC) is investigated in 17 increasing greenhouse gas experiments with different initial conditions. The AMOC declines in all experiments by 15% to 31%, with typically the largest declines in those experiments with the strongest initial AMOC. In all cases, changes in surface heat fluxes, rather than changes in surface freshwater fluxes, are the dominant cause for the transient AMOC decrease. Surface freshwater fluxes actually switch from reducing the transient AMOC decrease, for low values of atmospheric CO2, to reinforcing the transient AMOC decrease, for higher values of atmospheric CO2. In addition, we find that due to changes in the strengths of feedbacks associated with water vapour and snow/sea ice, the climate sensitivity and transient climate response of the UVic model strongly depends on the mean climate state.

Zickfeld, K., M. Eby, and A. J. Weaver (2008), Carbon-cycle feedbacks of changes in the Atlantic meridional overturning circulation under future atmospheric CO2, *Global Biogeochem. Cycles*, **22**, GB3024, doi:10.1029/2007GB003118

An Earth System model of intermediate complexity is used to quantify the effects of potential reorganizations of the Atlantic meridional overturning circulation, ranging from a weakening to a complete shutdown, on future uptake of excess CO2 by the ocean and the terrestrial biosphere. Circulation changes significantly reduce oceanic CO2 uptake, with the largest effects occurring under a complete shutdown. The reduction in uptake is caused to a large extent by a decline in marine export of organic particulate matter. On land, soil carbon increases because of reduced soil respiration in the mid-latitudes of the Northern Hemisphere. This gain is partially compensated by loss of vegetation carbon associated with reduced primary production in the northern high latitudes due to a cooler and dryer climate. Altogether, these processes act to modestly enhance CO2 concentration levels in the atmosphere, thereby leading to a small positive feedback. The rise in atmospheric CO2 ranges from 13 ppm to 34 ppm in 2500, depending on the amount of AMOC weakening, the magnitude of the anthropogenic CO2 perturbation, and the future CO2 fertilization effect.

4.1.3 Deep Water Formation

Saenko, O. A., 2009a, Sensitivity of the subpolar Atlantic climate to local winds, *Geophys. Res. Lett.*, **36**, L03604, doi:10.1029/2008GL036308

The mild climate of northern Europe is thought to be in part maintained by the deep water formation in the northern North Atlantic and the associated meridional overturning circulation. It has been argued that this circulation is controlled by the wind stress in the Southern Ocean. Using a coupled climate model it is shown that the subpolar Atlantic wind stress also plays an important role. A partial or a complete suppression of this wind stress results in the low salinity Arctic waters filling the subpolar Atlantic interior. As a result, the regions of deep water sinking shift southward and the associated overturning circulation, convective activity and oceanic heat loss in the northern North Atlantic strongly weaken. The sea ice advances southward and the North Atlantic climate, including over much of Europe, becomes colder.

Våge, K., R. S. Pickart, V. Thierry, G. Reverdin, C. M. Lee, B. Petrie, T. A. Agnew, A. Wong, and M. H. Ribergaard, 2009, Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007-2008, *Nature Geoscience*, **2**: 67-72, doi:10.1038/ngeo382

In the process of open-ocean convection in the subpolar North Atlantic Ocean, surface water sinks to depth as a distinct water mass, the characteristics of which affect the meridional overturning circulation and oceanic heat flux. In addition, carbon is sequestered from the atmosphere in the process. In recent years, this convection has been shallow or non-existent, which could be construed as a consequence of a warmer climate. Here we document the return of deep convection to the subpolar gyre in both the Labrador and Irminger seas in the winter of 2007–2008. We use profiling float data from the Argo programme to document deep mixing. Analysis of a variety of *in situ*, satellite and reanalysis data shows that contrary to expectations the transition to a convective state took place abruptly, without going through a phase of preconditioning. Changes in hemispheric air temperature, storm tracks, the flux of fresh water to the Labrador Sea and the distribution of pack ice all contributed to an enhanced flux of heat from the sea to the air, making the surface water sufficiently cold and dense to initiate deep convection. Given this complexity, we conclude that it will be difficult to predict when deep mixing may occur again.

Schmittner, A., E. D. Galbraith, S. W. Hostetler, T. F. Pedersen, and R. Zhang, 2007, Large fluctuations of dissolved oxygen in the Indian and Pacific oceans during Dansgaard-Oeschger oscillations caused by variations of North Atlantic Deep Water subduction, *Paleoceanography*, **22**, PA3207, doi:10.1029/2006PA001384

Paleoclimate records from glacial Indian and Pacific oceans sediments document millennial-scale fluctuations of subsurface dissolved oxygen levels and denitrification coherent with North Atlantic temperature oscillations. Yet the mechanism of this teleconnection between the remote ocean basins remains elusive. Here we present model simulations of the oxygen and nitrogen cycles that explain how changes in deepwater subduction in the North Atlantic can cause large and synchronous variations of oxygen minimum zones throughout the Northern Hemisphere of the Indian and Pacific oceans, consistent with the paleoclimate records. Cold periods in the North Atlantic are associated with

reduced nutrient delivery to the upper Indo-Pacific oc eans, thereby decreas ing productivity. Reduced export prod uction diminishes subsurface respiration of organic matter leading to hi gher oxygen concentrations and less denitrification. This effect of reduced oxygen consum ption dominates at low latitudes . At high latitudes in the Southern Ocean and Nort h Pacific, incre ased mixed layer depths and steepening of isopycnals im prove ocean ventilation and oxygen supply to the subsurface. Atmospheric teleconnections through changes in wind-driv en ocean circulation modify this basin-scale patte rn regionally. These re sults suggest that changes in the Atlantic Ocean circu lation, similar to those projected by climate models to possibly occur in the centuri es to com e because of anthropogenic climate warming, can have large effects on m arine ecosystems and biogeochemical cycles even in remote areas.

4.1.4 Labrador Current

Gamboa, G., J. Halfar, S. Hetzinger, W. Ad ey, T. Zack, B. Kunz, and D. E. Jacob, 2010, Mg/Ca ratios in co ralline algae record northwest Atlantic tem perature variations and North Atlantic Osci llation relationships, *J. Geophys. Res.*, **115**, C12044, doi:10.1029/2010JC006262

Climate variability in the North Atlan tic has been link ed in par t to the North Atlantic Oscillation (NAO). The NAO in fluences marine ecosystems in the northwestern Atlantic and transpo rt variability of the co ld Labrador Current. Understanding historic patterns of NAO va riability requires long-term and high-resolution climate records that are no t available from instrumental data. Here we present the first cen tury-scale proxy record of sea surface tem perature (SST) variability from the Ne wfoundland shelf, a region from which other annual-resolution shallow m arine proxies are unavailable. The 116 year record was obtained from three sites along the eas tern Newfoundland shelf using laser ablation inductively coupled mass spectrometry–determined Mg/Ca ratios in the crustose coralline alga *Clathromorphum compactum*. The alga is characterized by a high Mg-calcite skeleton exhibiting a nnual growth increm ents and a century-scale lifespan. Results indicate positive correlations between interannual variations in Mg/Ca ratios and both stati on-based and gridded instrum ental SST. In addition, the record shows high spatial correlations to SST across the Newfoundland shelf and the Gulf of St. Lawrence. Before 1950 the Mg/Ca proxy record reveals significant departures from gridded temperature records. While the Newfoundland shelf is generally considered a region of negativ e correlations to the NAO, the algal tim e series as well as a recent m odeling study suggest a variable negative relationship with the NAO wh ich is strongest after ~1960 and before the mid-1930s.

Han, G., Z. Lu, Z. Wang, J. Helbig, N. Chen, and B. deYoung, 2008, Seasonal variability of the Labrador Current and sh elf circulation off Newfoundl and, *J. Geophys. Res.*, **113**, C10013, doi:10.1029/2007JC004376

Three-dimensional finite element models were established for the Newfoundland and Labrador Shelf to investigate c limatological monthly mean wind- and density-driven circulation. The m odel was forced using w ind stresses from the

National Center for Environmental Prediction-National Center for Atmospheric Research reanalysis data prescribed at the sea surface, large-scale remote forcing determined from a North Atlantic model, monthly mean temperature and salinity climatology, and M_2 tide on the open boundary. The model results were examined against various in situ observations (moored current meter, tide gauge, and vessel-mounted acoustic Doppler current profiler data) and satellite drift measurements and discussed together with literature information. The seasonal mean circulation solutions were investigated in terms of relative importance of wind to density forcing for the Labrador Current. The model results indicate significant seasonal and spatial variations, consistent generally with previous study results and in approximate agreement with observations for the major currents. The region is dominated by the equatorward flowing Labrador Current along the shelf edge and along the Labrador and Newfoundland coasts. The Labrador Current is strong in the fall/winter and weak in the spring/summer. The mean transport of the shelf edge Labrador Current is 7.5 Sv at the Seal Island transect and 5.5 Sv through the Flemish Pass. The seasonal ranges are 4.5 and 5.2 Sv at the two sections, respectively. Density- and wind-driven components are both important in the inshore Labrador Current. The density-driven component dominates the mean component of the shelf edge Labrador Current while the large-scale wind-forcing contributes significantly to its seasonal variability.

Han, G., K. Ohashi, N. Chen, P. G. Myers, N. Nunes, and J. Fischer, 2010, Decline and partial rebound of the Labrador Current 1993–2004: Monitoring ocean currents from altimetric and conductivity-temperature-depth data, *J. Geophys. Res.*, **115**, C12012, doi:10.1029/2009JC006091

Monitoring and understanding of Labrador Current variability is important because it is intimately linked to the meridional overturning circulation and the marine ecosystem off northeast North America. Nevertheless, knowledge of its decadal variability is inadequate because of scarcity of current meter data. By using a novel synthesis of satellite altimetry with conductivity-temperature-depth (CTD) data, we assess the Labrador Current variability north of the Hamilton Bank (56°N) over 1993–2004. Our analysis shows a decline of the surface-to-bottom transport of current by 6.3 ± 1.5 Sv (1 Sv = 10^6 m^3 s^{-1}) in the 1990s (significant at the 99% confidence level) and a likely partial rebound of 3.2 ± 1.7 Sv in the early 2000s (significant at the 89% confidence level only). The inferred multiyear changes in the Labrador Current transport seem to be primarily barotropic and positively correlated (at the 99% level) with the North Atlantic Oscillation at zero lag implying a fast response of the regional circulation to the atmospheric forcing variability. The results compare favorably with direct current measurements and recent model-based findings on the multiyear variability of the subpolar gyre and its underlying mechanisms. The study demonstrates the feasibility of combining altimetry and CTD data for assessing the climatic variability of the boundary currents.

4.1.5 Gulf Stream

Mirshak, R., M. R. Nedimovic, B. J. W. Greenan, B. R. Ruddick, 2010, Coincident Reflection Images of the Gulf Stream from Seismic and Hydrographic Data, *Geophys. Res. Lett.*, **37**, L05602, doi:10.1029/2009GL042359

The development of seismic oceanography requires direct comparison of seismic data to high-resolution oceanographic measurements over long horizontal scales. Here, we compare multichannel seismic (MCS) reflection images to 300 km of spatially-coincident, high-resolution (<1 km) expendable bathythermograph (XBT) surveys that were collected near a frontal region of the Gulf Stream. Fronts, eddies, tendrils, and interleaving were among the features identified in both data sets. In some cases, identification of features would be difficult if only hydrographic data were collected at conventional spatial scales. Comparing MCS reflection images with others derived purely from hydrographic data reveal many similarities and show that interleaving can be clearly identified with seismic methods. Varied time lags between MCS and hydrographic data collection identified the need for the separation between collecting both data sets to be short (i.e. hours to days), with advective processes and decorerlation time scales of desired features affecting acceptable sampling strategies.

Zhai, X., R. J. Greatbatch, and J.-D. Kohlmann, 2008, On the seasonal variability of eddy kinetic energy in the Gulf Stream region, *Geophys. Res. Lett.*, **35**, L24609, doi:10.1029/2008GL036412

In the Gulf Stream region, eddy kinetic energy (*EKE*) peaks in summer while, as measured by the baroclinic eddy growth time scale, the ocean is most baroclinically unstable in late winter. We argue that the seasonally-varying Ekman pumping is unlikely to be responsible for the seasonal variation in growth time, and that the summer peak in EKE results from a reduction in dissipation in summer compared to winter.

4.2 North Atlantic

Våge, K., R. S. Pickart, G. W. K. Moore, and M. H. Ribergaard, 2008, Winter Mixed Layer Development in the Central Irminger Sea: The Effect of Strong, Intermittent Wind Events, *J. Phys. Oceanogr.*, **38**(3): 541–565, doi:10.1175/2007JPO3678.1

The impact of the Greenland tip jet on the wintertime mixed layer of the southwest Irminger Sea is investigated using in situ moored profiler data and a variety of atmospheric datasets. The mixed layer was observed to reach 400 m in the spring of 2003 and 300 m in the spring of 2004. Both of these winters were mild and characterized by a low North Atlantic Oscillation (NAO) index. A typical tip jet event is associated with a low pressure system that is advected by upper-level steering currents into the region east of Cape Farewell and interacts with the high topography of southern Greenland. Heat flux time series for the mooring site were constructed that include the enhancing influence of the tip jet events. This was used to force a one-dimensional mixed layer model, which was able to reproduce the observed envelope of mixed layer deepening in both winters. The deeper mixed layer of the first winter was largely due to a higher number of robust tip jet events,

which in turn was caused by the steering currents focusing more storms adjacent to southern Greenland. Application of the mixed layer model to the winter of 1994–95, a period characterized by a high-NAO index, resulted in convection exceeding 1700 m. This prediction is consistent with hydrographic data collected in summer 1995, supporting the notion that deep convection can occur in the Irminger Sea during strong winters.

Yang, D. and P. G. Myers, 2007, Impact of extended NAO buoyancy forcing on the subpolar North Atlantic and climate variability over the last millenium, *Paleoceanography*, **22**, PA3104, doi:10.1029/2007PA001439

We examine the impact of forcing a regional eddy-permitting ocean model of the subpolar North Atlantic with anomalous buoyancy fluxes corresponding to extended extreme states of the North Atlantic Oscillation (NAO). We find a weakened (enhanced) Meridional Overturning Circulation (MOC) in our low (high) NAO simulations. Such results may be consistent with ideas that suggest the Medieval Warm Period (MWP) and the Little Ice Age are associated with periods when the NAO is predominantly in one phase. Our results also show multidecadal MOC variability with a period of 70 years in our high-NAO simulation, in comparison to an equilibrium-like circulation under low-NAO related forcing. A less stable climatic state is therefore suggested to occur under high-NAO forcing, which may be consistent with ideas that suggest the warming associated with the MWP did not occur synchronously over the North Atlantic. The variability appears to be brought about by internal oceanic processes.

Wu, Y., C. L. Tang, and E. Dunlap, 2010, Assimilation of sea surface temperature into CECOM by flux correction, *Ocean Dyn.*, **60**:403-412, doi:10.1007/s10236-010-0266-6

Sea surface temperature (SST) from a near realtime data set produced from satellites data has been assimilated into a coupled ice-ocean forecasting model (Canadian East Coast Ocean Model) using an efficient data assimilation method. The method is based on an optimal interpolation scheme by which SST is melded into the model through the adjustment of surface heat flux. The magnitude and space-time variation of the adjustment depend on the depth of heat diffusion into the water column in response to changes in surface flux, the correlation time scale of the data, and model and data errors. The diffusion depth is scaled by the eddy diffusivity for temperature. The ratio of the model and data errors is treated as an adjustable parameter. To evaluate the quality of the assimilation, the results from the model with and without assimilation are compared to independent ship data from the Atlantic Zone Monitoring Program and the World Ocean Circulation Experiment. It is shown that the assimilation has a significant impact on the modeled SST, reducing the root mean square difference (RMSD) between the model SST and the ship SST by 0.63°C or 37%. The RMSD of the assimilated SST is smaller than that of the satellite SST by 0.23°C. This suggests that model simulations or predictions with data assimilation can provide the best estimate of the true SST. A sensitivity study is performed to examine the change of the model RMSD with the adjustable parameter in the assimilation equation. The results

show that there is an optimal value of the parameter and the model SST is not very sensitive to the parameter.

4.2.1 The Labrador Sea

Arbic, B. K., J. X. Mitrovica, D. R. MacAyeal, and G. A. Milne, 2008, On the factors behind large Labrador Sea tides during the last glacial cycle and the potential implications for Heinrich events, *Paleoceanography*, **23**, PA3211, doi:10.1029/2007PA001573

Labrador Sea (LS) tidal elevations over the last glacial cycle are investigated in a near-global numerical model that accurately captures the present-day tides. From ~65 ka to ~7 ka, the modeled elevations at the debouchement point of the Hudson Strait ice stream in the LS are exceptionally large, comparable to the largest elevations seen anywhere in the present-day ocean. New numerical simulations performed for this article demonstrate that both local changes in basin geometry (e.g., ice cover over Hudson Bay) and changes outside of the LS led to enhanced LS paleotides. New simulations run at higher horizontal resolution and a considered examination of uncertainties, including uncertainties in the adopted sea level models, strengthen confidence in the robustness of the large LS paleotides. The tide model is run with both spatially uniform sea level drops (taken from curves of eustatic and Red Sea sea levels versus time) and spatially variable sea level maps (taken from two different gravitationally self-consistent viscoelastic solid earth /sea level models, which both account for ice sheet geometry). The tides are larger when the spatially variable sea level models are used. Observations in present-day Antarctica indicate that the mechanical action of tides significantly impacts the dynamics of both continental ice streams and their associated floating ice shelves. It is postulated here that large LS paleotides played a key role in the formation of Heinrich event icebergs, that is, massive discharges of ice from the LS into the glacial North Atlantic ocean. The paleotide calculations described here provide a potential explanation for why the LS region, more than any other, dominated the production of Heinrich event icebergs. Most previous hypotheses of a tidal role in climate variability and ice sheet dynamics focus on tidal mixing. In contrast, here the role of tidal mechanical forcing of ice sheets is emphasized.

Tang, C. L., 2009, A coupled multi-category sea ice model and POM for Baffin Bay and the Labrador Sea, *Chin. J. Polar Sci*., **19**(2): 149-158,

An overview of the seasonal variation of sea-ice cover in Baffin Bay and the Labrador Sea is given. A coupled ice-ocean model, CECOM, has been developed to study the seasonal variation and associated ice-ocean processes. The sea-ice component of the model is a multi-category ice model in which mean concentration and thickness are expressed in terms of a thickness distribution function. Ten categories of ice thickness are specified in the model. Sea ice is coupled dynamically and thermodynamically to the Princeton Ocean Model. Selected results from the model including the seasonal variation of sea ice in Baffin Bay, the North Water polynya and ice growth and melt over the Labrador Shelf are presented.

Kulan, N. and P. G. Myers, 2009, Comparing Two Climatologies of the Labrador Sea: Geopotential and Isopyncal, *Atmos.-Ocean*, **47**(1): 19–39, doi:10.3137/OC281.2009

Two climatologies, one using an isopycnic approach and the other employing a more classical geopotential approach, are produced for the Labrador Sea region. These differ from existing climatologies through the use of smaller search radii, more data and a carefully chosen depth dependent correction scheme. This results in the preservation of the strong fronts that exist between cold, fresh boundary currents and warmer, more saline interior waters and, in general, less smoothing of features. The waters of the West Greenland Current, the Labrador Current and the interior are well represented, especially Labrador Sea Water and the Deep Western Boundary Current. We consider that our 'best' results are produced by the isopycnal climatology. Isopycnal averaging gives more realistic results by reducing artificial mixing of water properties and preserving the baroclinicity of the flow. We estimate the total transport, using the results from the isopycnal climatology in a diagnostic model driven by climatological winds. For the Labrador Current/subpolar gyre at 53°N we find a transport of 46.6 Sv southward, with 9.7 Sv of that being Labrador Sea Water, 12.1 Sv being Gibbs Fracture Zone Water and 8.0 Sv being Denmark Strait Overflow Water. Transport into the Labrador Sea is 41.2 Sv with 6.6 Sv of Labrador Sea Water exported back to the Irminger Sea. Total southward freshwater transport by the Labrador Current (including slope and 'gyre' branches) is 239 mSv at 53°N, with almost 60% of this carried in the upper layer. Import of fresh water to the Labrador Sea from the east in the East Greenland Current is 129 mSv, which is divided almost equally among all layers. Our estimate of the long-term mean formation rate of Labrador Sea Water is between 3.6 and 3.8 Sv.

Lu, Y., D. G. Wright, and I. Yashayaev, 2007, Modelling hydrographic changes in the Labrador sea over the past five decades, *Prog. Oceano.*, **73**(3-4): 406-426, doi:10.1016/j.pocean.2007.02.007

Inter-annual to inter-decadal changes of hydrographic structure and circulation in the subpolar North Atlantic are studied using a coarse resolution ocean circulation model. The study covers 1949 through 2001, inclusive. A "time-mean state nudging" method is applied to assimilate the observed hydrographic climatology into the model. The method significantly reduces model biases in the long-term mean distribution of temperature and salinity, which commonly exist in coarse-resolution ocean models. By reducing the time-mean biases we also significantly improve the model's representation of inter-annual to inter-decadal variations. In the central Labrador Sea, the model broadly reproduces the heat and salt variations of the Labrador Sea Water (LSW) as revealed by hydrographic observations. Model sensitivity experiments confirm that the low-frequency hydrographic changes in the central Labrador Sea are closely related to changes in the intensity and depth of deep convection. Changes in surface heat flux associated with the winter North Atlantic Oscillation (NAO) index play a major role in driving the changes in T–S and sea surface height (SSH). Changes in wind stress play a secondary role in driving these changes but are important in driving

the changes in the depth-integrated circulation. The total changes in both SSH and depth-integrated circulation are almost a linear combination of the separate influences of variable buoyancy and momentum fluxes.

Myers, P. G., S. A. Josey, B. Wheler, and N. Kulan, 2007, Interdecadal variability in Labrador Sea precipitation minus evaporation and salinity, *Prog. Ocean.*, **73**: 341–357, doi:10.1016/j.pocean.2006.06.003

Changes in the air–sea freshwater flux (equivalently Precipitation minus Evaporation, $P - E$) over the interior of the Labrador Sea have been examined using the NCEP/NCAR and ERA40 reanalyses. A major increase in the net precipitation, equivalent to 9 cm yr^{-1}, is observed in the mid-1970s, consistent with a recent study that reported a similar change in the eastern sub-polar gyre. The increase in the Labrador Sea is primarily driven by changes in the P component which occur in spring (and to a lesser extent summer). The seasonality of the change is markedly different to that found for the eastern gyre which had a strong winter increase in precipitation. Potential links between the Labrador Sea $P - E$ increase and the NAO and other leading modes of atmospheric variability have been explored, but it has been found that the increase is not driven by long-term trends in these modes. The magnitudes of the increase in freshwater content for a range of depths (500, 1000, 1500, 2000 m) in the Labrador Sea are then calculated. Finally, it is suggested that the $P - E$ increase must have played some role in causing the observed freshening of the Labrador Sea and the wider North Atlantic sub-polar gyre region in recent decades, although the exact impact cannot be quantified.

Myers, P. G. and C. Donnelly, 2008, Water Mass Transformation and Formation in the Labrador Sea, *J. Clim.*, **21**: 1622-1638, doi:10.1175/2007JCLI1722.1

Objectively analyzed surface hydrographic fields and NCEP–NCAR reanalysis fluxes are used to estimate water mass transformation and formation rates in the Labrador Sea, focusing on Labrador Sea Water (LSW). The authors estimate a mean long-term transformation of between 2.1 ± 0.2 and 3.9 ± 0.3 Sv (Sv $\equiv 10^6$ m^3 s^{-1}) over the years 1960–99 to water with densities greater than $\sigma = 27.65$ kg m^{-3}, depending on the correction used for the latent and sensible heat fluxes. Mean long-term formation rates are found between 0.9 ± 0.2 and 1.7 ± 0.3 Sv for $\sigma = 27.675 - 27.725$ kg m^{-3} and 1.2 ± 0.2 and 2.0 ± 0.3 Sv for $\sigma > 27.725$ kg m^{-3}. There is tremendous variability associated with these formation rates with years of strong water formation (5.7–6.6 ± 0.5–0.7 or 9.5–10.8 ± 0.7–1.1 Sv) mixed with years of little or no formation in the given density ranges. The North Atlantic Oscillation (NAO) is linked (correlation coefficient of 0.45, significant at the 99% level) with the overall formation rate for $\sigma > 27.625$ kg m^{-3}. The observed long-term increase in net precipitation over the Labrador Sea does not seem to have had any significant effect on LSW, potentially reducing LSW transformation rates by 0.1 Sv. A reduction in surface salinity leads to formation occurring at a reduced density, but with little change in the amount of water transformed.

Rattan, S., P. G. Myers, A.-M. Treguier, S. Theetten, A. Biastoch, and C. Böning, 2010, Towards an understanding of Labrador Sea salinity drift in eddy-permitting simulations, *Ocean Modelling,* **35**(1-2): 77-88, doi:10.1016/j.ocemod.2010.06.007

Model drift in the Labrador Sea in eddy permitting model simulations is examined using a series of configurations based on the NEMO numerical framework. There are two phases of the drift that we can identify, beginning with an initial rapid 3-year period, associated with the adjustment of the model from its initial conditions followed by an extended model drift/adjustment that continued for at least another decade. The drift controlled the model salinity in the Labrador Sea, over-riding the variability. Thus, during this initial period, similar behavior was observed between the inter-annually forced experiments as with perpetual year forcing. The results also did not depend on whether the configuration was global, or regional North Atlantic Ocean. The inclusion of an explicit sea-ice component did not seem to have a significant impact on the interior drift. Clear cut evidence for the drift having an advective nature was shown, based on two separate currents/flow regimes. We find, as expected, the representation of freshwater in the sub-polar gyre's boundary currents important. But this study also points out another, equally important process and pathway: the input of high salinity mode water from the subtropical North Atlantic. The advective regime is dependent on the details of the model, such as the representation of the freshwater transport in the model's East Greenland Current being very sensitive to the strength of the local sea surface salinity restoring (and the underlying field that the model is being restored to).

Rykova, T., F. Straneo, J. M. Lilly, and I. Yashayaev, 2009, Irminger Current Anticyclones in the Labrador Sea observed in the hydrographic record, 1990-2004, *J. Mar. Res.*, **67**(3): 361-384, doi:10.1357/002224009789954739

A significant fraction of the lateral heat transport into the Labrador Sea's interior, needed to balance the net heat loss to the atmosphere, is attributed to the Irminger Current Anticyclones. These mesoscale eddies advect warm, salty boundary current water, of subtropical origin, from the boundary current to the interior—but when or how they release their anomalous heat content has not been previously investigated. In this study, we discuss the seasonal and interannual evolution of these anticyclones as inferred from the analysis of hydrographic data from the Labrador Sea from 1990 to 2004. The 29 identified anticyclones fall into two categories, which we refer to as unconvected and convected. Unconvected anticyclones have properties that are close to those of the boundary current, including a fresh surface layer, and they are found near the boundaries and never observed in winter. Convected anticyclones, on the other hand, contain a mixed layer, lack a freshwater cap and are observed throughout the year. Using a one-dimensional mixing model, it is shown that the convected eddies are those Irminger Current Anticyclones that have been modified by the large winter buoyancy loss of the region. This provides evidence that such eddies can survive the strong winter buoyancy loss in the Labrador Sea and that their anomalous heat and salt content is not trivially mixed into the Sea's interior. Finally, we observe a clear trend in the eddies' properties toward warmer and saltier conditions after

1997 reflecting changes in the source waters and the reduced atmospheric forcing over the Labrador Sea.

Tripsanis, E. K. and D. J. W. Piper, 2008, Late Quaternary stratigraphy and sedimentology of Orphan Basin: implications for meltwater dispersal in the southern Labrador Sea, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **260**(3-4): 521-539, doi:10.1016/j.palaeo.2007.12.016

Orphan Basin is a deep-water basin on the continental margin off Newfoundland, which throughout the late Quaternary received proglacial sediment from local ice that crossed the continental shelf. Sediment from more distant sources was transported southward in the Labrador Current as proglacial plumes and in icebergs. Five sedimentary facies related to glacial processes are distinguished in cores recovered from Orphan Basin: hemipelagic sediment, nepheloid-layer deposits (layered mud), beds rich in ice-rafted detritus (IRD), sand and mud turbidites, and glaciogenic debris-flow deposits. IRD-rich beds correspond to periods of intensified iceberg calving, and layered mud, turbidites, and glaciogenic debris-flow deposits with glacial meltwater discharge.

In the Late Wisconsinan, eight periods of meltwater discharge and iceberg calving from the Newfoundland ice sheet are interpreted from the sediment facies in Orphan Basin. These discharges coincide with the terminations of the colder periods of the D–O cycles recorded in Greenland ice cores. The oldest minor meltwater event (27.5–28.5 cal ka) corresponds to the first Late Wisconsinan ice advance across the Grand Banks and NE Newfoundland Shelf. The following three meltwater discharges (23–23.5, 23.8–24.5, and 25–27 cal ka) deposited sand turbidites and glaciogenic debris-flow deposits seaward of Trinity Trough, which was occupied by an ice stream at this time, and mud turbidites in the southern part of the basin derived from a mid-shelf ice margin on the Grand Banks. Four periods of meltwater discharge occurred during the deglaciation and are centered at 15, 18.5, 19.75, and 20.75 cal ka. The youngest is correlated to Heinrich event 1. In the literature, the 18.5 and 20.75 cal ka events have been recorded in multiple glacial settings in the North Atlantic, and therefore, are interpreted as large-scale events of meltwater discharge and iceberg calving, but in Orphan Basin the 19.75 cal ka event is also of similar scale.

Wu, Y., T. Platt, C. L. Tang, and S. Sathyendranath, 2007, Short-term changes in chlorophyll distribution in response to a moving storm – a modelling study, *Mar. Eco. Prog. Ser.*, **335**: 57-68, doi:10.3354/meps335057

Using a 3-D ocean circulation model of the Labrador Sea, we investigated the immediate response, through vertical redistribution of the chlorophyll field, to a steadily moving storm. The model is forced by a prescribed wind and pressure field. The numerical experiments included a control run to analyze the horizontal and vertical structure of the chlorophyll field, and several sensitivity runs to investigate the response to changes in the storm parameters (translation speed, size and intensity) and the seasonal distribution of chlorophyll. The model results showed that after the passage of the storm, surface chlorophyll in the Labrador

Sea is generally increased by vertical mixing. The largest increase occurs in autumn. In summer (control run), the surface chlorophyll concentration is 1 to 3 mg m^{-3} higher than the concentration before the storm in almost all the areas under the influence of the storm. In the shelf regions, however, the increase is very small. The changes in surface chlorophyll concentration are shown to be primarily controlled by the mixed-layer depth and the initial chlorophyll distribution. Nitrate brought from the deep reservoir to the mixed layer by entrainment was estimated from the model. For a typical storm in summer, 3.35×10^3 mol of new nitrate is added to the mixed layer for each km of storm track. Primary production rates following the introduction of new nitrate will contribute to further change in surface chlorophyll, but on a longer time scale.

Wu, Y., C. Tang, S. Sathyendranath, and T. Platt, 2007, The impact of bio-optical heating on the properties of the upper ocean: a sensitivity study using a 3-D circulation model for the Labrador Sea, *Deep Sea Res. II*, **54**(23-26): 2630-2642, doi:10.1016/j.dsr2.2007.08.019

The impact of bio-optical heating on the properties of the upper Labrador Sea water was investigated by considering changes in light attenuation in water associated with the seasonal change of chlorophyll distribution. The time- and depth-dependent attenuation coefficients were obtained from remotely sensed SeaWiFS ocean-colour data. Sea-surface temperature (SST) and mixed-layer depth (MLD) were computed from a three-dimensional ocean circulation model. The model was integrated from 1999 to 2003 with 6-hourly atmospheric forcing. The changes in SST and MLD attributable to bio-optical heating were determined by comparing the model results using the observed attenuation coefficients (chlorophyll) to those using a weak and constant attenuation (clear water). The model results show that bio-optical heating is controlled mainly by chlorophyll concentration and MLD. The increase in SST is around 1 °C in most parts of the Labrador Sea and the shelves, and up to 2.7 °C in areas of shallow MLD and high chlorophyll concentrations (the Grand Banks and Northeastern Newfoundland Shelf). The increase is much higher than that found in previous studies, which was typically a fraction of a degree. Bio-optical heating also can enhance the stratification of the upper ocean and reduce the MLD by 20–50%.

Yashayaev, I., 2007, Hydrographic changes in the Labrador Sea, 1960–2005, *Prog. Ocean.*, **73**(3-4): 242-276, doi:10.1016/j.pocean.2007.04.015

The Labrador Sea has exhibited significant temperature and salinity variations over the past five decades. The whole basin was extremely warm and salty between the mid-1960s and early 1970s, and fresh and cold between the late 1980s and mid-1990s. The full column salinity change observed between these periods is equivalent to mixing a 6 m thick freshwater layer into the water column of the early 1970s. The freshening and cooling trends reversed in 1994 starting a new phase of heat and salt accumulation in the Labrador Sea sustained throughout the subsequent years. It took only a decade for the whole water column to lose most of its excessive freshwater, reinstate stratification and accumulate enough salt and heat to approach its record high salt and heat contents observed between

the late 1960s and the early 1970s. If the recent tendencies persist, the basin's storages of salt and heat will fairly soon, likely by 2008, exceed their historic highs.

The main process responsible for the net cooling and freshening of the Labrador Sea between 1987 and 1994 was deep winter convection, which during this period progressively developed to its record depths. It was caused by the recurrence of severe winters during these years and in its turn produced the deepest, densest and most voluminous Labrador Sea Water ($LSW_{1987–1994}$) ever observed. The estimated annual production of this water during the period of 1987–1994 is equivalent to the average volume flux of about 4.5 Sv with some individual annual rates exceeding 7.0 Sv. Once winter convection had lost its strength in the winter of 1994–1995, the deep $LSW_{1987–1994}$ layer lost "communication" with the mixed layer above, consequently losing its volume, while gaining heat and salt from the intermediate waters outside the Labrador Sea.

While the 1000–2000 m layer was steadily becoming warmer and saltier between 1994 and 2005, the upper 1000 m layer experienced another episode of cooling caused by an abrupt increase in the air-sea heat fluxes in the winter of 1999–2000. This change in the atmospheric forcing resulted in fairly intense convective mixing sufficient to produce a new prominent LSW class (LSW_{2000}) penetrating deeper than 1300 m. This layer was steadily sinking or deepening over the years following its production and is presently overlain by even warmer and apparently less dense water mass, implying that LSW_{2000} is likely to follow the fate of its deeper precursor, $LSW_{1987–1994}$. The increasing stratification of the intermediate layer implies intensification in the baroclinic component of the boundary currents around the mid-depth perimeter of the Labrador Sea.

The near-bottom waters, originating from the Denmark Strait overflow, exhibit strong interannual variability featuring distinct short-term basin-scale events or pulses of anomalously cold and fresh water, separated by warm and salty overflow modifications. Regardless of their sign these anomalies pass through the abyss of the Labrador Sea, first appearing at the Greenland side and then, about a year later, at the Labrador side and in the central Labrador Basin.

The Northeast Atlantic Deep Water (2500–3200 m), originating from the Iceland–Scotland Overflow Water, reached its historically freshest state in the 2000–2001 period and has been steadily becoming saltier since then. It is argued that $LSW_{1987–1994}$ significantly contributed to the freshening, density decrease and volume loss experienced by this water mass between the late 1960s and the mid 1990s via the increased entrainment of freshening LSW, the hydrostatic adjustment to expanding LSW, or both.

Yashayaev, I., and A. Clarke, 2008, Evolution of North Atlantic Water Masses Inferred from Labrador Sea Salinity Series, *Oceanogr.* **21**(1): 30-45

The Labrador Sea is the coldest and freshest basin of the North Atlantic. Winter cooling in this sea produces Labrador Sea Water. This intermediate water plays an important role in the exchange of heat, freshwater, and other substances between the atmosphere and the abyssal ocean, affecting the water masses, circulation, and, ultimately, climate of the subpolar North Atlantic basins. The subpolar gyre of the North Atlantic has exhibited large changes in temperature, salinity, and volume over the past six decades, largely in response to changing winter conditions over the Labrador Sea. The signature of these changes can be seen in the lower limb of the Meridional Overturning Circulation down into the North Atlantic tropics.

Zhu, J., E. Demirov, F. Dupont, and D. Wright, 2010, Eddy-permitting simulations of the sub-polar North Atlantic: impact of the model bias on water mass properties and circulation, *Ocean Dynamics*, **60**(5): 1177-1192, doi 10.1007/s10236-010-0320-4

Some previous studies demonstrated that model bias has a strong impact on the quality of long-term prognostic model simulations of the sub-polar North Atlantic Ocean. Relatively strong bias of water mass characteristics is observed in both eddy-permitting and eddy-resolving simulations, suggesting that an increase of model resolution does not reduce significantly the model bias. This study is an attempt to quantify the impact of model bias on the simulated water mass and circulation characteristics in an eddy-permitting model of the sub-polar ocean. This is done through comparison of eddy-permitting prognostic model simulations with the results from two other runs in which the bias is constrained by using spectral nudging. In the first run, the temperature and salinity are nudged towards climatology in the whole column. In the second run, the spectral nudging is applied in the surface 30 m layer and at depths below 560 m only. The biases of the model characteristics of the unconstrained run are similar to those reported in previous eddy-permitting and eddy-resolving studies. The salinity in the surface and intermediate waters of the Labrador Sea waters increases with respect to the climatology, which reduces the stability of the water column. The deep convection in the unconstrained run is artificially intensified and the transport in the sub-polar gyre stronger than in the observations. In particular, the transport of relatively salty and warm Irminger waters into the Labrador Sea is unrealistically high. While the water mass temperature and salinity in the run with spectral nudging in the whole column are closest to the observations, the depth of the winter convection is underestimated in the model. The water mass characteristics and water transport in the run with spectral nudging in the surface and deep layers only are close to observations and at the same time represent well the deep convection in terms of its intensity and position. The source of the bias in the prognostic model run is discussed.

4.2.1.1 Biophysical Processes

Harrison, W. G., and W. K. W. Li, 2007, Phytoplankton Growth and Regulation in the Labrador Sea: Light and Nutrient Limitation, *J. Northw. Atl. Fish. Sci.*, **39**: 71–82, doi:10.2960/J.v39.m592

The importance of light and nutrients in regulating phytoplankton growth in the Labrador Sea was evaluating using climatological data, 12 years of measurements made as part of the Labrador Sea Monitoring Program (LSMP) and physiological information from the literature. Light limits primary production and phytoplankton growth much of the year, even during summer when surface irradiance is at its seasonal peak. Nutrients, nitrogen (nitrate) and silicate, are reduced to low levels in surface waters in summer/autumn and can limit phytoplankton production and growth at this time of year. Nitrate appears to be the nutrient in shortest supply on the Labrador Shelf while silicate is in shortest supply in the central Labrador Basin. Multiyear trends in regional hydrography (increases in water temperatures, decreases in mixed layer depth) and changes in nitrate and silicate supply over the past decade (*i.e.* increases in nitrate and decreases in silicate) may be linked to changes in phytoplankton community composition and structure (*i.e.* decreases in large forms such as diatoms and increases in small picoplankton and nanoplankton forms).

Wu, Y., T. Platt, C. L. Tang, S. Sathyendranath, E. Devred, and S. Gu, 2008, A summer phytoplankton bloom triggered by high wind events in the Labrador Sea, July 2006, *Geophys. Res. Lett.*, **35**, L10606, doi:10.1029/2008GL033561

The mechanisms of nutrient resupply for an episodic phytoplankton bloom observed in the central Labrador Sea in July 2006 were investigated. Two physical processes, mixed-layer deepening and Ekman pumping, are proposed to account for the implied nutrient replenishment. The nutrient flux and chlorophyll concentration before and during the bloom were estimated from a simple coupled nitrate-phytoplankton model. The model results show that the enrichment of nutrients in the euphotic layer and the subsequent bloom were related to two wind events (storms) in the period July 7–10. As the mixed layer deepened, nutrient from below the nitricline were entrained into the euphotic zone. The Ekman pumping, which was most intense at the storm centre, enhanced the transport of the nutrients by raising the nitricline. However, Ekman pumping alone was not able to transport sufficient nitrate to the euphotic layer to support the observed phytoplankton bloom.

Wu, Y. S., T. Platt, C. L. Tang, and S. Sathyendranath, 2008, Regional differences in the timing of the spring bloom in the Labrador Sea, *Mar. Ecol. Prog. Ser.*, **355**: 9-20, doi:10.3354/meps07233

The environmental factors that control the timing of the spring bloom in the Labrador Sea were investigated using ocean color data from satellites, historical oceanographic data and a primary production model. From the satellite data, the onset of the spring bloom was found to progress with the season from south to north, with the exception of the northern Labrador Sea. The onset for the northern Labrador Sea occurred at approximately the same time as in the southern Labrador Sea. Two possible factors for the regional differences were examined from the data: irradiance and mixed-layer depth (MLD). The early bloom in the northern Labrador Sea is related to the very shallow mixed layer associated with low-salinity water. The temporal variations of the mean chlorophyll concentration

in 4 regions of the Labrador Sea (the Grand Banks, southern, central and northern Labrador Sea) during the growth phase of the spring bloom were modeled using a primary production model with MLD derived from historical temperature-salinity data. The temporal variations, in particular the early bloom in the northern Labrador Sea, were well reproduced by the model. A model sensitivity study showed that the onset of the spring bloom is highly sensitive to MLD. This confirms the finding from the data that MLD is a critical environmental factor for the spring bloom. The availability of the photosynthetically active radiation plays an important role, but is not a determining factor of the early bloom in the northern Labrador Sea. The sensitivity study also showed that pre-bloom oceanographic conditions and attenuation of light in water have a greater effect on the timing in a shallow mixed layer than in a deeper mixed layer.

Yebra, L., R. P. Harris, E. J. H. Head, I. Yashayaev, L. R. Harris, and A. G. Hirst, 2009, Mesoscale physical variability affects zooplankton production in the Labrador Sea, *Deep Sea Res.*, **56**(5): 703-715, doi:10.1016/j.dsr.2008.11.008

Surface distribution (0–100 m) of zooplankton biomass and specific aminoacyl-tRNA synthetases (AARS) activity, as a proxy of structural growth, were assessed during winter 2002 and spring 2004 in the Labrador Sea. Two fronts formed by strong boundary currents, several anticyclonic eddies and a cyclonic eddy were studied. The spatial contrasts observed in seawater temperature, salinity and fluorescence, associated with those mesoscale structures, affected the distributions of both zooplankton biomass and specific AARS activity, particularly those of the smaller individuals. Production rates of large organisms (200–1000 μm) were significantly related to microzooplankton biomass (63–200 μm), suggesting a cascade effect from hydrography through microzooplankton to large zooplankton. Water masses defined the biomass distribution of the three dominant species: *Calanus glacialis* was restricted to cold waters on the shelves while *Calanus hyperboreus* and *Calanus finmarchicus* were widespread from Canada to Greenland. Zooplankton production was up to ten-fold higher inside anticyclonic eddies than in the surrounding waters. The recent warming tendency observed in the Labrador Sea will likely generate weaker convection and less energetic mesoscale eddies. This may lead to a decrease in zooplankton growth and production in the Labrador basin.

4.2.1.2 Labrador Sea Water

Yashayaev, I., M. Bersch, and H. M. van Aken, 2007, Spreading of the Labrador Sea Water to the Irminger and Iceland basins, *Geophys. Res. Lett.*, **34**, L10602, doi:10.1029/2006GL028999

Labrador Sea Water (LSW) is a principal convectively-formed water mass of the subpolar North Atlantic (SPNA). Using extensive oceanographic archives we demonstrate striking changes in SPNA caused by massive LSW production during 1987–1994 and document recent salinification and warming, imminently bringing SPNA to the state last time seen in the 1960s. Two prominent LSW classes are spreading across SPNA since the 1980s. The first, record dense, deep, and voluminous, class has been progressively built by intense winter convection

through 1987–1994. Even though most of this LSW has left SPNA, its remnants are still present there. The second, shallower, class strengthens in 2000; over subsequent years its core becomes slightly thicker and deepens. The anomalous signals acquired by these LSW classes in their formation region arrive in the Irminger and Iceland basins with the characteristic delays of two and five years for deeper LSW and a year and four years for shallower LSW.

Yashayaev, I., H. M. van Aken, N. P. Holliday, and M. Bersch, 2007, Transformation of the Labrador Sea Water in the subpolar North Atlantic, *Geophys. Res. Lett.*, **34**, L22605, doi:10.1029/2007GL031812

Development, spreading and decay of the thermohaline properties of two Labrador Sea Water (LSW) classes are described. During the development phase, a specific LSW class repeatedly mixed by winter convection in the Labrador Sea becomes colder, denser, thicker and deeper. Once convection weakens, the LSW class becomes isolated from the upper layer and starts to decay, rapidly losing its volume while retaining the same density due to isopycnal mixing with the neighbouring warm saline intermediate waters. A similar pattern in temperature, salinity and density is seen in the other basins with different time lags from about two years in the Irminger Sea to ten years in the northern Iceland Basin and Rockall Trough regions. The influence of LSW on the thermohaline properties of other North Atlantic water masses is also discussed.

Yashayaev, I., N. P. Holliday, M. Bersch, and H. M. van Aken, 2008, The History of the Labrador Sea Water: Production, Spreading, Transformation and Loss, Arctic-Subarctic Ocean Fluxes, 569-612, doi:10.1007/978-1-4020-6774-7_25

North Atlantic Deep Water (NADW) is a water mass that is central to the oceanography of the deep Atlantic, the global meridional overturning circulation (MOC), and the climate of the Earth itself. The subpolar Atlantic is an especially important place for these phenomena because of the large changes wrought on NADW in these basins. Indeed, once it is discharged past 45°N, NADW temperature and salinity are altered at substantially slower rates before encountering Circumpolar Deep Waters in the subpolar ocean of the southern hemisphere (McCartney and Talley 1984; Reid et al. 1977). Formation of NADW, recirculation through the subpolar gyre, and injection into the subtropical ocean past Newfoundland are therefore central issues to ASOF science and are discussed here.

Yashayaev, I., and J. W. Loder, 2009, Enhanced production of Labrador Sea Water in 2008, *Geophys. Res. Lett.*, **36**, L01606, doi:10.1029/2008GL036162

A May 2008 oceanographic survey of the Labrador Sea and recent Argo float profiles have revealed that convective overturning extended to a depth of about 1600 m during the winter of 2008, resulting in the production of a large ''year class'' of Labrador Sea Water. This convection was the deepest since 1994, and substantially exceeded the convection to 500–1100 m in the past few years in both the Labrador and Irminger Seas. The resultant 0.2_C cooling of the intermediate-depth waters in the Labrador Sea has disrupted a steady warming of these waters

since 1994. The cumulative heat loss from the ocean to the atmosphere during the 2007–2008 cooling season was the largest since the mid-1990s and exceeded the 2000–2007 mean by about 50%. This indicates that enhanced atmospheric cooling, apparently associated with below-normal air temperatures in the region, was the predominant factor contributing to the enhanced LSW production in 2008.

4.3 Application of Satellite Altimetry

Devred, E., S. Sathyendranath, and T. Platt, 2009, Decadal changes in ecological provinces of the Northwest Atlantic Ocean revealed by satellite observations, *Geophys. Res., Lett.,* **36**, L19607, doi:10.1029/2009GL039896

Detecting the effect of climate change on ocean ecosystems is facilitated if the data are partitioned into ecological provinces. It is recognised that the boundaries of such provinces are dynamic, raising the imperative for frequent observations. Using satellite data, we have assembled a time series of ecosystem delineation for the Northwest Atlantic Ocean over a period of ten years. For each province identified in the study area, we have compiled data on sea-surface temperature, and on the biomass and community composition of phytoplankton. We find significant trends in these properties but they vary according to the province concerned, which emphasizes how the physical and biological changes are correlated at large scale. Comparisons between the trends computed using the average position of the provinces and the trends derived when accounting for the movements of the boundaries underline the value of the new approach.

Han, G., 2007, Satellite Observations of Seasonal and Interannual Changes of Sea Level and Currents over the Scotian Slope, *J. Phys. Oceanogr.*, **37**(4): 1051–1065

Seasonal and interannual sea level and current variations over the Scotian slope are examined using 10 years of Ocean Topography Experiment (TOPEX)/Poseidon (T/P) satellite altimeter data. Geostrophic surface current anomalies normal to ground tracks are derived from the along-track gradients of sea level anomalies. The altimetric current anomalies are combined with a climatological mean circulation field of a finite-element model to construct nominal absolute currents. The seasonal mean results indicate that the sea level is highest in late summer and lowest in late winter and that the surface slope circulation is strong in winter/autumn and weaker in summer/spring. The total transport associated with the westward shelf-edge current and with the eastward slope current, calculated by combining the T/P data with a climatological seasonal mean density field, reveals a substantial seasonal change dominated by the barotropic component. The present analysis reveals prominent interannual changes of the sea level and current anomalies for the study period. The sea level was lowest in 1996/97, when the Gulf Stream was in its most southern position. The mean winter circulation over the Scotian slope was strongest (up to 30 cm s^{-1} in both the southwestward shelf-edge current and northeastward slope current) in 1998 and weakest (weaker and broader shelf-edge current) in 1996, which may be related to the fluctuation of the equatorward Labrador Current strength and of the Gulf Stream north–south position. The study also suggests that the root-mean-

square current magnitude is positively correlated with the occurrence of the Gulf Stream warm-core rings (WCRs) on the interannual scale, while WCR yearly mean kinematic properties seem to have small variations.

Han, G. and J. Li, 2008, Sea level and geostrophic current features from tandem TOPEX/Poseidon-Jason data in the Newfoundland offshore, *Int. J. Rem. Sens.*, **29**(1): 265-280, doi:10.1080/01431160701271982

We have investigated sea level and surface currents features over the Newfoundland Shelf and Slope using the tandem TOPEX/Poseidon (T/P) and Jason altimetry data (2002-2003). The consistency and error characteristics of T/P and Jason measurements are examined not only in terms of sea level and cross-track current anomalies but also with respect to current anomalies at crossovers and the Labrador Current transport. Nominal absolute currents are constructed by adding the altimetric geostrophic current anomalies to a climatological-mean model circulation field. The comparison of the sea level and cross-track current anomalies from January to July 2002 shows overall good agreement between T/P and Jason, with correlation coefficients different from zero at the 95% confidence level at almost all locations for sea level and at most locations for currents. Errors are estimated to be 2.5 cm for sea level and 10 cm/s for cross-track current anomalies. Analyses of the current variability at crossovers indicate approximate agreement of T/P and Jason measurements, except for the Northeastern Newfoundland Shelf and Slope probably due to the ice presence during the period. Model-altimetry combined absolute currents are used to estimate near-surface transport associated with the shelf-edge Labrador Current, showing good correlation between T/P and Jason estimates and strong seasonal changes. The cross-track geostrophic current anomalies from September 2002 to December 2003 are used to calculate the root-mean-square (rms) current variability at crossovers and to derive the shelf-edge Labrador Current. The interleaved T/P and Jason observations can better capture the spatial distribution of shelf and slope circulation variability.

Han, G., J. Loder, and B. Petrie, 2010, Tidal and non-tidal sea level variability along Nova Scotia coast from satellite altimetry, *Int. J. of Remote Sensing*, **31**(17-18): 4791-4806, doi:10.1080/01431161.2010.485152

TOPEX/Poseidon (T/P) sea level data are used to investigate tidal and non-tidal sea level variability over the Scotian Shelf. Eight major diurnal and semi-diurnal tidal constituents are derived from the September 1992 to December 2001 T/P data. The present altimetric tides agree generally with *in situ* observations and show an error reduction of over 30° in phase over Han *et al.*'s [Han, G., Ikeda, M. and Smith, P.C., 1996, Oceanic tides on the Newfoundland and Scotian Shelves from TOPEX/POSEIDON altimetry. *Atmosphere-Ocean*, **34**, pp. 589-604] results for the diurnal tides. De-tided T/P sea level data are used to provide geo-referenced seasonal-mean sea surface topography during the period September 1992 to July 2002. The T/P data are explored to estimate seasonal-mean sea level along the Nova Scotia coast. Comparisons with sea level measurements from coastal tide gauges are carried out to evaluate the potential of altimetry data for

coastal sea level monitoring. Seasonally the sea level is highest along the coast in late autumn/early winter (associated with the peak of the Nova Scotian Current), and over the Scotian Slope in summer. On the interannual scale it was low in the early 1990s, high in the mid 1990s, and close to normal in the late 1990s and early 2000s.

Higginson, S., K. R. Thompson, and Y. Liu, 2009, Estimating ocean climatologies for short periods: A simple technique for removing the effect of eddies from temperature and salinity profiles, *Geophys. Res. Lett.*, **36**, L19602, doi:10.1029/2009GL039647

Existing temperature and salinity ocean climatologies are usually mean fields based on observations collected over many decades. Because of low frequency variability of major features such as the Gulf Stream it is often more appropriate to define the mean for shorter periods, but there are subsequently fewer observations and more problems with aliasing of mesoscale variability. We present a method for removing eddy-related noise from observations using satellite altimeter sea surface height measurements. We demonstrate the technique using Argo observations from the northwest Atlantic and produce mean temperature and salinity fields for an eight year period. The reduction in variance achieved is quantified. Comparison with an existing climatology shows that there is good agreement between the two analyses but that the representation of the Gulf Stream is more realistic in the new climatology.

Liu, Y. and K. R. Thompson, 2009, Predicting Mesoscale Variability of the North Atlantic Using a Physically Motivated Scheme for Assimilating Altimeter and Argo Observations, *Mon. Wea. Rev.*, **137**: 2223–2237, doi:10.1175/2008MWR2625.1

A computationally efficient scheme is described for assimilating sea level measured by altimeters and vertical profiles of temperature and salinity measured by Argo floats. The scheme is based on a transformation of temperature, salinity, and sea level into a set of physically meaningful variables for which it is easier to specify spatial covariance functions. The scheme also allows for sequential correction of temperature and salinity biases and online estimation of background error covariance parameters. Two North Atlantic applications, both focused on predicting mesoscale variability, are used to assess the effectiveness of the scheme. In the first application the background is a monthly temperature and salinity climatology and skill is assessed by how well the scheme recovers Argo profiles that were not assimilated. In the second application the backgrounds are short-term forecasts made by an eddy-permitting model of the North Atlantic. Skill is assessed by the quality of forecasts with lead times of 1–60 days. Both applications show that the scheme has useful skill.

Montenegro, A. and G. L. Weatherly, 2007, Deep variability in the Atlantic Western Boundary Current based on altimetric and expendable bathythermograph data, *J. Geophys. Res.*, **112**, C06018, doi:10.1029/2005JC003237

The deep variability in two areas of the Atlantic Western Boundary is studied. One site is located at 38°N, inshore of the Gulf Stream. The other is at 8°S, off the Brazilian coast. Analyses are centered on current time series estimated by a

method that uses expendable bathythermograph derived dynamic heights to remove the near-surface signal from altimetric sea surface height. Both series are approximately 6 years long. Currents are compared to scatterometer derived alongshore wind stress and basin-wide wind stress curl. In both areas, current variability is correlated to basin-averaged wind stress curl and also to alongshore wind stress. The relationship between currents and wind curl is coherent with the western boundary currents response to interior Sverdrup flow. We propose that alongshore wind stress exerts control over the flow by divergence of the Ekman flow at the coast. In the north, the variability is dominated by interannual oscillations of the wind curl. The effects of the alongshore stress are secondary and have annual frequency. In the southern site, the alongshore effect appears to be the dominant forcing. The main observed results are confirmed by data from a numerical model with 1/6° horizontal resolution.

Thompson, K. R., J. Huang, M. Véronneau, D. G. Wright, and Y. Lu, 2009, Mean surface topography of the northwest Atlantic: Comparison of estimates based on satellite, terrestrial gravity, and oceanographic observations, *J. Geophys. Res.*, **114**, C07015, doi:10.1029/2008JC004859

The accuracy of a new mean sea surface topography (MSST) of the northwest Atlantic is assessed. The MSST is estimated from 12 years of altimeter observations referenced with respect to a new regional geoid based on a blend of Gravity Recovery and Climate Experiment (GRACE), terrestrial, and altimeter-derived gravity data. The new MSST is first compared to a recently published mean surface topography calculated using an eddy-permitting model of the North Atlantic. Geostropic currents calculated from the GRACE-based MSST are next compared to mean surface currents in the northwest Atlantic estimated from the motion of near-surface drifters corrected for surface Ekman effects. Finally, the mean path of the Gulf Stream is compared to the line of zero skewness of sea level variability which provides a measure of the mean path of unstable, intense ocean currents. Overall the agreement amongst the various estimates of surface topography and circulation is excellent. There are, however, some significant differences that can be separately attributed to problems with the MSST and, in some cases, with the ocean model (in particular the ocean climatology to which it was nudged).

4.4 Atlantic Storms

Jiang, J., and W. Perrie, 2008, Climate change effects on North Atlantic cyclones, *J. Geophys. Res.*, **113**, D09102, doi:10.1029/2007JD008749

We investigated the possible climate change impacts on midlatitude northwest Atlantic storms using a mesoscale atmospheric model driven by the second-generation Coupled Global Climate Model (CGCM2) environmental fields, for control (1975–1994) and high-CO_2 (2040–2059) years of the Intergovernmental Panel on Climate Change (IPCC) IS92a scenarios. Using ensemble experiments, we show that for a given storm initialization location, the high-CO_2 climate change scenario results in slightly higher mean peak storm intensity than that of the control climate. However, the impact of averaged environmental scenario

fields on storm intensity and track is dependent on the storm initialization location within these averaged scenario fields. Under the climate change scenario, storms that are initially located south of 35° N and west of 65°W exhibit the largest differences in storm intensities and tracks, compared to the present climate. Storms with trajectories that move close to the upper level steering jet exhibit the largest differences in mean tracks, moving closer to the North American coast.

Jiang, J., and W. Perrie, 2009, The impacts of climate change on autumn North Atlantic midlatitude cyclones, *J. Clim.*, **20**: 1174-1187, doi:10.1175/JCLI4058.1

This study explores how midlatitude extratropical cyclone intensities, frequencies, and tracks can be modified under warming-induced conditions due to enhanced greenhouse gas (GHG) concentrations. Simulations were performed with the Canadian mesoscale compressible community (MC2) model driven by control and high CO_2 climate estimates from the Canadian Climate Centre model, the Second Generation Coupled Global Climate Model (CGCM2). CGCM2 simulations have effective CO_2 concentration forcing, following the Intergovernmental Panel on Climate Change (IPCC) IS92a scenario conditions, which define a near doubling of CO_2 concentrations by 2050 compared to the 1980s. The control and high CO_2 conditions were obtained from years 1975-94 and 2040–59 of CGCM2 simulations. For the northwest Atlantic, the CO_2-induced warming for this period (2040-59) varies from ~1°-2°C in the subtropics, near the main development region for Atlantic hurricanes, to ~1°C in the north. In simulations of northwest Atlantic storms, the net impact of this enhanced CO_2 scenario is to cause storms to increase in radius, with marginal tendencies to become more severe and to propagate faster (although not statistically significant), and for the mean storm tracks to shift slightly poleward.

Lalbeharry, R., R. Bigio, B. R. Thomas, and L. Wilson, 2009, Numerical Simulation of Extreme Waves During the Storm of 20–22 January 2000 Using Winds Generated by the CMC Weather Prediction Model, *Atmos.-Ocean*, **47**(1): 99–122, doi:10.3137/OC292.2009

The storm of 20–22 January 2000 over Canada's Atlantic Provinces was an exceptional storm for several reasons, these include extremely high coastal ocean waves, widespread coastal damage due to the storm surge, very strong winds over a large area, an extremely fast deepening rate, and a very low central pressure. It produced unusually large waves which caused significant damage in communities along the south coast of Newfoundland and the eastern shores of Nova Scotia. Bottom scouring was observed around the feet of three mobile offshore oil and gas drilling platforms operating near Sable Island. Using buoy data enhanced with a detailed data set from one of the platforms, this study examines the growth of destructive waves and the performance of two state-of-the-art third generation ocean wave models running in shallow water mode. The wave models perform well in numerically simulating the extreme waves associated with this storm. They correctly predict the growth of wind waves and handle the arrival of long-period swells well. Unprecedented waves that damaged buildings and a lighthouse in the Channel Head area of Port-Aux-Basques retained most of their deep-water

energy until they were less than one wavelength from the beach. Computations show that dynamic (or trapped) fetch was not a contributing factor in the generation of the observed extreme sea states although the long-period swells were supported by winds for a significant part of their transit northward. However, it appears that the model-generated enhanced wave growth at the buoy location just off the southwestern coast of Newfoundland may be partially linked to the creation of model trapped fetch. The January 2000 storm was indeed an extreme storm and was the most intense non-tropical storm to form over Atlantic Canada in decades.

Mulligan, R. P., A. E. Hay, and A. J. Bowen, 2008, Wave-driven circulation in a coastal bay during the landfall of a hurricane, *J. Geophys. Res.*, **113**, C05026, doi:10.1029/2007JC004500

A coupled wave/flow model was used to simulate the currents in a coastal bay during the landfall of a hurricane with large waves. Extensive wave breaking along the shoreline and over a midbay shoal induced the development of a strong mean circulation in the bay, in combination with currents forced by wind, tide, and storm surge. The general circulation pattern consisted of inflows along the shoreline and over the shoal region that were driven by radiation stress gradients, and outflows due to mass balance of the wave-driven inflow that were observed in deeper channels. The predicted currents agreed with observations only when wave forcing was included in the circulation model. Wave-driven flows accounted for over 50% of the high flushing rates during the storm and induced strong horizontal velocity gradients over short (~200 m) length scales.

Mulligan, R. P., A. J. Bowen, A. E. Hay, A. J. van der Westhuysen, and J. A. Battjes, 2008, Whitecapping and wave field evolution in a coastal bay, *J. Geophy. Res.*, **113**, C03008, doi:10.1029/2007JC004382

Evolution of the wave field in a coastal bay is investigated, by comparison between field observations and numerical simulations using a spectral wave model (Simulating WAves Nearshore (SWAN)). The simulations were conducted for the passage of an extratropical storm, during which surface elevation spectra were bimodal owing to local wind-sea generation and swell propagation into the bay. SWAN was run in stationary and nonstationary mode for two whitecapping source term formulations. The first was developed by Komen et al. (1984) and is dependent on spectrally averaged wave steepness, and thus includes swell in the calculation of whitecapping dissipation and typically overestimates wind sea in the presence of swell. The second, proposed by van der Westhuysen et al. (2007), estimates whitecapping of wind sea locally in the wave spectrum and is not coupled to swell energy. This formulation reproduced the magnitude and shape of the observed wind-sea spectral peak much better than the previous formulation. Whitecapping dissipation rates have been estimated from observations, using the equilibrium range theory developed by Phillips (1985), and are well correlated with both wind speed and acoustic backscatter observations. These rates agree with SWAN estimates using the spectrally local expression, and provide additional physical validation for the whitecapping source term.

Padilla-Hernández, R., W. Perrie, B. Toulany, P. C. Smith, 2007, Modeling of Two Northwest Atlantic Storms with Third-Generation Wave Models, *Wea. Forecasting*, **22**, 1229–1242, doi:10.1175/2007WAF2005104.1

In this study, three state-of-the-art operational forecast wave models are implemented on nested grids in order to achieve fine-resolution wave simulations (0.1°) in the Gulf of Maine and related northwest Atlantic waters. These models are the Simulating Waves Nearshore (SWAN) model, the Wave Action Model (WAM), and WAVEWATCH-III (hereafter WW3). Model performance is evaluated through comparisons with field measurements. Four composite model systems are compared: WAM and WW3 implemented on three nested domains, SWAN nested within WAM, and SWAN nested within WW3. Storm case studies include two intense midlatitude winter storms from January 2000 and January 2002. Although the models are comparable in terms of their overall performance and skill, it is found that WW3 provides a better statistical fit to the observed wave data compared with the other models, and that SWAN gives slightly better results if nested within WW3, rather than within WAM.

Perrie, W., W. Zhang, M. Bourassa, H. Shen, and P. W. Vachon, 2008, Impact of satellite winds on marine winds imulations, Wea. Forecasting, **23**(2): 290–303, doi:10.1175/2007WAF2006093.1

A variational data assimilation method is applied to remotely sensed wind data from Hurricanes Gustav (2002) and Isabel (2003) to produce enhanced marine wind estimates. The variational method utilizes constraints to ensure that an optimum combination of winds is determined, in the sense of minimization of a cost function measuring the misfit between observations and background input field data and constraining nongeophysical features in the spatial derivatives. Constraints are multiplied by weights, which are objectively determined by cross validation. Verification is obtained by comparison with available operational in situ buoy observations and analyses winds. It is shown that the newly constructed midlatitude wind fields represent an improvement relative to background wind field estimates and also relative to Quick Scatterometer–National Centers for Environmental Prediction reanalysis blended winds, and that the new winds have an impact on simulations of waves and upper-ocean currents.

Sheng, J., L. Wang, S. Andréfouët, C. Hu, B. G. Hatcher, F. E. Muller-Karger, B. Kjerfve, W. D. Heyman, and B. Yang, 2007, Upper ocean response of the Mesoamerican Barrier Reef System to Hurricane Mitch and coastal freshwater inputs: A study using Sea-viewing Wide Field-of-view Sensor (Sea WiFS) ocean color data and a nested-grid ocean circulation model, *J. Geophys. Res.*, **112**, C07016, doi:10.1029/2006JC003900

The passage of category-5 Hurricane Mitch through the Mesoamerican Barrier Reef System (MBRS) in October 1998 was an extreme event with the potential to create unusual patterns of reef connectivity. The impact of this hurricane on the upper ocean of the MBRS is investigated using a triply nested grid ocean circulation modeling system. The model results are validated with contemporaneous ocean color data from the Sea-viewing Wide Field-of-view

Sensor (SeaWiFS) satellite and oceanographic measurements in the MBRS. The nested grid system is forced by 6-hourly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) winds for the first 294 days prior to the arrival of the hurricane in the MBRS, and then by the combination of the NCEP/NCAR wind-forcing and an idealized vortex representative of Mitch for the following 20 days. The system is also forced by the monthly mean sea surface heat and freshwater fluxes and buoyancy forcing associated with major river discharges and storm-induced precipitation in the western Caribbean Sea. The simulated upper ocean circulation during Mitch is characterized by strong and divergent currents under the storm and intense near-inertial currents and sea surface temperature cooling behind the storm. The nested grid system also reproduces the buoyant estuarine plumes extending from the coast off Honduras as inferred from SeaWiFS satellite data and detected in field measurements at Gladden Spit in Belize shortly after the passage of Hurricane Mitch. The present model results suggest that populations of site-attached organisms associated with nearshore and offshore reef features that are dynamically isolated in normal conditions experienced greater potential for ecological connection under Mitch's extreme conditions.

Wang, L., J. Sheng, A. E. Hay, and D. J. Schillinger, 2007, Storm-Induced Circulation in Lunenburg Bay of Nova Scotia: Observations and Numerical Simulations, *J. Phys. Oceanogr.*, **37**(4): 873–895

An extreme weather event (Hurricane Juan) made landfall in Nova Scotia, Canada, in September 2003. The storm produced an ~70-cm storm surge and ~40 cm s^{-1} coastal currents in Lunenburg Bay, registered by a coastal observing system. A fine-resolution (60 m) coastal circulation model is used to examine the response of Lunenburg Bay to Hurricane Juan. The model is forced by local wind stress at the sea surface, and tides and remotely generated waves specified at model open boundaries. The model performance is assessed in terms of γ^2, the variance of the model errors normalized by the observed variance. The model reproduces very well the observed surface elevations with γ^2 values of less than 0.05, and reasonably well the observed currents with γ^2 values between 0.2 and 1.1 in the bay during Hurricane Juan. The model–data comparisons demonstrate that the coastal circulation in the bay is significantly affected by local wind associated with the storm. The model results are also used to demonstrate the importance of nonlinear dynamics in the barotropic response of the bay to the storm.

Yao, Y., W. Perrie, W. Zhang, and J. Jiang, 2008, The characteristics of atmosphere-ocean interactions along North Atlantic extratropical storm tracks, *J. Geophys. Res.*, **113**, D14124, doi:10.1029/2007JD008854

This study explores the characteristics of the air-sea interactions and extratropical autumn storms in the northwest Atlantic. Simulations are performed with a relatively fine resolution coupled atmosphere-ocean model system. The model system consists of the Canadian Mesoscale Compressible Community atmospheric model coupled to a recent version of the Princeton Ocean model.

Atmospheric boundary conditions for storm simulations are given by the Canadian Climate Centre model, Second Generation Coupled Global Climate Model (CGCM2), following the Intergovernmental Panel on Climate Change IS92a scenario conditions. The CGCM2 control conditions are obtained from simulated years 1975–1994. Our results show that interactions between extratropical storms and the upper ocean are affected by the upper ocean, latent and sensible heat fluxes across the air-sea interface, and the atmospheric structure, which propagates relative to the ocean surface as storms move along their storm tracks. Three types of numerical storm experiments are conducted, for storms that (1) make landfall, (2) move along the coastline without landfall, and (3) remain over the open ocean. Our results suggest that the locations of the maximum storm-induced sea surface temperature (SST) cooling are mainly dominated by the upper ocean thermostructure. The storm's intensity, as represented by its maximum wind speed, can cause further SST cooling. In turn, the upper ocean can reduce storm intensity by as much as 4–5 hPa in minimum sea level pressure, or 2–4 m s^{-1} in surface winds. Although the impacts of these effects are most notable in the lower atmospheric boundary layer, they extend to the top of the troposphere.

4.5 Carbon Cycle

Fennel, K., Wilkin, J., Previdi, M., and Najjar, R., 2008, Denitrification effects on air-sea CO_2 flux in the coastal ocean: Simulations for the northwest North Atlantic, *Geophys. Res. Lett.*, **35**, L24608, doi:10.1029/2008GL036147

The contribution of coastal oceans to the global air-sea CO_2 flux is poorly quantified due to insufficient availability of observations and inherent variability of physical, biological and chemical processes. We present simulated air-sea CO_2 fluxes from a high-resolution biogeochemical model for the North American east coast continental shelves, a region characterized by significant sediment denitrification. Decreased availability of fixed nitrogen due to denitrification reduces primary production and incorporation of inorganic carbon into organic matter, which leads to an increase in seawater pCO_2, but also increases alkalinity, which leads to an opposing decrease in seawater pCO_2. Comparison of simulations with different numerical treatments of denitrification and alkalinity allow us to separate and quantify the contributions of sediment denitrification to air-sea CO_2 flux. The effective alkalinity flux resulting from denitrification is large compared to estimates of anthropogenically driven coastal acidification.

Fennel, K. and J. Wilkin, 2009, Quantifying biological carbon export for the northwest North Atlantic continental shelves, *Geophys. Res. Lett.*, **36**, L18605, doi:10.1029/2009GL039818

It has been suggested that continental shelf systems contribute disproportionately to the oceanic uptake of atmospheric CO_2, but the magnitude of this flux and the relative contributions of different underlying mechanisms are poorly quantified. A biological continental shelf pump mechanism has been implied; however, the magnitude of this export depends on advective transport of carbon-rich water off the shelf, a process that is difficult to observe directly. Here we use a physical-biogeochemical model for the northeastern North American continental margin to

estimate the uptake of atmospheric CO_2, the fraction of this uptake that results from biological processes, and the transport of organic carbon off the shelf. Our results suggest that there is no systematic difference in the area-normalized CO_2 uptake between the shelf regions and the adjacent deep ocean. The advective transport of carbon-rich water off the shelf is insufficient to drive a Continental Shelf Pump in this region.

Kühn, W., J. Pätsch, H. Thomas, A. V. Borges, L.-S. Schiettecatte, Y. Bozec, and A. E. F. Prowe, 2010, Nitrogen and carbon cycling in the North Sea and exchange with the North Atlantic - A model study, Part II: Carbon budget and fluxes, *Cont. Shelf Res.*, **30**: 1701-1716, doi:10.1016/j.csr.2010.07.001

The 3-d coupled physical–biogeochemical model ECOHAM (version 3) was applied to the Northwest-European Shelf (47°41′–63°53′N, 15°5′W–13°55′E) for the years 1993–1996. Carbon fluxes were calculated for the years 1995 and 1996 for the inner shelf region, the North Sea (511,725 km^2). This period was chosen because it corresponds to a shift from a very high winter-time North Atlantic Oscillation Index (NAOI) in 1994/1995, to an extremely low one in 1995/1996, with consequences for the North Sea physics and biogeochemistry. During the first half of 1996, the observed mean SST was about 1 °C lower than in 1995; in the southern part of the North Sea the difference was even larger (up to 3 °C). Due to a different wind regime, the normally prevailing anti-clockwise circulation, as found in winter 1995, was replaced by more complicated circulation patterns in winter 1996. Decreased precipitation over the drainage area of the continental rivers led to a reduction in the total (inorganic and organic) riverine carbon load to the North Sea from 476 Gmol C yr^{-1} in 1995 to 340 Gmol C yr^{-1} in 1996. In addition, the North Sea took up 503 Gmol C yr^{-1} of CO_2 from the atmosphere. According to our calculations, the North Sea was a sink for atmospheric CO_2, at a rate of 0.98 mol C m^{-2} yr^{-1}, for both years. The North Sea is divided into two sub-systems: the shallow southern North Sea (SNS; 190,765 km^2) and the deeper northern North Sea (NNS; 320,960 km^2). According to our findings the SNS is a net-autotrophic system (net ecosystem production NEP>0) but released CO_2 to the atmosphere: 159 Gmol C yr^{-1} in 1995 and 59 Gmol C yr^{-1} in 1996. There, the temperature-driven release of CO_2 outcompetes the biological CO_2 drawdown. In the NNS, where respiratory processes prevail (NEP<0), 662 and 562 Gmol C yr^{-1} were taken up from the atmosphere in 1995 and 1996, respectively. Stratification separates the productive, upper layer from the deeper layers of the water column where respiration/remineralization takes place. Duration and stability of the stratification are determined by the meteorological conditions, in relation to the NAO. Our results suggest that this mechanism controlling the nutrient supply to the upper layer in the northern and central North Sea has a larger impact on the carbon fluxes than changes in lateral transport due to NAOI variations. The North Sea as a whole imports organic carbon and exports inorganic carbon across the outer boundaries, and was found to be net-heterotrophic, more markedly in 1996 than in 1995.

MacDonald, S. and R. M. Moore, 2007, Seasonal and spatial variations in methyl chloride in NW Atlantic waters, *J. Geophys. Res.*, **112**, C05028, doi:10.1029/2006JC003812

Methyl chloride concentrations were measured in the upper 200 m of the water column of the NW Atlantic during three cruises along the same track in spring, summer and fall of 2003. Distinct seasonality was apparent, with the surface waters being either undersaturated or close to equilibrium with the atmosphere in spring, but with supersaturation of the warmer waters in summer and fall. Cooler waters at the more northerly stations were always undersaturated, thus representing a continual sink for atmospheric methyl chloride. Even on an annual basis, the concentration anomaly (the difference between measured concentration and equilibrium with the atmosphere) was strongly dependent on sea surface temperature (SST). This empirical relationship can be used to extrapolate fluxes globally or to estimate the influence of global warming on ocean-to-atmosphere fluxes of methyl chloride. The global flux of methyl chloride to the atmosphere estimate based on the full-year relationship between concentration anomaly and SST is 17 Gmol/y, and is reduced to 6 Gmol/y if separate seasonal relationships are used. It appears that the ocean component of the flux is highly sensitive to temperature, but the actual source of the methyl chloride in ocean waters remains largely unknown.

Previdi, M., K. Fennel, J. Wilkin, and D. Haidvogel, 2009, Interannual variability in atmospheric CO_2 uptake on the northeast U.S. continental shelf, *J. Geophys. Res.*, **114**, G04003, doi:10.1029/2008JG000881

Continental shelf systems are thought to play an important role in the exchange of carbon dioxide (CO_2) between the atmosphere and ocean. Currently, our ability to quantify the air-sea flux of CO_2 on continental shelves is limited due to large spatial and temporal variability coupled with historically sparse oceanographic measurements (e.g., of surface water pCO_2). Here we use the Regional Ocean Modeling System (ROMS) to quantify the air-sea flux of CO_2 and its interannual variability on the northeast U.S. continental shelf, which includes the Middle Atlantic Bight (MAB) and Gulf of Maine (GOM). Two years marked by opposite phases of the North Atlantic Oscillation (NAO) are considered in the study. A novel analysis method, second-order Taylor series decomposition, is used to identify the important processes responsible for producing NAO-related changes in the CO_2 air-sea flux. On the northeast U.S. shelf, atmospheric CO_2 uptake as simulated by ROMS decreases from 2.4 Mt C yr^{-1} in 1985 (low NAO) to 1.8 Mt C yr^{-1} in 1990 (high NAO), with most of this decrease (0.5 Mt C yr^{-1}) occurring in the MAB. In the MAB the difference in annual air-sea flux of CO_2 is due mainly to changes in near-surface wind speed, while the flux difference in the GOM is controlled primarily by surface water pCO_2 (CO_2 partial pressure) changes resulting from changes in sea surface temperature and new production. The large magnitude of interannual variability in the air-sea flux of CO_2 simulated here suggests the potential for even more significant flux changes in the future as climate change accelerates.

Prowe, A. E. F., H. Thomas, J. Pätsch, W. Kühn, Y. Bozec, L.-S. Schiettecatte, A. V. Borges, and H. J. W. de Baar, 2009, Mechanisms controlling the air-sea CO_2 flux in the North Sea, *Cont. Shelf Res.*, **29**(15): 1801-1808, doi:10.1016/j.csr.2009.06.003

The mechanisms driving the air–sea exchange of carbon dioxide (CO_2) in the North Sea are investigated using the three-dimensional coupled physical–biogeochemical model ECOHAM (ECOlogical-model, HAMburg). We validate our simulations using field data for the years 2001–2002 and identify the controls of the air–sea CO_2 flux for two locations representative for the North Sea's biogeochemical provinces. In the seasonally stratified northern region, net CO_2 uptake is high ($2.06\ \mathrm{mol\ m^{-2}\ a^{-1}}$) due to high net community production (NCP) in the surface water. Overflow production releasing semi-labile dissolved organic carbon needs to be considered for a realistic simulation of the low dissolved inorganic carbon (DIC) concentrations observed during summer. This biologically driven carbon drawdown outcompetes the temperature-driven rise in CO_2 partial pressure (pCO_2) during the productive season. In contrast, the permanently mixed southern region is a weak net CO_2 source ($0.78\ \mathrm{mol\ m^{-2}\ a^{-1}}$). NCP is generally low except for the spring bloom because remineralization parallels primary production. Here, the pCO_2 appears to be controlled by temperature.

Schiettecatte, L.-S., H. Thomas, Y. Bozec, and A. V. Borges, 2007, High temporal coverage of carbon dioxide measurements in the Southern Bight of the North Sea, *Marine Chemistry*, **106**(1-2): 161-173, doi:10.1016/j.marchem.2007.01.001

A monthly survey of the partial pressure of CO_2 (pCO_2) was carried in the Southern Bight of the North Sea (SBNS) from June 2003 to May 2004. The spatial variability of the surface distribution of the pCO_2 was relatively small (within a range of 10–70 µatm) compared to the amplitude in the seasonal signal (~260 µatm). On an annual scale, the pCO_2 dynamics appeared to be controlled by biological processes (primary production in springtime and respiratory processes in summer), rather than temperature (in summer). The comparison with measurements carried out in 2001 and 2002 (13 cruises) shows that the inter-annual variability of pCO_2 was close to the range of the spatial variability and mostly observed in spring, associated to biological processes (primary production). Net ecosystem production estimated from dissolved inorganic carbon (DIC) temporal variations showed that the SBNS is autotrophic, at an annual rate of 6.3 mol C m^{-2} yr^{-1}. The decoupling in time between autotrophy in spring and heterotrophy in summer, associated to the relatively rapid flushing time of the water mass in the area (~70 days), might allow the export of a fraction of the springtime synthesized organic matter to the adjacent areas of the North Sea. The SBNS was on a yearly basis a sink of atmospheric CO_2 at a rate of −0.7 mol C m^{-2} yr^{-1}.

Shadwick, E. H., H. Thomas, A. Comeau, S. E. Craig, C. W. Hunt, and J. E. Salisbury, 2010, Air-Sea CO_2 fluxes on the Scotian Shelf: Seasonal to multi-annual variability, *Biogeosciences*, **7**: 3851-3867, doi:10.5194/bg-7-3851-2010

We develop an algorithm to compute pCO_2 in the Scotian Shelf region (NW Atlantic) from satellite-based estimates of chlorophyll-*a* concentration, sea-

surface temperature, and observed wind speed. This algorithm is based on a high-resolution time-series of pCO_2 observations from an autonomous mooring. At the mooring location (44.3° N and 63.3° W), the surface waters act as a source of CO_2 to the atmosphere over the annual scale, with an outgassing of −1.1 mol C m^{-2} yr^{-1} in 2007/2008. A hindcast of air-sea CO_2 fluxes from 1999 to 2008 reveals significant variability both spatially and from year to year. Over the decade, the shelf-wide annual air-sea fluxes range from an outgassing of −1.70 mol C m^{-2} yr^{-1} in 2002, to −0.02 mol C m^{-2} yr^{-1} in 2006. There is a gradient in the air-sea CO_2 flux between the northeastern Cabot Strait region which acts as a net sink of CO_2 with an annual uptake of 0.50 to 1.00 mol C m^{-2} yr^{-1}, and the southwestern Gulf of Maine region which acts as a source ranging from −0.80 to −2.50 mol C m^{-2} yr^{-1}. There is a decline, or a negative trend, in the air-sea pCO_2 gradient of 23 µatm over the decade, which can be explained by a cooling of 1.3 °C over the same period. Regional conditions govern spatial, seasonal, and interannual variability on the Scotian Shelf, while multi-annual trends appear to be influenced by larger scale processes.

Thomas, H., A. E. F. Prowe, S. van Heuven, Y. Bozec, H. J. W. de Baar, L.-S. Schiettecatte, K. Suykens, M. Koné, A. V. Borges, I. D. Lima, and S. C. Doney, 2007, Rapid decline of the CO_2 buffering capacity in the North Sea and implications for the North Atlantic Ocean, *Global Biogeochem. Cycles*, **21**, GB4001, doi:10.1029/2006GB002825

New observations from the North Sea, a NW European shelf sea, show that between 2001 and 2005 the CO2 partial pressure (pCO2) in surface waters rose by 22 µatm, thus faster than atmospheric pCO2, which in the same period rose approximately 11 µatm. The surprisingly rapid decline in air-sea partial pressure difference (ΔpCO2) is primarily a response to an elevated water column inventory of dissolved inorganic carbon (DIC), which, in turn, reflects mostly anthropogenic CO2 input rather than natural interannual variability. The resulting decline in the buffering capacity of the inorganic carbonate system (increasing Revelle factor) sets up a theoretically predicted feedback loop whereby the invasion of anthropogenic CO2 reduces the ocean's ability to uptake additional CO2. Model simulations for the North Atlantic Ocean and thermodynamic principles reveal that this feedback should be stronger, at present, in colder midlatitude and subpolar waters because of the lower present-day buffer capacity and elevated DIC levels driven either by northward advected surface water and/or excess local air-sea CO2 uptake. This buffer capacity feedback mechanism helps to explain at least part of the observed trend of decreasing air-sea ΔpCO2 over time as reported in several other recent North Atlantic studies.

Thomas, H., L.-S. Schiettecatte, K. Suykens, Y. J. M. Koné, E. H. Shadwick, A. E. F. Prowe, Y. Bozec, H. J. W. de Baar, and A. V. Borges, 2008, Enhanced ocean carbon storage from anaerobic alkalinity generation in coastal sediments, *Biogeosciences*, **6**: 267-274, doi:10.5194/bgd-5-3575-2008

The coastal ocean constitutes the crucial link between land, the open ocean and the atmosphere. Furthermore, its shallow water column permits close interactions

between the sedimentary and atmospheric compartments, which otherwise are decoupled at short time scales (<1000 yr) in the open oceans. Despite the prominent role of the coastal oceans in absorbing atmospheric CO_2 and transferring it into the deep oceans via the continental shelf pump, the underlying mechanisms remain only partly understood. Evaluating observations from the North Sea, a NW European shelf sea, we provide evidence that anaerobic degradation of organic matter, fuelled from land and ocean, generates alkalinity (A_T) and increases the CO_2 buffer capacity of seawater. At both the basin wide and annual scales anaerobic A_T generation in the North Sea's tidal mud flat area irreversibly facilitates 7–10%, or taking into consideration benthic denitrification in the North Sea, 20–25% of the North Sea's overall CO_2 uptake. At the global scale, anaerobic A_T generation could be accountable for as much as 60 % of the uptake of CO_2 in shelf and marginal seas, making this process, the anaerobic pump, a key player in the biological carbon pump. Under future high CO_2 conditions oceanic CO_2 storage via the anaerobic pump may even gain further relevance because of stimulated ocean productivity.

Thomas, H., A. E. Friederike Prowe, I. D. Lima, S. C. Doney, R. Wanninkhof, R. J. Greatbatch, U. Schuster, and A. Corbière, 2008, Changes in the North Atlantic Oscillation influence CO_2 uptake in the North Atlantic over the past 2 decades, *Global Biogeochem. Cycles*, **22**, GB4027, doi:10.1029/2007GB003167

Observational studies report a rapid decline of ocean CO_2 uptake in the temperate North Atlantic during the last decade. We analyze these findings using ocean physical-biological numerical simulations forced with interannually varying atmospheric conditions for the period 1979–2004. In the simulations, surface ocean water mass properties and CO_2 system variables exhibit substantial multiannual variability on sub-basin scales in response to wind-driven reorganization in ocean circulation and surface warming/cooling. The simulated temporal evolution of the ocean CO_2 system is broadly consistent with reported observational trends and is influenced substantially by the phase of the North Atlantic Oscillation (NAO). Many of the observational estimates cover a period after 1995 of mostly negative or weakly positive NAO conditions, which are characterized in the simulations by reduced North Atlantic Current transport of subtropical waters into the eastern basin and by a decline in CO_2 uptake. We suggest therefore that air-sea CO_2 uptake may rebound in the eastern temperate North Atlantic during future periods of more positive NAO, similar to the patterns found in our model for the sustained positive NAO period in the early 1990s. Thus, our analysis indicates that the recent rapid shifts in CO_2 flux reflect decadal perturbations superimposed on more gradual secular trends. The simulations highlight the need for long-term ocean carbon observations and modeling to fully resolve multiannual variability, which can obscure detection of the long-term changes associated with anthropogenic CO_2 uptake and climate change.

4.6 Biophysical Processes

Brickman, D., L. Taylor, A. Gudmundsdottir, and G. Marteinsdottir, 2007, Optimized biophysical model for Icelandic cod (*Gadus morhua*) larvae, *Fish. Oceanogr.*, **16**(5): 448-458, doi:10.1111/j.1365-2419.2007.00449.x

A characteristic of biophysical models (BPM) is that they contain a number of parameters that are poorly known or only known within a range of possible values. This paper describes an efficient optimized BPM developed to simulate the Icelandic cod pelagic 0-group survey data. The method is based on presenting the results as a probability density function (PDF) that a particle released from a given spawning drifts downstream to a given grid location some time later. The model determines egg production model parameters (peak spawning time, spawning duration, number of eggs released) for each of 15 spawning grounds as the solution of a bound constrained optimization problem that minimizes model-data misfits in abundance and age distributions. The model is applied to simulating the 2002 and 2003 summer survey data. The model does a reasonable job of simulating the observed inshore/offshore abundance gradient and spatial age gradient for each year. Problem areas are explained from the point of view of model limitations. We caution that the results from an optimized model should always be assessed with the model's limitations in mind and with respect to whatever biological data are available.

Brickman, D., G. Marteinsdottir, and L. Taylor, 2007, Formulation and application of an efficient optimized biophysical model, *Mar. Ecol. Prog. Ser.*, **347**: 275-284, doi:10.3354/meps06984

The formulation of an efficient optimized biophysical model is described, and the model is applied to the simulation of the climatological 0-group distribution of Icelandic cod *Gadus morhua* larvae. The method is based on representing the results from particle tracking as drift probability density functions describing the probability that particles released from a given spawning ground are found at a specific downstream grid location some time later. Spawning is considered to take place from 15 spawning grounds, and the model is used to determine 45 egg production model parameters as the solution of a bound constrained optimization problem that minimizes model-data misfits in abundance and age distributions. The problem is solved using a direct search minimization routine. Two cost functions are used. One penalizes misfits in the gridded abundance and age distributions (Model 1). The other directly penalizes the misfit in the spatial age gradient (Model 2). A simple age-based settlement module is tested to determine whether it improves the model fit. Results from Model 1 show a large error in the spatial age gradient. Model 2 achieves a 20-fold reduction in this error, with only a small degradation of the gridded abundance and age distributions. The settlement model does not improve the model fit. The results indicate that the addition of more processes to a model does not always improve model performance, while focusing on gradients in age instead of simple age distributions can lead to overall improved performance. The technique presented

in the present paper allows quantitative evaluation of various model processes in a computationally efficient framework.

Dawe, E. G. L. C. Hendrickson, E. B. Colbourne, K. F. Drinkwater, and M. A. Showell, 2007, Ocean climate effects on the relative abundance of shortfinned (Illex illecebrosus) and long-finned (Loligo pealeii) squid in the northwest Atlantic Ocean, *Fish. Oceanogr.*,**16**(4): 303–316, doi:10.1111/j.1365-2419.2007.00431.x

An unusually high abundance of long-finned squid (*Loligo pealeii*) was observed around southern Newfoundland in August–September 2000. The prevalence of maturing females and mature males, along with the collection of a single viable egg mop, provide the first evidence of spawning of this species at the northern limit of its geographic range of distribution. Northward expansion of the long-finned squid population may be related to a general warming trend in Newfoundland near-shore waters. However, trends in size and abundance of short-finned squid (*Illex illecebrosus*) suggest that this expansion may also be related to reduced competition. We hypothesize that these two squid species share, to a large extent, a common niche on the eastern USA shelf and that opposing responses to ecosystem variation affect their relative abundance. We address this hypothesis by applying time-series analysis of species-specific fishery- and survey-based abundance indices with biologic and environmental input variables. Our models indicate that direct competition is not important, but that variation in atmospheric forcing, as well as latitudinal position of the Shelf-Slope Front (SSF), are closely related to direct oceanographic processes that exert opposing effects on these two species. While the direct oceanographic mechanisms that regulate year-class strength remain unknown, we present a hypothesis to account for opposing population responses to oceanographic variation that operates early in the life history of both species. For the oceanic and highly migratory short-finned squid, variation in the latitudinal position of the SSF is related to efficiency of downstream dispersal by the Gulf Stream and survival of young stages. For the neritic long-finned squid, variation in local inshore temperature affects the time exposed to intense predation through its effect on rates of embryonic development and growth. The expansion of long-finned squid population abundance in 2000 was associated with both warm local water temperatures and an unusual eastward displacement of the atmospheric features associated with the North Atlantic Oscillation (NAO). These conditions may have resulted in an unfavorable oceanic regime for short-finned squid but a favorable regime for long-finned squid on the continental shelf as far north as southern Newfoundland.

Devred, E., S. Sathyendranath, and T. Platt, 2007, Delineation of ecological provinces in the North West Atlantic using visible spectral radiometry (ocean colour), *Mar. Ecol. Prog. Ser.*, **346**: 1-13, doi:10.3354/meps07149

In 2003, Canadian Surface Ocean Lower Atmosphere Study conducted 3 research expeditions (April–May, July and October) to the Northwest Atlantic to study gas exchange at the air–sea interface. Interpreting the relationships between gas exchange and biological activity measured in these expeditions is facilitated if the

water masses sampled can be identified in a large-scale context. Longhurst et al. (1995) tackled the issue of water mass characterisation by defining biogeochemical provinces for the world ocean and in particular for the NW Atlantic. To avoid the limitations that arise from the static arrangement of provinces with rectilinear boundaries as used in Longhurst et al. (1995), we developed a dynamic method based on statistical analysis of geophysical and biological data to delineate the boundaries of Longhurst's provinces in real time. This new method was applied to satellite-retrieved sea-surface temperature (SST) and phytoplankton biomass data averaged over the length of the research cruises (22, 17 and 16 d in spring, summer and fall respectively). CTD casts at various stations along the ship track were used to validate the method. A sensitivity study on primary production estimations performed with both definitions (static and dynamic) showed a negligible difference at the basin scale; however, variations at the province scale were significant. The regional description afforded by the new method was useful for the interpretation of expedition data.

Fisher, J. A. D., K. T. Frank, B. Petrie, W. C. Leggett, and N. L. Shackell, 2008, Temporal dynamics within a contemporary latitudinal diversity gradient, *Ecol. Lett.*, **11**(9): 883-897, doi:10.1111/j.1461-0248.2008.01216.x

Poleward declines in species diversity [latitudinal diversity gradients (LDG)] remain among the oldest and most widespread of macroecological patterns. However, their contemporary dynamics remain largely unexplored even though changing ecological conditions, including global change, may modify LDG and their respective ecosystems. Here, we examine temporal variation within a temperate Northwest Atlantic LDG using 31 years of annual fisheries-independent surveys and explore its dynamics in relation to a dominant climate signal [the wintertime North Atlantic Oscillation (NAO)] that varies interannually and alters the latitudinal gradient of Northwest Atlantic continental shelf bottom water temperatures. We found that the slopes of the annual LDG vary dramatically due to changes in geographic distributions of 100+ species, variations that are concealed within the cumulative, static LDG. These changes are strongly associated with changes in NAO sign and strength. This is the first illustration of temporal dynamics in a contemporary LDG and the first demonstration of the speed at which local environmental variations can alter an LDG. Our findings underscore the need to investigate factors that modify LDG separately from those that contribute to their origins.

Frank, K. T., B. Petrie, and N. L. Shackell, 2007, The ups and downs of trophic control in continental shelf ecosystems, *Trends in Ecology and Evolution*, **22**(5): 236-242, doi:10.1016/j.tree.2007.03.002

Traditionally, marine ecosystem structure was thought to be determined by phytoplankton dynamics. However, an integrated view on the relative roles of top-down (consumer-driven) and bottom-up (resource-driven) forcing in large-scale, exploited marine ecosystems is emerging. Long time series of scientific survey data, underpinning the management of commercially exploited species

such as cod, are being used to diagnose mechanisms that could affect the composition and relative abundance of species in marine food webs. By assembling published data from studies in exploited North Atlantic ecosystems, we found pronounced geographical variation in top-down and bottom-up trophic forcing. The data suggest that ecosystem susceptibility to top-down control and their resiliency to exploitation are related to species richness and oceanic temperature conditions. Such knowledge could be used to produce ecosystem guidelines to regulate and manage fisheries in a sustainable fashion.

Greenan, B. J. W., B. D. Petrie, W. G. Harrison, and P. M. Strain, 2008, The onset and evolution of a spring bloom on the Scotian Shelf, *Limnol. Oceanogr.*, **53**(5): 1759-1775, doi:10.4319/lo.2008.53.5.1759

The spring bloom on the Scotian Shelf is examined using a mooring array deployed from 18 March 2002 to 18 April 2002 to provide physical, chemical, and biological measurements with high temporal and vertical resolution. These measurements are complemented by the Atlantic Zone Monitoring Program (AZMP) biweekly occupations of a station near the mooring site (HL2). Results from AZMP sampling and Sea-viewing Wide Field-of-view Sensor (Sea WiFS) ocean color imagery in early March show that coastal upwelling played an important role in the initiation of the spring bloom near the coast. This was a period of very strong horizontal gradients in surface chlorophyll. The main bloom at HL2 was sustained for most of the mooring period with peak chlorophyll levels reaching 6 mg m^{-3}. Following the drawdown of nutrients in the upper 20 m, the bloom continued for 9 d and then disappeared at the surface but remained at the depth of the nutricline (30-50 m). The onset and evolution of the spring bloom on the inner Scotian Shelf is a complex process in which nutrient inventory, vertical mixing, and coastal upwelling play roles of varying importance throughout its lifetime. Mesozooplankton biomass does not change significantly until the very end of the mooring period indicating the grazing by this component of the zooplankton did not have as important a role in the termination of the bloom as the exhaustion of near-surface nutrients.

Halliday, R. G., and A. T. Pinhorn, 2009, The roles of fishing and environmental change in the decline of Northwest Atlantic groundfish populations in the early 1990s, *Fish. Res.*, **97**(3): 163-182, doi:10.1016/j.fishres.2009.02.004

The cause of the large decline in groundfish populations in the Northwest Atlantic about 1990 remains unresolved although the prevailing view is that it was due predominantly to fishing. A similar but less extreme decline in these populations that occurred in the early 1970s is also attributed to fishing. However, observational data on commercial fishing effort suggest that fishing effort in the late 1980s was likely less than in the late 1960s–early 1970s, even when efficiency increases are accounted for. Also, the biological changes observed in groundfish populations in the late 1980s were not consistent with a hypothesis that the early 1990s declines in biomass were caused by recruitment overfishing. There is, however, a strong coincidence between fluctuations in groundfish biomass, and other biological characteristics, and variations in the North Atlantic

Oscillation (NAO), suggesting that the rapid changes in these characteristics in the early 1990s were largely due to environmental variations, and that this equally may have been true for early 1970s population changes. A corollary to such a hypothesis is that the 1960s, when NAO anomalies were consistently and strongly negative, was a period uniquely favourable for groundfish productivity and should not be taken as a long-term norm.

Han, G. and D. Kulka, 2009, Dispersion of eggs, larvae and pelagic juveniles of white hake (*Urophycis tenuis*) in relation to ocean currents of the Grand Bank: a modelling approach. *J. Northwest Atl. Fish. Sci.*, **41**: 183-196, doi:10.2960/J.v41.m627

White hake (*Urophycis tenuis*) is a temperate demersal fish species distributed in the northwest Atlantic. On the Grand Bank, it is concentrated mainly to the southwest where water temperatures are warmest. Survey data indicate that mature adult females aggregate on the southwest (SW) Grand Bank slope in spring and first-year juveniles settle on the southern, shallow Grand Bank in autumn. Dispersion patterns and survival potential of eggs, larvae and juveniles were investigated with respect to the effects of location (horizontal and vertical) and timing (monthly) of spawning under monthly-mean circulation fields, *M2* tidal currents and associated turbulent mixing computed from a three-dimensional regional ocean circulation model. The results indicate that releases below the surface Ekman layer and in late spring have the highest chances for juveniles to settle in the southern Grand Bank nursery area in autumn. On an interannual scale, the strong recruitment of the 1999 yearclass has been used as an example to examine the potential linkage between recruitment and the strength of the Labrador Current. A weak along-slope current and strong on-bank flow contributed to the strong recruitment of the 1999 year-class.

Head, E. J. H. and D. D. Sameoto, 2007, Inter-decadal variability in zooplankton and phytoplankton abundance on the Newfoundland and Scotian shelves, *Deep Sea Res.*, **54**(23-26): 2686-2701, doi:10.1016/j.dsr2.2007.08.003

Continuous Plankton Recorder (CPR) sampling on the Newfoundland and Scotian shelves covers three multi-year periods characterised by negative (1962–1971), positive (1992–2000) and negative/neutral (2001–2003) values of the NAO index. Water temperatures respond differently to changes in the NAO in different regions: a positive NAO index tends to lead to reduced temperatures on the Newfoundland shelf and to increased temperatures on the central/western Scotian shelf, and a negative NAO index to the reverse. Since the 1960s, the hydrographic changes due to the NAO have been superimposed on a freshening of the water column throughout the region, which is attributed to increased contribution of Arctic water outflow. Changes in plankton abundance measured by the CPR for the three time periods were generally, but not always, similar on the Newfoundland and eastern and western regions of the Scotian shelf, although Arctic species (e.g. *Calanus glacialis*, *Calanus hyperboreus*) were notably more abundant and warm water species (e.g. *Metridia lucens*, euphausiids) less abundant on the Newfoundland shelf than on the Scotian shelf. Three categories of phytoplankton (colour, diatoms, dinoflagellates) increased in abundance in the

1990s, and these increases generally persisted into 2001–2003. This is believed to be a response to the persistent freshening of the water column, probably due to increased stratification. The Arctic species *C. glacialis* and *C. hyperboreus* also showed persistent increases in abundance after 1992, perhaps due to increased transport from the Arctic, although the abundance of the Arctic slope water species *Metridia longa* decreased. Two groups, *Calanus* 1–4 and euphausiids, both thought to play important roles in the food chain, showed persistent decreases in abundance after 1992, especially on the Newfoundland shelf. In all regions, *Calanus finmarchicus* 5–6, *Oithona* spp. and *Centropages hamatus* abundance changed in association with variations in the NAO, although no common mechanism could be identified. *C. finmarchicus* 5–6 abundance decreased in the 1990s and increased after 2001, while the other two species showed the opposite pattern. *Centropages typicus* and *M. lucens* abundance on the Scotian shelf increased with rising temperature. This is attributed to increased production rates for the former and an increased influx of warm, *M. lucens*-rich, slope water on to the shelf for the latter. A comparison between ring net and CPR sampling on the Newfoundland shelf suggests that the *Calanus* 1–4 category is dominated by *C. finmarchicus* and that late stage *C. glacialis* and *C. hyperboreus* are grossly under-sampled compared to late stage *C. finmarchicus*.

Jones, J. B., and S. E. Campana, 2009, Stable oxygen isotope reconstruction of ambient temperature during the collapse of a cod (*Gadus morhua*) fishery, *Ecological Applications*, **19**:1500–1514, doi:10.1890/07-2002.1

Changing environmental conditions set against a backdrop of high exploitation can result in severe consequences for commercially harvested stocks. The collapse of the Eastern Scotian Shelf cod (*Gadus morhua* L.) off eastern Canada was primarily due to overexploitation but may have been exacerbated by a widespread temperature decline. Recent studies have called for accurate determination of ambient temperature (the actual temperature exposure history of the fish) before discarding environmental conditions as a factor in the collapse. We used the stable oxygen isotope composition of otoliths ($\delta^{18}O_{oto}$) to reconstruct the ambient temperature history of Eastern Scotian Shelf cod from 1970 to 2000 in order to determine whether the stock experienced the temperature decline or shifted their distribution to avoid it. To correct $\delta^{18}O_{oto}$ for seawater isotope content (δO_w), we generated a new meta-equation for the relationship between $\delta^{18}O_w$ (per mil) and salinity (S, in psu) on the Eastern Scotian Shelf: $\delta^{18}O_w = 0.539 \times S - 18.790$. The ambient temperature series revealed that the large-scale geographic distribution of mature cod remained constant through the cooling period, although their ambient temperature was cooler than expected in warmer periods and warmer than expected in cooler periods, indicating small-scale thermoregulatory movement. Although the mean hydrographic temperature was 4°C, mature cod usually inhabited the coldest available waters (mean ambient temperature = 3°C), while the juveniles usually inhabited warmer waters (mean ambient temperature = 5.5°C). Length-at-age was significantly related to ambient temperature, especially in the early years of growth, and therefore declining ambient temperatures were at least partially responsible for declines in asymptotic

length (up to age 8 yr). The most active thermoregulatory movement occurred during a moderate warming period; therefore extreme warming events (such as those predicted under climate change) may force large-scale northward latitudinal shifts in this historically sedentary stock. Retroactive stable isotope chronologies can be an important tool in sustainable management strategies under the shifting climate conditions predicted for years to come.

Koeller, P., C. Fuentes-Yaco, T. Platt, S. Sathyendranath, A. Richards, P. Ouellet, D. Orr, U. Skúladóttir, K. Wieland, L. Savard, and M. Aschan, 2009, Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean, *Science*, **324**(5928): 791-793, doi:10.1126/science.1170987

Climate change could lead to mismatches between the reproductive cycles of marine organisms and their planktonic food. We tested this hypothesis by comparing shrimp (*Pandalus borealis*) egg hatching times and satellite-derived phytoplankton bloom dynamics throughout the North Atlantic. At large spatial and long temporal (10 years or longer) scales, hatching was correlated with the timing of the spring phytoplankton bloom. Annual egg development and hatching times were determined locally by bottom water temperature. We conclude that different populations of *P. borealis* have adapted to local temperatures and bloom timing, matching egg hatching to food availability under average conditions. This strategy is vulnerable to interannual oceanographic variability and long-term climatic changes.

Lehmann, M. K., K. Fennel, and R. He, 2009, Statistical validation of a 3-D bio-physical model for the western North Atlantic, *Biogeosciences*, **6**: 1961-1974

High-resolution, physical-biological models of coastal and shelf regions typically use a single functional phytoplankton group, which limits their ability to represent ecological gradients (e.g. highly productive shelf systems adjacent to oligotrophic regions), as these are dominated by different functional phytoplankton groups. We implemented a size-structured ecosystem model in a high-resolution, regional circulation model of the northeast North American shelf and adjacent deep ocean in order to assess whether the added functional complexity of two functional phytoplankton groups improves the model's ability to represent surface chlorophyll concentrations along an ecological gradient encompassing five distinct regions. We used satellite-derived SST and sea-surface chlorophyll for our model assessment, as these allow investigation of spatial variability and temporal variations from monthly to interannual, and analyzed three complimentary statistical measures of model-data agreement: model bias, root mean square error and model efficiency (or skill). All three measures were integrated for the whole domain, for distinct subregions and were calculated in a spatially explicit manner. Comparison with a previously published simulation that used a model with a single phytoplankton functional group indicates that the inclusion of an additional phytoplankton group representing picoplankton markedly improves the model's skill.

Li, W. K. W., M. R. Lewis, and W. G. Harrison, 2008, Multiscalarity of the nutrient-chlorophyll relationship in coastal phytoplankton, *Estuar. Coasts*, **33**(2): 440-447, doi:10.1007/s12237-008-9119-7

The relationship between nitrogen (N) and phytoplankton chlorophyll a (Chl) establishes a basis for understanding eutrophication in coastal marine ecosystems. A substantial literature exists on cross-ecosystem analysis of this relationship, but there is little information on cross-scale patterns. A collection of observational records in Bedford Basin (Canada) was used to construct the N–Chl relationship at four time scales: intra-day, intra-annual, interannual, and interdecadal. Additionally, a dataset of contingent observations from 16 biogeochemical ocean provinces was used to construct the N–Chl relationship at large spatial scale. In Bedford Basin, N statistically predicts Chl at time scales that are short (intra-day, intra-annual) and long (interdecadal) but not intermediate (interannual). There is an apparent stoichiometric regularity in the dependence of Chl on N that crosses time scales. Further, an apparent similitude exists between the local pattern at long time scale and the global pattern at large space scale.

Li, W. K. W. and W. G. Harrison, 2008, Propagation of an atmospheric climate signal to phytoplankton in a small marine basin, *Limnol. Oceanogr.*, **53**(5): 1734-1745, doi:10.4319/lo.2008.53.5.1734

A 14-yr record of weekly observations in Bedford Basin (Canada) was used to describe the direction and magnitude of departures from long-term mean conditions in both climate and plankton components, for the purpose of detecting common patterns. Seasonal vertical stratification of the water column is determined primarily by temperature, but multiyear change in the annual deseasonalized average stratification is induced by salinity, which is linked to precipitation and river discharge. Stratification anomalies explain significant amounts of variability in the anomalies of nutrients and total phytoplankton biomass, especially that contributed by diatoms, but not the biomass of nanophytoplankton and picophytoplankton. Instead, the responses of the small phytoplankton groups appear directly related to temperature. Trophic linkage between phytoplankton and copepods is not statistically demonstrable, but there is strong evidence of linkage between phytoplankton and bacterioplankton. Temporal sign switching, which is the coherent departure from norm in both an ecosystem driver and response, strongly indicates the propagation of an atmospheric signal to phytoplankton in surface waters of Bedford Basin and thence further through trophic linkage and export.

Mattern, J. P., M. Dowd, and K. Fennel, 2010, Sequential data assimilation applied to a physical-biological model for the Bermuda Atlantic Time Series station, *J. Mar. Sys.*, **79**(1-2): 144-156, doi:10.1016/j.jmarsys.2009.08.004

In this study, we investigate sequential data assimilation approaches for state estimation and prediction in a coupled physical–biological model for the Bermuda Atlantic Time Series (BATS) site. The model is 1-dimensional (vertical) in space and based on the General Ocean Turbulence Model (GOTM). Coupled to GOTM is a biological model that includes phytoplankton, detritus, dissolved inorganic

nitrogen, chlorophyll and oxygen. We performed model ensemble runs by introducing variations in the biological parameters, each of which was assigned a probability distribution. We compare and contrast here 2 sequential data assimilation methods: the ensemble Kalman filter (EnKF) and sequential importance resampling (SIR). We assimilated different types of BATS observations, including particulate organic nitrogen, nitrate + nitrite, chlorophyll *a* and oxygen for the 2-year period from January 1990 to December 1991, and quantified the impact of the data assimilation on the model's predictive skill. By applying a cross-validation to the data-assimilative and deterministic simulations we found that the predictive skill was improved for 2-week forecasts. In our experiments the EnKF, which exhibited a stronger effect on the ensemble during the assimilation step, showed slightly higher improvements in the predictive skill than the SIR, which preserves dynamical model consistency in our implementation. Our numerical experiments show that statistical properties stabilize for ensemble sizes of 20 or greater with little improvement for larger ensembles.

Mattern, J.P., K. Fennel, and M. Dowd, 2010, Introduction and assessment of measures for quantitative model-data comparison using satellite images, *Remote Sensing*, **2**(3): 794-818, doi:10.3390/rs2030794

Satellite observations of the oceans have great potential to improve the quality and predictive power of numerical ocean models and are frequently used in model skill assessment as well as data assimilation. In this study we introduce and compare various measures for the quantitative comparison of satellite images and model output that have not been used in this context before. We devised a series of test to compare their performance, including their sensitivity to noise and missing values, which are ubiquitous in satellite images. Our results show that two of our adapted measures, the Adapted Gray Block distance and the entropic distance D2, perform better than the commonly used root mean square error and image correlation.

Pahlow, M., A. F. Vézina, B. Casault, H. Maass, L. Malloch, D. G. Wright, and Y. Lu, 2008, Adaptive model of plankton dynamics for the North Atlantic, *Prog. Oceanogr.*, **76**(2): 151-191, doi:10.1016/j.pocean.2007.11.001

Plankton ecosystems in the North Atlantic display strong regional and interannual variability in productivity and trophic structure, which cannot be captured by simple plankton models. Additional compartments subdividing functional groups can increase predictive power, but the high number of parameters tends to compromise portability and robustness of model predictions. An alternative strategy is to use property state variables, such as cell size, normally considered constant parameters in ecosystem models, to define the structure of functional groups in terms of both behaviour and response to physical forcing. This strategy may allow us to simulate realistically regional and temporal differences among plankton communities while keeping model complexity at a minimum.

We fit a model of plankton and DOM dynamics globally and individually to observed climatologies at three divers e locations in the North Atlantic. Introducing additional property state variables is shown to improve the model fit both locally and globally, make the model more portable, and help identify model deficiencies. The zooplankton formula tion exerts strong control on m odel performance. Our results suggest that the current paradigm on zooplankton allometric functional relationships m ight be at odds with observed plankton dynamics. Our param eter estimation resulted in m ore realistic estim ates of parameters important for prim ary production than previous data assim ilation studies.

Property state variables gene rate complex em ergent functional relationships, and might be used like tracers to differentia te between locally pr oduced and advected biomass. The model results suggest that the observed tem perature dependence of heterotrophic growth efficiency [R ivkin, R.B., Legendre, L., 2001. Biogenic carbon cycling in the upper ocean: effects of microbial respiration. Science 291 (5512) 2398–2400] could be an e mergent relation due to intercorrelations a mong temperature, nutrient concentration and growth efficiency. A major advantage of using property state variables is that no additional parameters are required, such that differences in model performance can be directly related to model structure rather than parameter tuning.

Shackell, N. L., K. T. Frank, J. A. D. Fisher, B. P etrie, and W. C. Leggett, 2009, Decline in top predator body size and changing clim ate alter trophic structure in an oceanic ecosystem, *Proc. R.. Soc. B. Biol. Sci.*, doi:10.1098/rspb.2009.1020

Globally, overfishing large-bodied gr oundfish populations has resulted in substantial increases in th eir prey populations. Where it has been exam ined, the effects of overfishing have cascaded down the food chain. In an intensively fished area on the western Scotian Shelf, Northwest Atlantic, the biomass of prey species increased exponentially (doubling tim e of 11 years) even though the aggregate biomass of their predators remained stable over 38 years. Concom itant reductions in herbivorous zooplankton a nd increases in phytoplankt on were also evident. This anomalous trophic pattern led us to examine how declines in predator body size (approx. 60% in body m ass since the early 1970s) and clim atic regime influenced lower trophic levels. The incr ease in prey biom ass was associated primarily with declines in predator body size and secondarily to an increase in stratification. Sea surface temperature and predator biom ass had no influence. A regression model explained 65 per cent of prey biom ass variability. Trait-mediated effects, namely a reduction in predator size, resulted in a weakening of top predation pressure. Increased stra tification may have enhanced growing conditions for prey fi sh. Size-selective harvesting under changing clim atic conditions initiated a trophic restructuring of the food ch ain, the effects of which may have influenced three trophic levels.

Snelgrove, P. V. R., I. R. Bradbury, B. deYoung, and S. Fraser, 2008, Temporal variation in fish egg and larval production by pelagic and bottom spawners in a large

Newfoundland coastal embayment, *Canadian J. Fish. Aquatic Sci.* **65**: 159-175, doi:10.1139/f07-148

In highly seasonal environments such as coastal Newfoundland, local production, advection, and life history may influence ichthyoplankton community structure. The spring bloom occurs in cold water that slows development of eggs from pelagic spawners and may transport propagules from optimal nearshore areas before hatch. For bottom spawners that affix eggs to the bottom, the problem is reduced because only actively swimming larval stages are pelagic. We hypothesize that larvae of pelagic spawners are limited to warmer, summer waters, whereas larvae of bottom spawners are less constrained temporally and less subject to flushing from the nearshore environment. Ichthyoplankton taxa sampled in Placentia Bay, Newfoundland, during spring–summer in 1997–1999 showed consistent seasonal peaks in egg and larval abundance. Although pelagic egg production spanned spring and summer, larval abundance peaked late in summer or early fall in the most productive areas of the bay. Larval abundance of bottom spawners peaked in spring for most taxa. Thus, pelagic eggs hatch quickly in summer, and larvae can utilize the late peak in nearshore copepod abundance. Bottom spawners can utilize spring zooplankton because temperature-dependent development does not influence egg advection. Coastal advection and temperature influence how different life history groups exploit spatial and temporal peaks in production.

4.7 Atmosphere-Ocean

Wang, L., R. M. Moore, and J. J. Cullen, 2009, Methyl iodide in the NW Atlantic: Spatial and seasonal variation, *J. Geophys. Res.*, **114**, C07007, doi:10.1029/2007JC004626

While the global ocean is an important source of atmospheric methyl iodide (CH_3I), the major producers of CH_3I within the ocean remain unclear. During a seasonal study in the NW Atlantic, the relationship between CH_3I and some characteristic phytoplankton pigments was examined in order to identify possible phytoplankton producers of CH_3I. Although no characteristic pigments exhibited a strong positive correlation with CH_3I, in the surface mixed layer, there was a weak correlation ($R = 0.35$, n = 70, $p = 0.003$) between the concentrations of CH_3I and zeaxanthin, a pigment characteristic of cyanobacteria in the open ocean. In this study, a moderate correlation was observed between the surface mixed layer CH_3I concentration and depth-averaged daily radiant exposure ($R = 0.61$, n = 15, $p = 0.02$), which indicates a positive influence of solar radiation on CH_3I production. However, the results from this study do not conclusively show whether the influence was exerted through photochemistry or other pathways. A positive correlation between the CH_3I concentration and sea surface temperature was also observed ($R = 0.61$, n = 79, $p \ll 0.001$).

Zhai, X., and R. J. Greatbatch, 2007, Wind work in a model of the northwest Atlantic Ocean, *Geophys. Res. Lett.*, **34**, L04606, doi:10.1029/2006GL028907

The work done by the wind over the northwest Atlantic Ocean is examined using a realistic high-resolution ocean model driven by synoptic wind forcing. Two model runs are conducted with the difference only in the way the wind stress is

calculated. Our results show that the effect of including ocean surface currents in the wind stress formulation is to reduce the total wind work integrated over the model domain by about 17%. The reduction is caused by a sink term in the wind work calculation associated with the presence of ocean currents. In addition, the modelled eddy kinetic energy decreases by about 10%, in response to direct mechanical damping by the surface stress. A simple scaling argument shows that the latter can be expected to be more important than bottom friction in the energy budget.

Zhai, X., R. J. Greatbatch, and C. Eden, 2007, Spreading of near-inertial energy in a 1/12° model of the North Atlantic Ocean, *Geophys. Res. Lett.*, **34**, L10609, doi:10.1029/2007GL029895

Near-inertial energy in the ocean is thought to be redistributed by β-dispersion, whereby near-inertial waves generated at the surface by wind forcing propagate downward and equatorward. In this letter, we examine the spreading of near-inertial energy in a realistic 1/12° model of the North Atlantic driven by synoptically varying wind forcing. We find that (1) near-inertial energy is strongly influenced by the mesoscale eddy field and appears to be locally drained to the deep ocean, largely by the chimney effect associated with anticyclonic eddies, and (2) the interior of the subtropical gyre shows very low levels of near-inertial energy, contrary to expectations based on the β-dispersion effect.

4.8 Coastal and Nearshore Processes

Almeida, E., M. Dowd, J. M. Flemming, and W. K. W. Li, 2009, Extraction of interannual trends in seasonal events for ecological time series, *Limnol. Oceanogr.*, 7: 833-847

The statistical analysis of environmental monitoring data is an important issue in detecting year-to-year changes in levels and timings of important ecological events. In many cases, this trend detection must explicitly view interannual changes from the context of an evolving seasonal cycle. This study analyses weekly sampling data from a long-term ocean monitoring program near Halifax, Nova Scotia, Canada. A state space model of evolving seasonality with a quadratic trend is fit to these time series to extract the signal from the noisy and irregularly sampled data. The procedure uses Kalman filter innovations to estimate model parameters. A fixed interval smoother is then applied to estimate the system state. The resultant state estimates are subjected to a trend analysis carried out with respect to key ecological events: the level and timing of the peak, trough, spring, and fall abundances. These events are identified using derivative information, followed by a regression-based trend analysis. The analysis found a number of significant linear trends in the biogeochemical variables considered. More generally, the approach used here is suitable for use with monitoring data exhibiting a unimodal seasonal signal with noise and missing values.

Lin, Y., R. J. Greatbatch, and J. Sheng, 2010, The influence of Gulf of Mexico Loop Current intrusion on the transport of the Florida Current, *Ocean Dyn.*, **60**(5): 1075-1084, doi:10.1007/s10236-010-0308-0

Based on an empirical orthogonal function analysis of satellite altimeter data, guidance from numerical model results, and CANEK transport estimates, we propose an index, based on differences in satellite-measured sea surface height anomalies, for measuring the influence of Gulf of Mexico Loop Current intrusion on vertically integrated transport variability through the Yucatan Channel. We show that the new index is significantly correlated at low frequencies (cut-off 120 days) with the cable estimates of transport between Florida and the Bahamas. We argue that the physical basis for the correlation is the geometric connectivity between the Yucatan Channel and the Straits of Florida.

Zhai, L., J. Sheng, and R. J. Greatbatch, 2007, Observations of the dynamical response of a coastal embayment to wind, tide, and buoyancy forcing, *Cont. Shelf Res.*, **27**(20): 2534-2555, doi:10.1016/j.csr.2007.07.001

Sea level, current, and hydrographic observations made in Lunenburg Bay of Nova Scotia, Canada, in the summer and fall of 2003 are used to investigate the dynamical response of the bay to wind, tide and buoyancy forcing. The temperature and salinity variability at periods of >10 d was similar to that on the inner Scotian Shelf, whereas the variability at periods of 1–10 d was mainly related to the local wind forcing. The five major tidal constituents (M_2, N_2, S_2, K_1 and O_1) extracted from the observed sea levels accounted for about 99% of the total tidal variance during the study period. Tidal elevation in Upper South Cove had reduced amplitude and a phase lag of about an hour compared to Lunenburg Bay itself. The observed non-tidal sea levels were related with the local wind forcing. The semi-diurnal M_2 tidal flow extracted from current measurements was the major tidal constituent. The observed non-tidal currents had significant temporal variation, with the first EOF (empirical orthogonal function) correlated with the local wind forcing and the second EOF being weakly related to the baroclinic transport into the bay estimated using the thermal wind relation. The first EOF was characterized by inflow on one side of the bay and outflow on the other. It is shown that the circulation variability associated with the first EOF played an important role in the heat budget of the bay, exchanging heat (and also salt) with the neighbouring inner Scotian Shelf.

4.8.1 Modelling

Lin, Y., R. J. Greatbatch, and J. Sheng, 2009, A model study of the vertically integrated transport variability through the Yucatan Channel: Role of Loop Current evolution and flow compensation around Cuba, *J. Geophys. Res.*, **114**, C08003, doi:10.1029/2008JC005199

The relationship between Loop Current intrusion in the Gulf of Mexico and vertically integrated transport variations through the Yucatan Channel is examined using models and the available observations. Transport in the model is found to be a minimum when the Loop Current intrudes strongly into the Gulf of Mexico, typically just before a ring is shed, and to be a maximum during the next growth phase in association with the buildup of warm water off the northwest coast of Cuba. We argue that the transport variations are part of a "compensation effect" in which transport variations through the Yucatan Channel are at least

partly compensated by flow around Cuba. Numerical experiments show that the transport variations result from the interaction between the density anomalies associated with Loop Current intrusion and the variable bottom topography. The compensation effect is also shown to operate at shorter time scales (less than 30 days) in association with wind forcing.

Sheng, J. and B. Yang, 2008, Process study of coastal circulation over the inner Scotian Shelf using a nested-grid ocean circulation model, with a special emphasis on the storm-induced circulation during tropical storm Alberto in 2006, *Ocean Dynamics*, **58**(5-6): 375-396, doi:10.1007/s10236-008-0149-2

This study examines main physical processes affecting the three-dimensional (3D) circulation and hydrographic distributions over the inner Scotian Shelf (ISS) in June and July 2006 using a nested-grid coastal ocean circulation modeling system known as the NCOPS-LB. The nested-grid system has five relocatable downscaling submodels, with the outermost submodel of a coarse horizontal resolution of (1/12)° for simulating storm surges and barotropic shelf waves over the Eastern Canadian shelf and the innermost submodel of a fine resolution of ~180 m for simulating the 3D coastal circulation and hydrography over Lunenburg Bay of Nova Scotia in the default setup. The NCOPS-LB is driven by meteorological and astronomical forcing and used to study the storm-induced circulation over the ISS during tropical storm Alberto. Model results demonstrate that the coastal circulation and hydrographic distributions over the ISS are affected significantly by tides, local wind forcing, and remotely generated coastal waves during the study period.

Sheng, J. and B. Yang, 2010, A Nested-Grid Ocean Circulation Model for Simulating Three-Dimensional Circulation and Hydrography over Canadian Atlantic Coastal Waters, *Terrestrial, Atmospheric and Oceanic Sciences,* **21**(1): 27-44, doi:10.3319/TAO.2009.06.08.01

A one-way nested-grid coastal ocean circulation modeling system was developed for Canadian Atlantic coastal waters based on an operational prototype shelf circulation forecast system known as Dalcoast and a high-resolution coastal circulation model developed for Lunenburg Bay (LB) of Nova Scotia. The nested-grid system consists of five relocatable downscaling sub-models, including the outermost sub-model covering the eastern Canadian shelf with a coarse horizontal resolution of 1/12°, and the innermost sub-model covering LB with a fine resolution of about 180 m. The nested-grid system is driven by meteorological forcing converted from three-hourly weather forecast fields provided by the Meteorological Service of Canada and tidal forcing produced by WebTide using pre-calculated tidal harmonic constants. The nested-grid system is used to simulate the dynamic response of coastal waters over the inner Scotian Shelf in June and July 2006. A comparison of model results with observations made in LB demonstrates that the NCOPS-LB performs reasonably well in simulating sea surface elevations and tidal currents, and less well in simulating hydrography and non-tidal currents over the inner shelf.

Sheng, J., J. Zhao, and L. Zhai, 2009, Examination of circulation, dispersion and connectivity in Lunenburg Bay of Nova Scotia using a nested-grid circulation model – *J. Mar. Sys.*, **77**(3): 350-365, doi:10.1016/j.jmarsys.2008.01.013

A coastal ocean observatory has been established in Lunenburg Bay, Nova Scotia since summer 2002 as part of a multi-agency research program of marine environmental observation and prediction over Atlantic Canada coastal waters. The observatory was operational when a category-2 hurricane (Juan) made land fall within 50-km of the bay in September 2003. The coastal response of the bay to Hurricane Juan is examined using a nested-grid coastal circulation modelling system. The nested-grid system is forced by the local wind, tides, and remotely generated coastal waves. A comparison of model results with observed surface elevations and currents demonstrates that the nested-grid system has reasonable skills in simulating the three-dimensional (3D) storm-induced circulation in the study region. The 3D model currents are used to examine the transport and dispersion of passive tracers, local flushing time, and retention and connectivity of passive particles in the bay during Hurricane Juan. Numerical results demonstrate that local wind forcing plays a dominant role in generating large dispersion and hydrodynamic connectivity in the bay during the storm.

Sheng, J. and B. Yang, 2010, A nested-grid ocean circulation model for simulating three-dimensional circulation and hydrography over Canadian Atlantic coastal waters, *Terr. Atmos. Ocean. Sci.*, **21**(1): 27-44, doi:10.3319/TAO.2009.06.08.01(IWNOP)

A one-way nested-grid coastal ocean circulation modeling system was developed for Canadian Atlantic coastal waters based on an operational prototype shelf circulation forecast system known as Dalcoast3 and a high-resolution coastal circulation model developed for Lunenburg Bay (LB) of Nova Scotia. The nested-grid system consists of five relocatable downscaling sub-models, including the outermost sub-model covering the eastern Canadian shelf with a coarse horizontal resolution of 1/12°, and the innermost sub-model covering LB with a fine resolution of about 180 m. The nested-grid system is driven by meteorological forcing converted from three-hourly weather forecast fields provided by the Meteorological Service of Canada and tidal forcing produced by WebTide using pre-calculated tidal harmonic constants. The nested-grid system is used to simulate the dynamic response of coastal waters over the inner Scotian Shelf in June and July 2006. A comparison of model results with observations made in LB demonstrates that the NCOPS-LB performs reasonably well in simulating sea surface elevations and tidal currents, and less well in simulating hydrography and non-tidal currents over the inner shelf.

Thompson, C., L. Smith, and R. Maji, 2007, Hydrogeological modeling of submarine groundwater discharge on the continental shelf of Louisiana, *J. Geophys. Res.*, **112**, C03014, doi:10.1029/2006JC003557

A regional scale hydrogeologic model has been developed to estimate the magnitude of submarine groundwater discharge to the coastal waters of southeastern Louisiana. The model domain incorporates both the onshore recharge area of terrestrially derived freshwater, and fluid circulation within the

sediments on the continental shelf. The hydrogeologic properties of these sediments, which form part of the Coastal Lowlands Aquifer System, have been well-characterized in earlier studies. The low topographic relief of the coastal plain and an extensive zone of seawater intrusion are key features of the groundwater flow system. Model calculations suggest that no water containing a substantial component of terrestrial origin discharges on the continental shelf. Rather the near-shore coastal zone serves as a groundwater recharge area of saline water that then forms the seawater recirculation system beneath the coastal plain. The modeling results are consistent with interpretations of the rates of submarine groundwater discharge derived from geochemical tracers, presented in a companion paper by McCoy et al. (2007).

Thompson, K. R., K. Ohashi, J. Sheng, J. Bobanovic, and J. Ou, 2007, Suppressing bias and drift of coastal circulation models through the assimilation of seasonal climatologies of temperature and salinity, *Cont. Shelf Res.*, **27**(9): 1303-1316, doi:10.1016/j.csr.2006.10.011

Recently Thompson et al. (2006. A simple method for reducing seasonal bias and drift in eddy resolving ocean models. Ocean Modelling 13, 109–125.) proposed a new method for suppressing the bias and drift of ocean circulation models. The basic idea is to nudge the model toward gridded climatologies of observed temperature and salinity in prescribed frequency–wavenumber bands; outside of these bands the model's dynamics are not directly affected by the nudging and the model state can evolve prognostically. Given the restriction of the nudging to certain frequency–wavenumber bands, the method is termed spectral nudging. The frequency–wavenumber bands are chosen to capture the information in the climatology and thus are centered on the climatological frequencies of zero, one cycle per year and its harmonics, and also low wavenumbers (reflecting the smooth nature of gridded climatologies). The new method is applied in this study to a fully nonlinear, 3D baroclinic circulation model of the continental shelves and inland seas of Atlantic Canada and the northeast US. It is shown that the scheme can suppress drift and bias in a nine month integration (February–October, 2002) while still allowing realistic evolution of tides, surges and wind and tide-driven coastal upwelling. It is also shown that density stratification can affect significantly tidal elevations in some regions. The implications for ocean hindcasting and short-term forecasting are discussed.

Zhai, L. and J. Sheng, 2008, Improve the utility of a coastal circulation model by assimilating hydrographic observations into the model momentum equation, *Geophys. Res. Lett.*, **35**, L24603, doi:10.1029/2008GL035640

A numerical scheme is presented to assimilate hydrographic observations into the momentum equation of a limited-area coastal ocean circulation model. This new scheme has an advantage of assimilating observed hydrography into the model momentum equations and leaving the model temperature and salinity equations to be fully prognostic and is well suited for tracer studies. The performance of this new scheme is assessed using a nested-grid coastal circulation model developed for Lunenburg Bay of Nova Scotia, Canada. Model results demonstrate that this

new scheme improves significantly the performance of the coastal circulation model in simulating the temperature and salinity distributions and circulation over coastal waters.

Zhai, L., J. Sheng, and R. J. Greatbatch, 2008a, Application of a nested-grid ocean circulation model to Lunenburg Bay of Nova Scotia: Verification against observations, *J. Geophys. Res.*, **113**, C02024, doi:10.1029/2007JC004230

A nested-grid ocean circulation modeling system is used to study the response of Lunenburg Bay in Nova Scotia, Canada, to local wind-forcing, tides, remotely generated waves, and buoyancy forcing in the summer and fall of 2003. Quantitative comparisons between observations and model results demonstrate that the modeling system reproduces reasonably well the observed sea level, temperature, salinity, and currents in the bay. Numerical results reveal that the spatial and temporal variability of temperature and salinity in the bay during the study period is mainly forced by the local wind stress and surface heat/freshwater fluxes, with some contribution from tidal circulation. In particular, the local heat balance on the monthly timescale is dominated by cooling due to vertical advection and warming due to horizontal advection and net surface heat flux, while high-frequency variations (timescales of 1–30 days) are mainly associated with vertical advection, i.e., wind-induced upwelling and downwelling. There is also a strong baroclinic throughflow over the deep water region outside Lunenburg Bay that is strongly influenced by wind-forcing. The vertically integrated momentum balance analysis indicates a modified geostrophic balance on the monthly timescale and longer, and is dominated by the pressure term and wind minus bottom stress in the high-frequency band.

Zhai, L., J. Sheng, and R. J. Greatbatch, 2008b, Baroclinic dynamics of wind-driven circulation in a stratified bay: A numerical study using models of varying complexity, *Cont. Shelf Res.*, doi:10.1016/j.csr.2008.05.005

The baroclinic response of a stratified coastal embayment (Lunenburg Bay of Nova Scotia) to the observed wind forcing is examined using two numerical models. A linear baroclinic model based on the normal mode approach shows skill at reproducing the observed isotherm movements and sub-surface currents during a time of strong stratification in the bay. The linear model also shows that the isotherm movement in Lunenburg Bay is influenced by the wind forcing and propagation of baroclinic Kelvin waves from neighbouring Mahone Bay. The effects of nonlinearity and topography are investigated using a three-dimensional nonlinear coastal circulation model. The nonlinear model results demonstrate that the nonlinear advection terms generate a gyre circulation at the entrance of Lunenburg Bay, and the slope bottom topography at the mouth of the bay strengthens the sub-surface time-mean inflow on the southern side of the bay. A comparison of model-calculated currents in different numerical experiments clearly shows that baroclinicity plays a dominant role in the dynamics of wind-driven circulation in Lunenburg Bay.

4.8.2 GOMOOS

Bogden, P., J. Cannon, R. Y. Morse, I. Ogilvie, B. Blanton, and W. Perrie, 2008, A Glimpse of the Future Web: Forecasting storm damage on the Maine coast, *J. Ocean Technol.*, **3**(3): 7-11

No abstract, this is the introduction

The Internet has helped globalize the economy and change social interactions, but the full impact on coastal science has yet to be realized. This essay provides a glimpse of the future. We demonstrate how Web 2.0 technologies can stream line the transition from research to practical applications. Our partners at the National Weather Service (NWS) are meteorologists whose forecast warnings save lives and livelihoods. Our research partners work on the most advanced technologies on the planet for environmental prediction. Gulf of Maine Ocean Observing System (GoMOOS), Inc. (www.GoMOOS.org) has brought these two communities together to prototype new ways to mitigate the impact of coastal storms in New England. A case study tells the story.

Pettigrew, N. R., H. Xue, J. D. Irish, W. Perrie, C. S. Roesler, A. C. Thomas, and D. W. Townsend, 2008, The Gulf of Maine Ocean Observing System: Generic lessons learned in the first seven years of operation (2001-2008), *Mar. Technol. Soc. J.*, **42**(3): 91-102, doi:10.4031/002533208786842444

The Gulf of Maine Ocean Observing System (GoMOOS) was established in the summer of 2001 as a prototype real-time observing system that now includes eleven solar powered buoys with physical and optical sensors, four shore-based long-range HF radar systems for surface current measurement, operational circulation and wave models, satellite observations, inshore nutrient monitoring, and hourly web delivery of data. The observing system in the Gulf of Maine (GoM) is one of the most comprehensive and operational of the Integrated Ocean Observing Systems (IOOS) systems that have been established in the United States to date. It has also been a very successful system, with data returns routinely in the 85-95% range.

The Gulf of Maine is a harsh operational environment. Winter storms pose severe challenges, including high waves and the build-up of sea ice on buoy sensors, superstructure, and solar panels, and in summer its productive waters present severe biofouling problems that can affect the optical sensors. The periods of most difficult field operations often coincide with periods of greatest data value in terms of marine safety, search and rescue, and monitoring biological productivity. The challenges of the Gulf of Maine physical environment were paired with the unexpected challenges of the funding environment that have been the hallmark of the turn of this century. Funding for the system has been chronically short and subject to the unpredictable fluctuations of the congressional appropriations process. The inadequacy and variability of funding has substantially hampered the operations of many of the Integrated Ocean Observing Systems, including GoMOOS, and has hindered technological advancements and maintenance measures. As a result, the design of the GoMOOS infrastructure is little improved from that developed almost a decade ago, and it has deteriorated with age, usage,

and suboptimal replacement schedules. In the absence of an adequate and reliable funding stream, the system is fast approaching the end of its expected operational lifetime. Unless this trend is reversed, the system will no longer well serve the many citizens, organizations, and agencies that have come to rely on the data it provides.

In this article, we present lessons learned by the scientific and technical groups that have been responsible for the data acquisition of GoMOOS. We believe that these lessons are generic, rather than peculiar to the GoMOOS system, and that they have value for others who are embarking on similar endeavors. However, it is important to make clear that these lessons are from the perspective of the scientists, and that the views of others involved in complementary aspects of GoMOOS, including public outreach, fundraising, and providing data and products to the more general user community, are not represented here.

4.8.3 River Plumes

Milligan, T. G., P. S. Hill, and B. A. Law, 2007, Flocculation and the loss of sediment from the Po River plume, *Cont. Shelf Res.*, **27**(3-4): 309-321, doi:10.1016/j.csr.2006.11.008

In October 2000, a 100-year flood event in the Po River resulted in the formation of a fine-grained sediment deposit extending up to 10 km from the river mouth. Soon after this event, and for a subsequent period of 2 years, box cores were collected on a grid of stations off of the Po Delta to observe the evolution of the flood deposit. Using a process-based parameterization of the disaggregated inorganic grain size distribution, the evolution of the surficial sediment on the Po shelf since the 2000 flood has been interpreted in the context of particle flocculation dynamics. This method produces estimates of floc limit, the diameter at which the flux of single grains to the seabed equals the flux of flocs, and floc mass fraction, the amount of material deposited as flocs. Floc limit depends on the extent of flocculation in suspension, and floc mass fraction describes the extent of flocculation in the sediment. Immediately after the flood, these two parameters were high at stations located beneath the path of the flood plume as observed in satellite images. The occurrence of a highly flocculated deposit below the path of the plume leads to two hypotheses: (1) the high sediment concentration in the river flood plume produced extensive sediment flocculation in the plume and (2) post-depositional remobilization of sediment delivered from the plume to the seabed was limited in the relatively low-energy environment of the Po prodelta. Floc limit and floc mass fraction estimated from bottom sediment sampling 3 and 10 months after the initial sampling were lower, indicating that during normal discharge, flocculated fine-grained sediment from the Po River settles close to the mouth, leaving only a small amount of material in suspension in the plume for direct deposition onto the prodelta. These findings are consistent with laboratory studies of suspended sediment that show that sediment concentration and turbulent energy exert dominant control on the extent of flocculation and the loss of sediment from suspension.

4.8.4 Estuaries

Bourgault, D., D. E. Kelley, and P. S. Galbraith, 2008, Turbulence and boluses on an internal beach, *J. Mar. Res.*, **66**(5): 563-588, doi:10.1357/002224008787536835

In a manner similar to that of surface waves on beaches, high-frequency interfacial waves (IWs) may break when approaching the 'internal coastline,' where the undisturbed pycnocline intersects the shoaling bottom. This process has been studied previously in idealized laboratory and numerical experiments but there are few field observations to document the properties of IWs shoaling on natural internal beaches. This paper presents observations of currents, density and turbulence collected inshore of the break point of an internal beach of the St. Lawrence Estuary. A series of large- and small-amplitude complex-shaped and unorganized internal boluses was observed. The structure of these boluses is discussed, along with their role in boundary turbulence and transport.

Curran, K. J., P. S. Hill, T. G. Milligan, O. A. Mikkelsen, B. A. Law, X. Durrieu de Madron, and F. Bourrin, 2007, Settling velocity, effective density, and mass composition of suspended sediment in a coastal bottom boundary layer, Gulf of Lions, France, *Cont. Shelf Res.*, **27**(10-11): 1408-1421, doi:10.1016/j.csr.2007.01.014

Particle size distribution and size-specific settling velocity are critical parameters for understanding the transport of fine sediment on continental margins. In this study, observed floc size versus settling velocity, volume distributions of particles 2 μm–1 cm in diameter, and calculated effective densities for all particle sizes provided estimates of the mass distribution in suspension, which is used to apportion mass among component particles, microflocs, and macroflocs. Measurements were made during relatively quiescent environmental conditions. Observations of size distributions based on mass demonstrate an increase in the component particle fraction through time. The increase in the percentage of component particles in suspension had implications on water column properties, as small changes in the component particle fraction affected water column optical transmission in a way that was not as easily detected by changes in the volume concentration distribution or total mass concentration. Flocs larger than 133 μm in diameter only comprised one quarter to one third of the mass in suspension. This finding may explain why suspension bulk clearance rates are often an order of magnitude lower than those predicted by other methods.

Mareuil, A., R. Leconte, F. Brissette, and M. Minville, 2007, Impacts of climate change on the frequency and severity of floods in the Châteauguay River basin, Canada, *Can. J. Civil Eng.*, **34**(9): 1048-1060, doi:10.1139/l07-022

This study aims at evaluating the hydrologic impacts of climate change on the Châteauguay River basin in the province of Quebec, Canada. Three global climate models (GCMs) covering a range of climate sensitivities were selected, and their output was employed to adjust the parameters of a stochastic weather generator using simple transformation rules for precipitation and temperature. Values of monthly precipitation and temperature were extracted from the GCMs for the current (1960-1990) and future (2040-2060) climate. The International Panel on Climate Change emission scenario known as B2 was selected. It represents an

average scenario and corresponds approximately to a doubling of the atmospheric CO_2 concentration. Resorting to stochastically generated climate scenarios allowed assessing whether the modelled effects of climate change on flows were statistically significant. Results indicate that spring and summer-fall peak flows were reduced on average by 30% and 12%, respectively, using the Echam4 model derived scenarios. The Hadcm3 model produced a weaker signal that was not statistically significant. The CGCM2 model produced a statistically significant reduction in spring peak flows of 8% on average, whereas the simulated reduction in summer flows was not statistically significant for many of the return periods considered. Many sources of uncertainties were partially considered in this study. One is the downscaling of the GCM climatology at the watershed scale. The approach employed to generate the future climate scenarios changed the precipitation variability through an adjustment of the parameters of the Gamma distribution function used to model precipitation amounts. Whether this approach is truly typical of climate change effect remains to be ascertained. Using more physically based hydrological models would help reduce uncertainties in climate change impacts studies.

Rachel D. Simons, R. D. , S. G. Monismith, F. J. Saucier, L. E. Johnson, and G. Winkler, 2010, Modelling Stratification and Baroclinic Flow in the Estuarine Transition Zone of the St. Lawrence Estuary, *Atmos-Ocean*, **48**(2): 132–146, doi:10.3137/OC316.2010

This paper presents a hydrodynamic study of the St. Lawrence Estuary's estuarine transition zone, a 100 km region where fresh water from the river mixes with salt water from the estuary. The circulation of the estuarine transition zone is driven by strong tides, a large river flow, and well-defined salinity gradients. For this study, a three-dimensional hydrodynamic model was applied to the estuarine transition zone of the St. Lawrence Estuary and used to examine stratification and density-driven baroclinic flow. The model was calibrated to field observations and subsequently predicted water level elevations, along-channel currents, and salinity with mean errors of less than 9%, 11%, and 17%, respectively. The baroclinic density-driven currents were distinguished from the tidal barotropic currents by using principal component analysis. Stratification and baroclinic flow were observed to vary throughout the estuarine transition zone on tidal and subtidal spring-neap time scales. On a semidiurnal tidal time scale, stratification was periodic, and baroclinic flow was represented by pulses of sheared exchange flow, suggesting that neither buoyancy forcing nor turbulent mixing is dominant at this scale. On a subtidal spring-neap time scale, stratification and baroclinic flow varied inversely with tidal energy, increasing on weak neap tides and decreasing on strong spring tides.

Zhang, Y., H. Xie, C. G. Fichot, and G. Chen, 2008, Dark production of carbon monoxide (CO) from dissolved organic matter in the St. Lawrence estuarine system: Implication for the global coastal and blue water CO budgets, *J. Geophys. Res.*, **113**, C12020, doi:10.1029/2008JC004811

We investigated the thermal (dark) production of carbon monoxide (CO) from dissolved organic matter (DOM) in the water column of the St. Lawrence

estuarine system in spring 2007. The production rate, Q_{co}, decreased seaward horizontally and downward vertically. Q_{co} exhibited a positive, linear correlation with the abundance of chromophoric dissolved organic matter (CDOM). Terrestrial DOM was more efficient at producing CO than marine DOM. The temperature dependence of Q_{co} can be characterized by the Arrhenius equation with the activation energies of freshwater samples being higher than those of salty samples. Q_{co} remained relatively constant between pH 4–6, increased slowly between pH 6–8 and then rapidly with further rising pH. Ionic strength and iron chemistry had little influence on Q_{co}. An empirical equation, describing Q_{co} as a function of CDOM abundance, temperature, pH, and salinity, was established to evaluate CO dark production in the global coastal waters (depth < 200 m). The total coastal CO dark production from DOM was estimated to be from 0.46 to 1.50 Tg CO-C a^{-1} (Tg carbon from CO a^{-1}). We speculated the global oceanic (coastal plus open ocean) CO dark production to be in the range from 4.87 to 15.8 Tg CO-C a^{-1} by extrapolating the coastal water-based results to blue waters (depth > 200 m). Both the coastal and global dark source strengths are significant compared to the corresponding photochemical CO source strengths (coastal: ~2.9 Tg CO-C a^{-1}; global: ~50 Tg CO-C a^{-1}). Steady state deepwater CO concentrations inferred from Q_{co} and microbial CO uptake rates are <0.1 nmol L^{-1}.

4.8.5 Tidal Processes

Han, G., S. Paturi, B. deYoung, Y. Yi, and C.-K. Shum, 2010, A 3-D Data-Assimilative Tidal Model of the Northwest Atlantic, *Atmos.-Ocean*, **47**(4): 39–57, doi:10.3137/OC303.2010

A three-dimensional (3-D) barotropic tidal model for the northwest Atlantic is developed for eight leading semi-diurnal (M2, S2, N2, K2) and diurnal (K1, O1, P1, Q1) tidal constituents based on the Princeton Ocean Model (POM). Multi-mission altimetric tidal data are assimilated into the model using a simple nudging scheme. The assimilative model results are validated against independent in situ observations and compared with a nonassimilative run and previous tidal models. The root-sum-square error for the assimilative M2, S2, N2, K1 and O1 tidal elevations is 3.1 cm excluding the Bay of Fundy region and 11.1 cm otherwise. Assimilation improves the accuracy of the model tidal elevation by 40–60% and that of the tidal currents by 20–30%. The semi-diurnal tidal currents agree better with observations than do the diurnal constituents. The model K1 and O1 tidal currents are intensified on several outer-shelf areas, qualitatively consistent with shelf-wave theory and moored measurements, but quantitatively overestimated. Results show that the present assimilative model reproduces the primary tidal constituents better than previous regional and inter-regional models. In particular, the present model results are as accurate as those of Egbert and Erofeeva (2002) for the northwest Atlantic shelf seas as a whole and better if the Bay of Fundy is excluded, pointing to the importance of the high-resolution multi-satellite tides to partially compensate for the simple assimilation technique.

Karsten, R. H., J. M. McMillan, M. J. Lickley, and R. D. Haynes, 2008, Assessment of tidal current energy in the Minas Passage, Bay of Fundy, **222**(5): 493-507, doi:10.1243/09576509JPE555

The tidal power available for electricity generation from in-stream turbines placed in the Minas Passage of the Bay of Fundy is examined. A previously derived theory is adapted to model the effect of turbine drag on the flow through the Minas Passage and the tidal amplitude in the Minas Basin. The theoretical maximum power production over a tidal cycle is determined by the product of the amplitude of the forcing tide in the Bay of Fundy and the undisturbed volumetric flowrate through the Minas Passage. Although the extraction of the maximum power will reduce the flow rate through the Minas Passage and the tides in the Minas Basin by over 30 per cent, a significant portion of the maximum power can be extracted with little change in tidal amplitude as the initial power generation causes only an increase in the phase lag of the basin tides. Two-dimensional, finite-element, numerical simulations of the Bay of Fundy–Gulf of Maine system agree remarkably well with the theory. The simulations suggest that a maximum of 7 GW of power can be extracted by turbines. They also show that any power extraction in the Minas Passage pushes the Bay of Fundy–Gulf of Maine system closer to resonance with the forcing tides, resulting in increased tidal amplitudes throughout the Gulf of Maine. Although extracting the maximum power produces significant changes, 2.5 GW of power can be extracted with a maximum 5 per cent change in the tidal amplitude at any location. Finally, the simulations suggest that a single turbine fence across the Minas Passage can extract the same power as turbines throughout the passage but that partial turbine fences are less efficient.

4.8.6 Sea Level

Bernier, N. B. and K. R. Thompson, 2007, Tide-surge interaction off the east coast of Canada and northeastern United States, *J. Geophys. Res.*, **112**, C06008, doi:10.1029/2006JC003793

Sea level observations and a dynamical model are used to investigate tide-surge interaction in the coastal waters off the east coast of Canada and northern USA. The study is motivated in part by the need to improve operational forecasts of total water level and coastal flooding. Two statistical methods are used to search for evidence of tide-surge interaction in hourly sea level records from 23 coastal locations. The methods are based on comparison of the statistical properties of the sea level residuals (observed sea level minus tide) occurring at different stages of the tidal cycle. While recognizing the limitations of such an approach, it is concluded that tide-surge interaction does occur in the Northumberland Strait which is located in the southern Gulf of St. Lawrence. Results for the Gulf of Maine and Bay of Fundy are less conclusive. A dynamical model is also used to quantify tide-surge interaction in the study region and to identify its physical causes. Tide-surge interaction in the model is strongest in the Northumberland Strait where the amplitude of the effect can reach 20 cm during and following strong storm surge events. This is large enough to be of practical significance in terms of flood forecasting. A series of sensitivity experiments with the model

shows that the nonlinear parameterization of bottom stress is the principal contributor to tide-surge interaction.

Bernier, N., K. R. Thompson, J. Ou, and H. Ritchie, 2007, Mapping the return periods of extreme sea levels: Allowing for short sea level records, seasonality, and climate change, *Global and Planetary Change*, **57**(1-2): 139-150, doi:10.1016/j.gloplacha.2006.11.027

This study of extreme sea levels is motivated by concern over increased coastal erosion and flooding under plausible climate change scenarios. Extremal analyses are performed on the annual and seasonal maxima from 24 tide gauge stations in the Northwest Atlantic. At data poor locations, a 40 yr surge hindcast and information from short observation records are used to reconstruct sea level records prior to the annual and seasonal analysis of extremes. A Digital Elevation Model is used to generate spatial maps of the return period of extreme sea levels associated with specified flooding probabilities under current conditions and under projected global sea level rise scenarios for the next century. It is the first time such maps have been produced. Their primary advantage is that extreme sea levels are expressed in terms of inundated areas as opposed to a critical flood value about an arbitrary datum. Another novel aspect of this study is that the extremal analyses are carried out for specific seasons.

Bernier, N. B., and K. R. Thompson, 2010, Tide surge and energy budgets for Eastern Canadian and Northeast US waters, *Cont. Shelf Res.*, **30**: 353-364

A depth averaged barotropic model is used to quantify the effect of tides and storm surges on the energy budget for the coastal waters bordering the Northwest Atlantic. The model is first shown capable of producing realistic predictions of both tides and surges through comparison with independent sea level observations. In particular, it is shown that the model can predict tidal range with a typical RMS error of 20 cm, and realistic semi-diurnal to diurnal amplitude ratios. Storm surge hindcasts are also shown to be predicted with typical RMS errors less than 8cm.Following successful validation of the model we produce, for the first time, spatial maps of maximum speed due to combined tide and surge (due to atmospheric forcing) current, tidal only current, and surge only current. The model is next used to examine the energy budget of the study area. It is shown that the energy flux vectors for the semi-diurnal and diurnal tides are very different. O1 vectors tends to be more aligned with the bathymetry than the M2 vectors. Most dissipation was found to occur in the high tide region of the Bay of Fundy. It is also shown that in the mean (i.e. over a season or a year), surges and tide–surge interaction do not play an important role in the energy budget. However, during a large surge event this is not true; surge and tide–surge interaction can have an order one impact on the energy balance. We discuss how such infrequent and unusually large events impact the nearshore environment.

Han, G. and Y. Shi, 2008, Development of an Atlantic Canadian Coastal Water Level Neural Network Model, *J. Atmos. Oceanic Technol.*, **25**(11): 2117–2132, doi:10.1175/2008JTECHO569.1

Coastal water-level information is essential for coastal zone management, navigation, and oceanographic research. However, long-term water-level observations are usually only available at a limited number of locations. This study discusses a complementary and simple neural network (NN) approach, to predict water levels at a specified coastal site from the data gathered at other nearby or remote permanent stations. A simple three-layer, feed-forward, back-propagation network and a neural network ensemble, named Atlantic Canadian Coastal Water Level Neural Network (ACCSLENNT) models, was developed to correlate the nonlinear relationship of sea level data among stations by learning from their historical characteristics. Instantaneous hourly observations of water level from five stations along the coast of Atlantic Canada—Argentia, Belledune, Halifax, North Sydney, and St. John's—are used to formulate and validate the ACCSLENNT models. Qualitative and quantitative comparisons of the network output with target observations showed that despite significant changes in sea level amplitudes and phases in the study area, appropriately trained NN models could provide accurate and robust long-term predictions of both tidal and nontidal (tide subtracted) water levels when only short-term data are available. The robust results indicate that the NN models in conjunction with limited permanent stations are able to supplement long-term historical water-level data along the Atlantic Canadian coast. Because field data collection is usually expensive, the ACCSLENNT models provide a cost-effective alternative to obtain long-term data along Atlantic Canada.

Horton, B. P., W. R. Peltier, S. J. Culver, R. Drummond, S. E. Engelhart, A. C. Kemp, D. Mallinson, E. R. Thieler, S. R. Riggs, D. V. Ames, and K. H. Thomson, 2009, Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models, *Quat. Sci. Rev.*, **28**(17-18): 1725-1736, doi:10.1016/j.quascirev.2009.02.002

We have synthesized new and existing relative sea-level (RSL) data to produce a quality-controlled, spatially comprehensive database from the North Carolina coastline. The RSL database consists of 54 sea-level index points that are quantitatively related to an appropriate tide level and assigned an error estimate, and a further 33 limiting dates that confine the maximum and minimum elevations of RSL. The temporal distribution of the index points is very uneven with only five index points older than 4000 cal a BP, but the form of the Holocene sea-level trend is constrained by both terrestrial and marine limiting dates. The data illustrate RSL rapidly rising during the early and mid Holocene from an observed elevation of −35.7 ± 1.1 m MSL at 11062–10576 cal a BP to −4.2 m ± 0.4 m MSL at 4240–3592 cal a BP.

We restricted comparisons between observations and predictions from the ICE-5G(VM2) with rotational feedback Glacial Isostatic Adjustment (GIA) model to the Late Holocene RSL (last 4000 cal a BP) because of the wealth of sea-level data during this time interval. The ICE-5G(VM2) model predicts significant spatial variations in RSL across North Carolina, thus we subdivided the observations into two regions. The model forecasts an increase in the rate of sea-

level rise in Region 1 (Albemarle, Currituck, Roanoke, Croatan, and northern Pamlico sounds) compared to Region 2 (southern Pamlico, Core and Bogue sounds, and farther south to Wilmington). The observations show Late Holocene sea-level rising at 1.14 ± 0.03 mm year^{-1} and 0.82 ± 0.02 mm year^{-1} in Regions 1 and 2, respectively. The ICE-5G(VM2) predictions capture the general temporal trend of the observations, although there is an apparent misfit for index points older than 2000 cal a BP. It is presently unknown whether these misfits are caused by possible tectonic uplift associated with the mid-Carolina Platform High or a flaw in the GIA model. A comparison of local tide gauge data with the Late Holocene RSL trends from Regions 1 and 2 support the spatial variation in RSL across North Carolina, and imply an additional increase of mean sea level of greater than 2 mm year^{-1} during the latter half of the 20th century; this is in general agreement with historical tide gauge and satellite altimetry data.

Lefaivre, D., S. Hamdi, and B. Morse, 2009, Statistical Analysis of the 30-Day Water Level Forecasts in the St. Lawrence River, *Marine Geodesy*, **32**(1): 30-41, doi:10.1080/01490410802661971

Forecasts of water levels in the St. Lawrence River on the east coast of Canada have been issued every working day since 1997 using a one-dimensional hydrodynamic model (One-D) for periods extending up to 30 days. In order to assess the performance of these forecasts, a comparison between the model forecasts and the observations of the water levels during 2005 was done at 12 stations of the SINECO network located between Montreal and Quebec City. The statistical analysis shows that mean errors are small compared to the water level fluctuations. Confidence intervals of the forecasted values for all stations are evaluated.

Massey, A. C., W. R. Gehrels, D. J. Charman, G. A. Milne, W. R. Peltier, K. Lambeck, and K. A. Selby, 2008, Relative sea-level change and postglacial isostatic adjustment along the coast of south Devon, United Kingdom, *J. of Quaternary Sci.*, **23**: 415–433, doi:10.1002/jqs.1149

Previous sea-level studies suggest that southwest Britain has the fastest subsiding coastline in the United Kingdom, but tide-gauge data, GPS and gravity measurements and geophysical models show little evidence of anomalous subsidence in this region. In this paper we present 15 new sea-level index points from four coastal barrier systems in south Devon. Eight are from compaction-free basal sediments and others were corrected for autocompaction. Our data suggest that relative sea level along the south Devon coastline has risen by 21 ± 4 m during the past 9000 years. Sea-level rise slowed during the middle and late Holocene and a rise of 8 ± 1 m has occurred since ca. 7000 cal. yr BP. Anomalous ages for many rejected points are attributed to sediment reworking during barrier transgression. The relative sea-level history during the early and middle Holocene shows a good fit with geophysical model predictions, but the geological and modelled data diverge in the later Holocene. Unlike the geophysical models, sea-level index points cannot differentiate between late Holocene relative sea-level histories of south Devon and southwest Cornwall. It is suggested that this

discrepancy can be resolved by obtaining additional high-quality sea-level index points covering the past 4000 years.

Thompson, K. R., N. B. Bernier, and P. Chan, 2009, Extreme sea levels, coastal flooding and climate change with a focus on Atlantic Canada, *Nat. Hazards*, **51**: 139-150, doi:10.1007/s11069-009-0380-5

Estimation of the probability distribution of extreme sea levels, for the present time and the next century, is discussed. Two approaches are described and their strengths and weaknesses are compared. The first approach is based on dynamics and uses a storm surge model forced by tides, winds and air pressure fields. The second approach is based on the statistical analysis of observed hourly sea level records using a new first-order Markov process that can capture non-Gaussian characteristics (such as skewness) in the non-tidal component of the observed sea level record. It is shown that both approaches can provide good estimates of present day flooding probabilities for regions with relatively strong tides. The limitations of both approaches in terms of assessing the effect of global sea level rise, glacial-isostatic adjustment of the land, and changes in the frequency and severity of storms and hurricanes, are illustrated using recent results for the Northwest Atlantic. Some sensitivity studies are carried out to transform uncertainty in climate change projections into uncertainties in the probability of coastal flooding.

Zhong, L., M. Li, and M. Foreman, 2007, Resonance and sea level variability in Chesapeake Bay, *Cont. Shelf Res.*, **28**(18): 2565-2573, doi:10.1016/j.csr.2008.07.007

A numerical model is used to determine the resonant period and quality factor *Q* of Chesapeake Bay and explore physical mechanisms controlling the resonance response in semi-enclosed seas. At the resonant period of 2 days, the mouth-to-head amplitude gain is 1.42 and *Q* is 0.9, indicating that Chesapeake Bay is a highly dissipative system. The modest amplitude gain results from strong frictional dissipation in shallow water. It is found that the spatial distribution of energy dissipation varies with forcing frequency. While energy at tidal frequencies is dissipated around topographic hotspots distributed throughout the Bay, energy dissipation at subtidal frequencies is mainly concentrated in the shallow-water lower Bay. An analytic calculation shows that the bottom friction parameter is much larger in Chesapeake Bay than in other coastal systems with strong resonance response. The model-predicted amplitude gains and phase changes agree well with the observations at semidiurnal and diurnal tidal frequencies. However, the predicted amplitude gain in the resonant frequency band (34–54 h period) falls below that inferred from band-passed sea level observations. This discrepancy can be attributed to the local wind forcing which amplifies the sea level response in the upper Bay. The model is also used to show that rising sea levels associated with global warming will shift the resonance period of Chesapeake Bay closer to the diurnal tides and thus exacerbate flooding problems by causing an increase in tidal ranges.

4.9 Shelf Shelf/Slope Processes

Craig, J. and D. Gilbert, 2008, Estimation of Mixed Layer Depth at the AZMP Fixed Stations. AZMP Bull. PMZA, 7: 37-42

abstract in French only

Nous examinons des données récoltées aux sept stations fixes du Programme de Monitorage de la Zone Atlantique afin de comparer des méthodes d'estimation de la profondeur de la couche mélangée (*Mixed layer depth*, MLD). Ces sites sont diversifiés du point de vue océanographique, géographique et des facteurs climatiques qui les affectent et fournissent donc d'excellents contrastes pour évaluer la méthode du seuil, du gradient et une méthode mixte d'estimation du MLD. Nous avons trouvé que les estimations du MLD basées sur le maximum du gradient de densité étaient toujours plus élevées que celles obtenues par la méthode du seuil ou la méthode mixte du seuil du gradient. Malgré que ce résultat soit dû en partie au fait que la zone de mélange immédiatement au-dessus du milieu de la pycnocline soit incluse dans l'estimation par la méthode du maximum du gradient, le cycle annuel plus marqué révélé par cette méthode en fait un indice plus robuste dans la perspective de relier les processus biologiques et physiques.

Gilbert, D. and É. Nault, 2008, Temperature, Salinity and Oxygen Measurements from Argo Profiling Floats in the Slope Water Region, *AZMP Bull. PMZA*, 7: 47-52

abstract in French only

Le programme Argo de suivi du climat océanique mondial permet l'acquisition en temps réel de profils verticaux de température et de salinité entre 2000 m de profondeur et la surface. Parmi les quelques 3000 flotteurs-profileurs Argo déployés dans l'océan mondial, près d'une centaine sont équipés de senseurs d'oxygène et cinq de ceux-ci ont été déployés dans les eaux de la pente continentale au sud de Terre-Neuve et de la Nouvelle-Écosse. Dans cet article, nous présentons des statistiques de température, salinité et oxygène, dans la région comprise entre les latitudes 35°N et 48°N et entre les longitudes 45°O et 75°O, calculées à partir de l' ensemble des données recueillies par les flotteurs-profileurs Argo de 1998 à 2007.

Mikkelsen, O. A., P. A. Hill, and T. G. Milligan, 2007, Seasonal and spatial variation of floc size, settling velocity, and density on the inner Adriatic Shelf (Italy), *Cont. Shelf Res.*, **27**(3-4): 417-430, doi:10.1016/j.csr.2006.11.004

Measurements of floc sizes, floc settling velocities and effective floc densities were obtained at three locations on the inner Adriatic shelf (Italy) in February and May/June 2003 using the in situ size and settling column tripod INSSECT (Mikkelsen et al., 2004. INSSECT—an instrument platform for investigating floc properties close to the seabed. Limnology and Oceanography: Methods 2, 226–236). Measurements were carried out in a water depth of 8–12 m and the final data set comprised 2491 flocs. Relationships of observed floc size vs. floc settling velocity and floc size vs. effective floc density were similar to those observed by other authors working in similar settings. The raw data showed significant scatter around mean trends, indicating that only a relatively small fraction of variability

in floc settling velocity and effective floc density was explained by floc size. For bin-averaged data, however, much of the variability in settling velocity and density was explained by floc size. On the Adriatic shelf mean floc settling velocities varied from 0.48 to 1.35 mm s^{-1}, while mean effective floc densities varied from 8.1 to 27.5 kg m^{-3}; within the range reported by other authors. Analysis of variance showed significant differences in floc settling velocities, effective floc densities and floc size in space and time (seasons). Thus, floc settling velocities, effective floc densities and floc size on the inner Adriatic shelf could not be characterized by a common mean, but were more appropriately characterized by a range of values, varying in time and space.

Milligan, T. G. and A. Cattaneo, 2007, Sediment dynamics in the western Adriatic Sea: From transport to stratigraphy, *Cont. Shelf Res.*, **27**(3-4): 287-295, doi:10.1016/j.csr.2006.11.001

No abstract, this is the introduction

Sediment transport and accumulation on continental margins is a fundamental process that impacts the exploitation of resources and protection of the environment and its ecosystems. Continental margins represent a crucial hinge zone for sediment transport between the emerged land masses and the deep marine basins, and are economically significant for fisheries as well as for hydrocarbon and aggregate extraction. Anthropogenic influences on land and near-shore areas can significantly impact the transport and accumulation of sediment on continental margins sometimes with unexpected consequences. Continental margins act as the final sink for many of the contaminants brought to the sea from the land. The Adriatic Sea represents an ideal site to study sediment transport due to its extended and documented history of human impacts (since Roman times), its long-term monitoring of riverine and marine systems (since the end of the 19th century), and its extensive record of studies in marine sediment transport and high-resolution stratigraphy.

The series of papers presented in this special issue of Continental Shelf Research is the result of a successful collaboration between European and North American scientists through several European Union (EU) and US Office of Naval Research (ONR) funded projects. The research that was carried out covered a wide range of topics which significantly increased not only our understanding of the formation of sedimentary strata on continental margins, but also the processes which govern the transport of sediment on the continental shelf. The main focus of this special issue is sediment dynamics in the Western Adriatic Sea including many aspects of continental shelf sedimentation. Our goal with this special issue is to link studies of the effect of water column processes on sediment with those addressing its accumulation on the sea bed and ultimately to its inclusion in the stratigraphic record.

Niu, H., A. Drozdowski, T. Husain, B. Veitch, N. Bose, and K. Lee, 2008, Modeling the dispersion of drilling muds using the bottom boundary layer transport model: The effects

of settling velocity, *Environ. Model. Assess.*, **14**(5): 585-594, doi:10.1007/s10666-008-9162-6

The benthic boundary layer transport (bblt) model was widely used in the Atlantic Canadian offshore region to assess the potential impact zones from drilling wastes discharges from offshore oil and gas drilling. The current version of the bblt uses a single-class settling velocity scenario, which may affect its performance, as settling velocity is size, shape, and material dependent. In this study, the effects of settling velocity on bblt predictions were assessed by replacing this single-class settling velocity scenario with a multi-class size-dependent settling velocity scenario. The new scenario was used in a hypothetical study to simulate the dispersion of barite and fine-grained drilling cuttings. The study showed that the effects of settling velocity on bblt predictions are spatial, temporal, and material dependent.

Petrie, B. 2007, Does the North Atlantic Oscillation Affect Hydrographic Properties on the Canadian Atlantic Continental Shelf? *Atmos.-Ocean*, **45**(3): 141–151, doi:10.3137/ao.450302

An analysis of hydrographic data from the eastern Canadian continental shelf indicates that large-scale spatial patterns of bottom temperature and salinity respond to sustained periods of weak and strong meteorological forcing represented by the winter North Atlantic Oscillation (NAO) index. Warm, salty (cold, fresh) conditions prevail on the Newfoundland-Labrador Shelf, the eastern Scotian Shelf and the Gulf of St. Lawrence during periods of negative (positive) NAO anomalies. The opposite response is seen on the central and western Scotian Shelf and in the Gulf of Maine. Comparison of years when the NAO anomaly was positive and had the same sign for at least the two preceding years with those years when the NAO anomaly was negative and had the same sign for at least the two preceding years, shows differences in bottom temperature and salinity, at the same location, of up to approximately 2°C and 0.4. A plausible explanation of the pattern lies in a combination of local forcing and the highly advective nature of the oceanography that responds to NAO forcing. Greater westward transport of Labrador Slope Water along the shelf edge and subsequent on-shelf penetration of hydrographic anomalies during periods of negative NAO anomalies give rise to the dipole nature of the temperature and salinity patterns. The effects on hydrographic properties appear to be integrated over several years of meteorological forcing, again likely related to advection in the region.

Tang, C. L., W. Perrie, A. D. Jenkins, B. M. DeTracey, Y. Hu, B. Toulany, and P. C. Smith, 2007, Observation and modelling of surface currents on the Grand Banks – a study of the wave effects on surface currents, *J. Geophys. Res.*, **112**, C10025, doi:10.1029/2006JC004028

We investigate the effects of surface waves on surface currents using surface drifter data from the Grand Banks and a coupled current-wave-drifter model. The theoretical basis of the study is Jenkins' theory of wave-current interaction in which wind-generated surface currents are modified by wind-wave and wave-current momentum transfers. The total surface current is the sum of the wave

modified current, the Stokes drift and the tidal current. Jenkins' formulation was incorporated into the Princeton Ocean Model and applied to the Labrador Sea and the adjacent shelves. The wave energy spectrum from Wavewatch III was used to calculate the momentum transfer and the Stokes drift. A series of model experiments were conducted to simulate the drifter trajectories and examine the sensitivity of the simulations to model parameters. The results show that the Stokes drift is the dominant wave effect, which increases the surface drift speeds by 35% and veers the currents toward the wind directions. The net effect of wind-to-wave and wave-to-current momentum transfers reduces the surface speeds by a few percent. A statistical analysis of the model currents and drifter data shows that the inclusion of the wave effects improves the model simulations significantly. Model errors due to uncertainties in the model parameters including the eddy viscosity, wave spectrum, air drag of the drifters, and bottom friction are investigated. The model surface currents are shown to be most sensitive to the surface eddy viscosity and the wave energy spectra.

Wu, Y., I. K. Peterson, C. L. Tang, T. Platt, S. Sathyendranath, and C. Fuentes-Yaco. 2007, The impact of sea-ice on the initiation of spring bloom on the Newfoundland and Labrador Shelves. *J. of Plankton Res.*, 29(6): 509-514, doi:10.1093/plankt/fbm035

The relationship between sea ice and the phytoplankton spring bloom over the Newfoundland and Labrador shelves is examined using remotely-sensed chlorophyll data and sea-ice data for the period 1998–2004. A regression analysis between the two data sets shows that the retreat of sea ice precedes the spring bloom, and the inter-annual variation of the spring bloom is closely correlated with the start time of ice retreat. The spring bloom off Canada's east coast usually starts on the eastern Grand Banks. Here, the water properties are strongly influenced by sea ice on the Newfoundland shelves in early spring when accelerated ice melting causes the ice edge to retreat north and the melt water is advected south by the Labrador Current. After the ice retreat, the water on the eastern Grand Banks is rapidly stratified and the mixed layer shallows as a result of surface freshening. The shallow mixed layer promotes phytoplankton growth. The regression analysis also reveals that an early spring bloom or ice retreat tends to prolong the duration of the spring bloom.

Zhai, L., T. Platt, C. Tang, S. Sathyendranath, C. Fuentes-Yaco, E. Devred, and Y. Wu, 2010, Seasonal and geographic variations in phytoplankton losses from the mixed layer on the Northwest Atlantic Shelf, *J. of Mar. Sys.*, **80**(1-2): 36-46,doi:10.1016/j.jmarsys.2009.09.005

The total daily phytoplankton loss from the mixed layer is estimated as the difference between the primary production and the realized change of phytoplankton carbon biomass. A Monte Carlo procedure is used to recover the total loss rates for ten geographic locations on the Northwest Atlantic continental shelf. The strong seasonal and geographic variations in mixed-layer loss rates of phytoplankton are tied closely to the primary production. The daily, mixed-layer, total loss ranges from 50 to 1000 mg C m^{-2} d^{-1}, which is compared with the output of process models, the closure error being generally less than 10% of the

total loss. The model results show that the annual respiration is generally greater than losses due to zooplankton grazing and sinking, except that zooplankton grazing dominates other loss terms on the west Greenland shelf.

4.9.1 Scotian Shelf

Ohashi, K., J. Sheng, K. R. Thompson, Ch. G. Hannah, and H. Ritchie, 2009a, Effect of stratification on tidal circulation over the Scotian Shelf and Gulf of St. Lawrence: a numerical study using a three-dimensional shelf circulation model, *Ocean Dyn.*, **59**: 809-825, doi:10.1007/s10236-009-0212-7

A three-dimensional shelf circulation model is used to examine the effect of seasonal changes in water column stratification on the tidal circulation over the Scotian Shelf and Gulf of St. Lawrence. The model is driven by tidal forcing specified at the model's lateral open boundaries in terms of tidal sea surface elevations and depth-averaged currents for five major tidal constituents (M2, N2, S2, K1, and O1). Three numerical experiments are conducted to determine the influence of baroclinic pressure gradients and changes in vertical mixing, both associated with stratification, on the seasonal variation of tidal circulation over the study region. The model is initialized with climatological hydrographic fields and integrated for 16 months in each experiment. Model results from the last 12 months are analyzed to determine the dominant semidiurnal and diurnal tidal components, M2 and K1. Model results suggest that the seasonal variation in the water-column stratification affects the M2 tidal circulation most strongly over the shelf break and over the deep waters off the Scotian Shelf (through the development of baroclinic pressure gradients) and along Northumberland Strait in the Gulf of St. Lawrence (through changes in vertical mixing and bottom stress). For the K1 constituent, the baroclinic pressure gradient and vertical mixing have opposing effects on the tidal circulation over several areas of the study region, while near the bottom, vertical mixing appears to play only a small role in the tidal circulation.

Ohashi, K., J. Sheng, K. R. Thompson, Ch. G. Hannah, and H. Ritchie, 2009b, Numerical study of three-dimensional shelf circulation on the Scotian Shelf using a shelf circulation model, *Cont. Shelf Res.*, **29**(17): 2138-2156, doi:10.1016/j.csr.2009.08.005

A numerical shelf circulation model was developed for the Scotian Shelf, using a nested-grid setup consisting of a three-dimensional baroclinic inner model embedded inside a two-dimensional barotropic outer model. The shelf circulation model is based on the Princeton Ocean Model and driven by three-hourly atmospheric forcing provided by a numerical weather forecast model and by tidal forcing specified at the inner model's open boundaries based on pre-calculated tidal harmonic constants. The outer model simulates the depth-mean circulation forced by wind and atmospheric pressure fields over the northwest Atlantic Ocean with a horizontal resolution of 1/12°. The inner model simulates the three-dimensional circulation over the Gulf of St. Lawrence, the Scotian Shelf, and the adjacent slope with a horizontal resolution of 1/16°. The performance of the shelf circulation model is assessed by comparing model results with oceanographic observations made along the Atlantic coast of Nova Scotia and in the vicinity of

Sable Island (on the Scotian Shelf) during two periods: October 2000–March 2001 and April–June 2002. Analysis of model results on Sable Island Bank indicates that tidal currents account for as much as ~80% of the total variance of near-bottom currents, and currents driven by local winds account for ~30% of the variance of the non-tidal near-bottom currents. Shelf waves generated remotely by winds and propagating into the region also play an important role in the near-bottom circulation on the bank.

Yang, B. and J. Sheng, 2008, Process study of coastal circulation over the inner Scotian Shelf using a nested-grid ocean circulation model, with a special emphasis on the storm-induced circulation during tropical storm Alberto in 2006, *Ocean Dyn*, **58**(5-6): 375-396, doi:10.1007/s10236-008-0149-2

This study examines main physical processes affecting the three-dimensional (3D) circulation and hydrographic distributions over the inner Scotian Shelf (ISS) in June and July 2006 using a nested-grid coastal ocean circulation modeling system known as the NCOPS-LB. The nested-grid system has five relocatable downscaling submodels, with the outermost submodel of a coarse horizontal resolution of (1/12)° for simulating storm surges and barotropic shelf waves over the Eastern Canadian shelf and the innermost submodel of a fine resolution of ~180 m for simulating the 3D coastal circulation and hydrography over Lunenburg Bay of Nova Scotia in the default setup. The NCOPS-LB is driven by meteorological and astronomical forcing and used to study the storm-induced circulation over the ISS during tropical storm Alberto. Model results demonstrate that the coastal circulation and hydrographic distributions over the ISS are affected significantly by tides, local wind forcing, and remotely generated coastal waves during the study period.

4.9.1.1 Invasive Species

Brickman, D. and P. C. Smith, 2007, Variability in invasion risk for ballast water exchange on the Scotian Shelf to eastern Canada, *Mar. Pollut. Bull.*, **54**(7): 863-874, doi:10.1016/j.marpolbul.2007.03.015

A semi-quantitative risk assessment model for dispersion of ballast water organisms in shelf seas is applied to the Scotian Shelf region of eastern Canada. The ballast water exchange process is simulated as the dispersion of tracer released into the surface layer of an ocean circulation model of the region. Circulation model variability is driven by wind stress from a cyclical year of forcing representing climatological storminess. Dispersion metrics related to invasion risk are developed and incorporated into a risk equation that computes the relative overall risk of invasion for ballast water exchange segments along vessel tracks crossing the shelf. Three hundred and sixty dispersion simulations are done for each segment of each of six tracks. Because the flow fields represent climatological variability in shelf circulation, the application of the risk assessment model captures the expected variability in invasion risk. Model results indicate that more than an order of magnitude variation in risk can exist along a given vessel track, and that tracks with offshelf segments provide a lower risk option compared to onshelf tracks. The model provides quantitative guidance to

regulators regarding what is an acceptable trip diversion and can aid in numerous other management decisions.

4.10 Gulf of St. Lawrence

Doniol-Valcroze, T., D. Berteaux, P. Larouche, and R. Sears, 2007, Influence of thermal fronts on habitat selection by four rorqual whale species in the Gulf of St. Lawrence, *Mar. Eco. Prog. Ser.*,**335**: 207-216, doi:10.3354/meps335207

Understanding the factors influencing habitat selection is critical to improving management and conservation plans for large whales. Many studies have linked the distribution of cetaceans to basic environmental features such as underwater topography and sea surface temperature (SST), but the mechanisms underlying these relationships are poorly understood. Dynamic mesoscale processes like thermal fronts are prime candidates to link physiographic factors to whale distribution because they increase biological productivity and aggregate prey. However, previous studies of large whales have found little evidence of such associations, possibly because they were not at the appropriate spatio-temporal scales. We quantified the relationship between SST fronts and the distribution of blue *Balaenoptera musculus*, finback *B. physalus*, humpback *Megaptera novaeangliae* and minke *B. acutorostrata* whales in the northern Gulf of St. Lawrence. We compared the distribution of 1094 whale sightings collected from boat surveys conducted in 1996 to 2000 to the locations of frontal areas determined from 61 satellite maps. The distributions of whales and thermal fronts were highly correlated (random resampling and Mantel tests of matrix similarity). Spatial distributions differed among species, probably reflecting differences in feeding strategies. Identification of surface fronts from satellite imagery thus effectively complemented field observations of whales. These findings significantly increase our understanding of habitat quality in rorqual whales, and encourage a greater use of dynamic environmental variables in future studies of whale habitat use.

Du, Y., P. Larouche, and P. W. Vachon, 2007, Multi-scale feature tracking in sequential satellite images with wavelet analysis to measure sea surface currents in the Gulf of St. Lawrence, *Can. J. Rem. Sens.*, **33**:534-540, doi:10.5589/m07-060

Measuring sea surface currents is a technological challenge in oceanography. Feature tracking in time series of remote sensing imagery has been proposed as a way to address this problem. The most commonly used approach is the maximum cross-correlation (MCC) method, originally developed to track cloud motion. We propose a new technique that makes use of Daubechies wavelet analysis combined with the MCC method. In our approach, satellite images are decomposed into various spatial scales using the wavelet transform, and the location with the MCC coefficient among all the scales is selected as the most likely new position of the tracked feature. Results from the analysis of five pairs of sequential National Oceanic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) images of the Gulf of St. Lawrence area show that wavelet analysis improves the estimated sea surface

current field by increasing the number of current vectors about 20% under the same confidence level (0.9) as compared with that using the MCC method alone.

Harvey, M., P. S. Galbraith, and A. Descroix, 2009, Vertical distribution and diel migration of macrozooplankton in the St. Lawrence marine system (Canada) in relation with the cold intermediate layer thermal properties, *Prog. Oceanogr.*, **80**(1-2): 1-21, doi:10.1016/j.pocean.2008.09.001

Vertical distribution of various species and stages of macrozooplankton (euphausiacea, chaetognatha, cnidaria, mysidacea, amphipoda) were determined for different times of the day and related to the physical environment. Stratified sampling with the BIONESS was carried out during seven cruises in spring and fall 1998, 2000, and 2001, and fall 1999, in two different habitats in the St. Lawrence marine system: the lower St. Lawrence Estuary and the NW Gulf of St. Lawrence. Our results indicate that the various macrozooplankton species were distributed throughout the whole water column including the surface layer, the cold intermediate layer (CIL), and the deep layer at different times of day and night in both areas during all periods. Moreover, three types of migrational patterns were observed within this zooplanktonic community: (1) nocturnal ascent by the whole population, (2) segregation into two groups; one which performed nocturnal accent and another which remained in the deep, and (3) no detectable migration. We also observed that the diel vertical migration (DVM) amplitude in most of the macrozooplankton species varied as a function of physical factors, in particular the spatio-temporal variations of the CIL thermal properties, including the upper and the lower limits of the CIL and the depth of the CIL core temperature. Finally, the different DVM patterns coupled with estuarine circulation patterns and bottom topography could place animals in different flow regimes by night and by day and contribute to their retention (aggregation) and/or dispersion in different areas, time of the day, and seasons.

Hundecha, Y., A. St-Hilaire, T. B. M. J. Ouarda, S. El Adlouni, and P. Gagnon, 2008, A nonstationary extreme value analysis for the assessment of changes in extreme annual wind speed over the Gulf of St. Lawrence, Canada, *J. Appl. Meteor. Clim.*, **47**(11): 2745-2759, doi:10.1175/2008JAMC1665.1

Changes in the extreme annual wind speed in and around the Gulf of St. Lawrence (Canada) were investigated through a nonstationary extreme value analysis of the annual maximum 10-m wind speed obtained from the North American Regional Reanalysis (NARR) dataset as well as observed data from selected stations of Environment Canada. A generalized extreme value distribution with time-dependent location and scale parameters was used to estimate quantiles of interest as functions of time at locations where significant trend was detected. A Bayesian method, the generalized maximum likelihood approach, is implemented to estimate the parameters. The analysis yielded shape parameters very close to 0, suggesting that the distribution can be modeled using the Gumbel distribution. A similar analysis using a nonstationary Gumbel model yielded similar quantiles with narrower credibility intervals. Overall, little change was detected over the period 1979–2004. Only 7% of the investigated grids

exhibited trends at the 5% significant level, and the analysis performed on the reanalysis data at locations of significant trend indicated a rise in the median extreme annual wind speed by up to 2 m s^{-1} per decade in the southern coastal areas with a corresponding increase in the 90% and 99% quantiles of the extreme annual wind speeds by up to 5 m s^{-1} per decade. Also in the northern part of the gulf and some offshore areas in the south, the 50%, 90%, and 99% quantile values of the extreme annual wind speeds are noted to drop by up to 1.5, 3, and 5 m s^{-1}, respectively. While the directions of the changes in the annual extremes at the selected stations are similar to those of the reanalysis data at nearby grid cells, the magnitudes and significance levels of the changes are generally inconsistent. Change at the same significance level over the same period of the NARR dataset was noted only at 2 stations out of 13.

Mei, Z.-P., F. J. Saucier, V. Le Fouest, B. Zakardjian, S. Sennville, H. Xie, M. Starr, 2010, Modeling the timing of spring phytoplankton bloom and biological production of the Gulf of St. Lawrence (Canada): Effects of colored dissolved organic matter and temperature, *Cont. Shelf Res.*, **30**(19): 2027-2042, doi:10.1016/j.csr.2010.10.003

The effects of colored dissolved organic matter (CDOM) from freshwater runoff and seasonal cycle of temperature on the dynamic of phytoplankton and zooplankton biomass and production in the Gulf of St. Lawrence (GSL) are studied using a 3-D coupled physical-plankton ecosystem model. Three simulations are conducted: (1) the reference simulation based on Le Fouest et al. (2005), in which light attenuation by CDOM is not considered and maximum growth rate (μ_{max}) of phytoplankton and zooplankton are not temperature-dependent (REF simulation); (2) light attenuation by CDOM is added to REF simulation (CDOM simulation); and (3) in addition to CDOM, the μ_{max} of phytoplankton and zooplankton are regulated by temperature (CDOM+TEMP simulation). CDOM simulation shows that CDOM substantially reduces phytoplankton biomass and production in the Lower St. Lawrence Estuary (LSLE), but slightly reduces overall primary production in the GSL. In the LSLE, the spring phytoplankton bloom is delayed from mid-March to mid-April, resulted from light attenuation by CDOM. The CDOM+TEMP simulation shows that the spring phytoplankton bloom in the LSLE is further delayed to July, which is more consistent with observations. Annual primary production is reduced by 33% in CDOM+TEMP simulation from REF and CDOM simulations. Zooplankton production is the same in all three simulations, and export of organic matter to depth is reduced in CDOM+TEMP simulation, suggesting that temperature controlled growth of phytoplankton and zooplankton enhances the coupling between primary production and zooplankton production under the seasonal temperature cycle of the GSL.

Ouellet, P., L. Savard, and P. Larouche, 2007, Spring oceanographic conditions and northern shrimp *Pandalus borealis* recruitment success in the north-western Gulf of St. Lawrence, *Mar. Eco. Prog. Ser.*, **339**: 229-241, doi:10.3354/meps339229

Time series of sea-surface temperature (SST), thermally mixed layer depth, and the SST warming rate in spring at the time of larval emergence were correlated

with indices of northern shrimp *Pandalus borealis* recruitment (cohort abundance and larval survival index) between 1994 and 2003 in the northwest Gulf of St. Lawrence, Canada. The recruitment index and larval survival index were negatively correlated to daily mean SST at the time of larval emergence. The recruitment index and larval survival index were positively correlated with the SST warming rate and with the mixed layer depth at the time of larval emergence. Overall, the analysis reveals that larval emergence during a period of weak density stratification and low SST in the spring, but followed by relatively high warming rates of the upper layer of the water column, is favourable for larval survival. We suggest that the observed relationships support the hypothesis that oceanographic conditions in the upper layer of the water column, which initiate and sustain high levels of biological production at the time of larval emergence and early development, are favourable for northern shrimp recruitment success. Thus, interannual variability in northern shrimp recruitment in the northwest Gulf of St. Lawrence may be explained by Cushing's match/mismatch hypothesis.

Saucier, F. J., F. Roy, S. Senneville, G. Smith, D. Lefaivre, D. Zakardjian, and J. F. Dumais, 2009, Modelling of the circulation in the Estuary and Gulf of St. Lawrence in response to variations in fresh water runoff and winds, *Rev. Sci. Eau* (*J. Water Sci.*), **22**(2): 159-176

We examine recent results issued from observations and numerical simulations of the general circulation and climate of the St. Lawrence Estuary and Gulf. We focus this study on the intensity of the estuarine circulation. The approach is presented with an emphasis on the integration, using numerical simulations, of key processes such as turbulent mixing associated with tides at the head of the Laurentian Channel and air-sea exchanges over the Lower Estuary and Gulf. The numerical simulations allow us to follow the evolution of circulation and climate over periods of a few hours to several years. We first examine the tidal variability of the circulation at the head of the Laurentian Channel and the Upper Estuary, illustrating the importance of processes that largely govern the estuarine circulation. The most important processes are the dynamical instabilities associated with tidal straining and internal hydraulic jumps near the sills. On the other hand, the wind stress dominates the variability of freshwater export from the Lower Estuary and Gulf to the Atlantic Ocean. Using sensitivity experiments, the effects of freshwater runoff and wind intensity on the estuarine circulation are isolated. The results show that the St. Lawrence model responds to the external forcings like a classical two-layer estuary during periods of higher stratification (spring and summer), when the freshwater drives more efficient withdrawal of the cold intermediate layer of the Gulf to a depth of approximately 150 m. On the other hand, in periods of lower stratification (fall and winter), the wind stress drives the deep water circulation (more than 150 m depth) and an excess freshwater input partly inhibits this ventilation, as in a marginal northern sea. These results suggest that an eventual reduction of freshwater runoff from the St. Lawrence River, associated with climate change or development, could reduce the estuarine circulation during spring and summer. During winter, such a reduction could favour the withdrawal of deep waters from the Laurentian Channel.

Shaw, J., G. Duffy, R. B. Taylor, J. Chassé, and D. Frobel, 2008, Role of a submarine bank in the evolution of the northeast coast of Prince Edward Island, Canada, J. *Coastal Res.*, **24**(5): 1249-1259, doi:10.2112/07-08607.1

In order to understand regional variations in coastal behavior on Prince Edward Island, Canada, we investigated the role of Milne Bank, a submarine bank at East Point, the eastern tip of the island. The objective was to determine how the bank might facilitate transfer sediment from the eroding north coast to the adjacent sediment-rich south coast. The study utilized grain-size and seismic data collected on Milne Bank in 1989 and multibeam sonar surveys in 1997 and 1999. The disturbing effect of East Point on the hydrodynamic regime controls sediment transport. The northern boundary of the bank is a steep sand wave located where southward tidal and wave-driven currents rounding East Point suddenly decelerate. Sand from the north coast enters Milne Bank and is carried south in a field of migrating sand waves that are shed from the northern bounding sand wave toward the prograding end of the bank. Milne Bank is a major sediment sink, rather than a link between the eroding north coast and the sediment-rich southfacing coast. Longshore transport in nearshore bars is more likely to be responsible for continued sediment accumulation on the south coast. Embayments on the south coast have filled up in a cascading fashion, each one facilitating sediment bypassing when it has reached full capacity.

Thibodeau, B., A. de Vernal, C. Hillaire-Marcel, and A. Mucci, 2010, Twentieth century warming in deep waters of the Gulf of St. Lawrence: A unique feature of the last millennium, *Geophys. Res. Lett.*, **37**, L17604, doi:10.1029/2010GL044771

The impact of human activities on Earth's climate is still subject to debate and the pattern of a sharp recent global temperature increase contrasting with much lesser variable temperatures during preceding centuries has often been challenged, partly due to the lack of unquestionable evidence. In this paper, oxygen isotope compositions of benthic foraminifer shells recovered from sediments of the Lower St. Lawrence Estuary and the Gulf are used to reconstruct temperature changes in a water mass originating from ~400 m deep North Atlantic waters. The data demonstrate that the 1.7 ± 0.3°C warming measured during the last century corresponds to a $\delta^{18}O$ shift of 0.4 ± 0.05‰, encompassing the temperature effect and related change in the isotopic composition of the corresponding water mass. In contrast, $\delta^{18}O$ values remained nearly constant over the last millennium, except for a small positive shift which we attribute to the Little Ice Age. We conclude that the 20th century warming of the incoming intermediate North Atlantic water has had no equivalent during the last thousand years.

4.11 The Mediterranean Sea

Demirov, E. K. and N. Pinardi, 2007, On the relationship between the water mass pathways and eddy variability in the Western Mediterranean Sea, *J. Geophys. Res.*, **112**, C02024, doi:10.1029/2005JC003174

The role of eddies on the formation and spreading of water masses in the Western Mediterranean Sea is studied with an ocean general circulation model. The model is forced with interannually variable surface forcing for the years from 1979 to 1999. It is found that the model reproduces the major features of the observed mesoscale variability in the Gulf of Lions and the large eddies evolution in the Algerian Basin. The seasonal evolution of circulation in the Gulf of Lions and processes of spreading of newly formed intermediate deep waters in the postconvection period is studied for years 1987 and 1992. The model results are compared with data from observations. It is shown that the instability of the transition zone between old and newly formed deep waters, which takes place after the violent mixing stages of the deep convection, leads to collapse of the mixed patch and formation of mesoscale eddies. Some of these eddies propagate out of the Gulf of Lions transporting deep waters into the Algerian Basin. The rest of the mesoscale eddies filled with newly formed deep waters remain in the Gulf of Lions and tend to merge and enlarge. After the cyclonic eddies reach the Algerian Basin they interact with the intense mesoscale field existing there. The energy analysis shows that the winter and spring are seasons of intensified baroclinic instability of the mean flow in the two regions of interest, the Gulf of Lions and Algerian Basin. The kinetic energy is released by baroclinic instability in spring and summer. The spring spectra in the two regions have maximums at horizontal scales of about 80–100 km which is the typical scale of the eddies in the model. These eddies propagate a cyclonic circuit. The resulting eddy-induced mass transport in deep and intermediate layers is directed out of the Gulf of Lions and toward the Gibraltar Strait. Equivalently, we can argue the intermediate and deep waters conveyor belt of the Western Mediterranean Sea is eddy-driven.

5 The Southern Ocean

Saenko, O. A., 2008, Influence of the enhanced mixing within the Southern Ocean fronts on the overturning circulation, *Geophys. Res. Lett.*, **35**, L09602, doi:10.1029/2008GL033565

Observations indicate that turbulent mixing is enhanced in the major fronts of the Antarctic Circumpolar Current (ACC), penetrating through much of the water column. Here we employ a simple representation of this process in a global climate model to evaluate its potential impact on the ocean's overturning circulation. Two effects are obtained. First, the frontally-intensified mixing in the Southern Ocean increases the transformation of NADW to UCDW. Second, by intensifying the dense water upwelling in the south, the vertical mixing in the ACC fronts returns a fraction of the northward flowing AABW/LCDW as UCDW, consistent with recent observational results; the corresponding abyssal overturning weakens. The results are interpreted using a single-basin model.

5.1 Antarctica Sea Ice

Geddes, J. A. and G. W. K. Moore, 2007, A climatology of sea ice embayments in the Cosmonaut Sea, Antarctica, *Geophys. Res. Lett.*, **34**, L02505, doi:10.1029/2006GL027910

The Cosmonaut Sea off the coast of Antarctica is characterized by highly variable sea ice conditions. As the sea ice expands during the austral fall and winter, embayments, open bodies of water surrounded on three sides by sea ice, as well as polynyas often form. Using sea ice concentration data provided by satellite-based passive microwave instruments from 1979 to 2004, we characterize these embayment events by their size and temporal evolution. The data suggests a striking periodicity in the occurrence of these embayments, with the exception of a "quiet" period between 1984 and 1987. The large embayment events seem to appear approximately every three years in the same location and persist for anywhere between mid-June to mid-August. These results indicate there is predictability in the occurrence of embayment events, adding important insight into the characterization of sea ice variability in this region.

Nicolaus, M., C. Haas, and S. Willmes, 2009, Evolution of first-year and second-year snow properties on sea ice in the Weddell Sea during spring-summer transition, *J. Geophys. Res.*, **114**, D17109, doi:10.1029/2008JD011227

Observations of snow properties, superimposed ice, and atmospheric heat fluxes have been performed on first-year and second-year sea ice in the western Weddell Sea, Antarctica. Snow in this region is particular as it does usually survive summer ablation. Measurements were performed during Ice Station Polarstern (ISPOL), a 5-week drift station of the German icebreaker RV *Polarstern*. Net heat flux to the snowpack was 8 W m^{-2}, causing only 0.1 to 0.2 m of thinning of both snow cover types, thinner first-year and thicker second-year snow. Snow thinning was dominated by compaction and evaporation, whereas melt was of minor importance and occurred only internally at or close to the surface. Characteristic differences between snow on first-year and second-year ice were found in snow thickness, temperature, and stratigraphy. Snow on second-year ice was thicker, colder, denser, and more layered than on first-year ice. Metamorphism and ablation, and thus mass balance, were similar between both regimes, because they depend more on surface heat fluxes and less on undergr ound properties. Ice freeboard was mostly negative, but floodi ng occurred mainly on first-year ice. Snow and ice in terface temperature did not reach the melting point during the observation period. Nevertheless, formation of discontinuous superimposed ice was observed. Color tracer experiments suggest considerable meltwater percolation within the snow, despite below-melting temperatures of lower layers. Strong meridional gradients of snow and sea-ice properties were found in this region. They suggest similar gradients in atmospheric and oceanographic conditions and implicate their importance for melt processes and the location of the summer ice edge.

5.2 Water Masses

Richardson, L. E., T. K. Kyser, N. P. James, and Y. Bone, 2009, Analysis of hydrographic and stable isotope data to determine water masses, circulation, and mixing in the eastern Great Australian Bight, *J. Geophys. Res.*, **114**, C10016, doi:10.1029/2009JC005407

Hydrographic and stable isotope data from waters in the eastern Great Australian Bight (GAB) sampled during March–April 1998 indicate that both mixing and evaporative processes are important on the shelf. Five water masses are defined on the basis of their temperature, salinity, δ^{2}H and δ^{18}O values. Two of these are end-members, the Flinders Current (FC) and the Great Australian Bight Plume (GABP), whereas the other three are a result of mixing between these two end-members. Water mass distribution reflects an anticyclonic gyre in the eastern GAB. Cool and fresh water present at depth along the Eyre Peninsula is sourced from upwelling of Flinders Current water directly from the shelf break. This water is progressively heated, evaporated, and mixed with warmer and more saline shelf waters as it flows around the gyre. High temperatures, salinities, and δ^{2}H values in surface waters in the central GAB suggest that the Great Australian Bight Plume has a greater spatial extent than previously recorded, also occurring along the shelf edge between 130°E and 133°E. A high temperature, high salinity, low δ^{2}H water mass that is isotopically similar to the Flinders Current occurs in the west of the study area, indicating intrusion of Flinders Current water into the central GAB. Differences in isotopic compositions of off-shelf water suggest that the Great Australian Bight Plume is flowing off the shelf and mixing with Flinders Current water at ˜132°E; however, this outflow does not generate an eastward flowing current during the period when samples were collected.

5.3 Atmosphere-Ocean

5.3.1 Effects of Changing Climate/CO_2

Fyfe, J. C., O., A. Saenko, K. Zickfeld, M. Eby and A. J. Weaver, 2007, The role of poleward intensifying winds on Southern Ocean warming, *J. Clim.*, **20:** 5391-5400, doi:10.1175/2007JCLI1764.1

Recent analyses of the latest series of climate model simulations suggest that increasing CO_2 emissions in the atmosphere are partly responsible for (i) the observed poleward shifting and strengthening of the Southern Hemisphere subpolar westerlies (in association with shifting of the southern annular mode toward a higher index state), and (ii) the observed warming of the subsurface Southern Ocean. Here the role that poleward-intensifying westerlies play in subsurface Southern Ocean warming is explored. To this end a climate model of intermediate complexity was driven separately, and in combination with, time-varying CO_2 emissions and time-varying surface winds (derived from the fully coupled climate model simulations mentioned above). Experiments suggest that the combination of the direct radiative effect of CO_2 emissions and poleward-intensified winds sets the overall magnitude of Southern Ocean warming, and that the poleward intensified winds are key in terms of determining its latitudinal

structure. In particular, changes in wind stress curl associated with poleward-intensified winds significantly enhance pure CO_2-induced subsurface warming around 45°S (through increased downwelling of warm surface water), reduces it at higher latitudes (through increased upwelling of cold deep water), and reduces it at lower latitudes (through decreased downwelling of warm surface water). Experiments also support recent high-resolution ocean model experiments suggesting that enhanced mesoscale eddy activity associated with poleward-intensified winds influences subsurface (and surface) warming. In particular, it is found that increased poleward heat transport associated with increased mesoscale eddy activity enhances the warming south of the Antarctic Circumpolar Current. Finally, a mechanism involving offshore Ekman sea ice transport (modulated by enhanced mesoscale activity) that acts to significantly limit the human-induced high-latitude Southern Hemisphere surface temperature response is reported on.

Sigmond, M. and J. C. Fyfe, 2010, Has the ozone hole contributed to increased Antarctic sea ice extent?, *Geophys. Res. Lett.*, **37**, L18502, doi:10.1029/2010GL044301

Since the 1970s sea ice extent has decreased dramatically in the Northern Hemisphere and increased slightly in the Southern Hemisphere, a difference that is potentially explained by ozone depletion in the Southern Hemisphere stratosphere. In this study we consider the impact of stratospheric ozone depletion on Antarctic sea ice extent using a climate model forced with observed stratospheric ozone depletion from 1979 to 2005. Contrary to expectations, our model simulates a year-round decrease in Antarctic sea ice due to stratospheric ozone depletion. The largest percentage sea ice decrease in our model occurs in the austral summer near the coast of Antarctica, due to a mechanism involving offshore Ekman sea ice transport. The largest absolute decrease is simulated in the austral winter away from the coast of Antarctica, in response to an ocean warming that is consistent with a poleward shift of the large-scale pattern of sea surface temperature. Our model results strongly suggest that processes not linked to stratospheric ozone depletion must be invoked to explain the observed increase in Antarctic sea ice extent.

Spence, P., O. A. Saenko, M. Eby, and A. J. Weaver, 2009, The Southern Ocean overturning: Parameterized versus permitted eddies, *J. Phys. Oceanogr.*, **39**: 1634-1651, doi:10.1175/2009JPO4120.1

Four versions of the same global climate model, with horizontal resolution ranging from 1.8° × 3.6° to 0.2° × 0.4°, are employed to evaluate the resolution dependence of the Southern Ocean meridional overturning circulation. At coarse resolutions North Atlantic Deep Water tends to upwell diabatically at low latitudes, so that the Southern Ocean is weakly coupled with the rest of the ocean. As resolution increases and eddy effects become less parameterized the interior circulation becomes more adiabatic and deep water increasingly upwells by flowing along isopycnals in the Southern Ocean, despite each model having the same vertical diffusivity profile. Separating the overturning circulation into mean and eddy-induced components demonstrates that both the permitted and the parameterized eddies induce overturning cells in the Southern Ocean with mass

fluxes across mean isopycnals. It is found that for some density classes the transformation rate derived from surface buoyancy fluxes can provide a proxy for the net meridional transport in the upper Southern Ocean. Changes in the Southern Ocean overturning in response to poleward-intensifying Southern Hemisphere winds concomitant with increasing atmospheric CO_2 through the twenty-first century are also investigated. Results suggest that the circulation associated with the formation of Antarctic Intermediate Water is likely to strengthen, or stay essentially unchanged, rather than to slow down.

Spence, J. P., J. C. Fyfe, A. Montenegro, and A. J. Weaver, 2010, Southern Ocean response to strengthening winds in an eddy-permitting global climate model, *J. Clim.*, **23**, 5332-5343, doi:10.1175/2010JCLI3098.1

A global climate model with horizontal resolutions in the ocean ranging from relatively coarse to eddy permitting is used to investigate the resolution dependence of the Southern Ocean response to poleward intensifying winds through the past and present centuries. The higher-resolution simulations show poleward migration of distinct ocean fronts associated with a more highly localized near-surface temperature response than in the lower-resolution simulations. The higher-resolution simulations also show increasing southward eddy heat transport, less high-latitude cooling, and greater sea ice loss than the lower-resolution simulations. For all resolutions, from relatively coarse to eddy permitting, there is poleward migration of the Antarctic Circumpolar Current in the Atlantic and the western half of the Indian basin. Finally, zonal transports associated with the Antarctic Circumpolar Current are shown to be sensitive to resolution, and this is discussed in the context of recent observed change.

5.3.2 Carbon Cycle

Tortell, P. D., C. D. Payne, Y. Li, S. Trimborn, B. Rost, W. O. Smith, C. Riesselman, R. B. Dunbar, P. Sedwick, and G. R. DiTullio, 2008, CO_2 sensitivity of Southern Ocean phytoplankton, *Geophys. Res. Lett.*, **35**, L04605, doi:10.1029/2007GL032583

The Southern Ocean exerts a strong impact on marine biogeochemical cycles and global air-sea CO_2 fluxes. Over the coming century, large increases in surface ocean CO_2 levels, combined with increased upper water column temperatures and stratification, are expected to diminish Southern Ocean CO_2 uptake. These effects could be significantly modulated by concomitant CO_2-dependent changes in the region's biological carbon pump. Here we show that CO_2 concentrations affect the physiology, growth and species composition of phytoplankton assemblages in the Ross Sea, Antarctica. Field results from in situ sampling and ship-board incubation experiments demonstrate that inorganic carbon uptake, steady-state productivity and diatom species composition are sensitive to CO_2 concentrations ranging from 100 to 800 ppm. Elevated CO_2 led to a measurable increase in phytoplankton productivity, promoting the growth of larger chain-forming diatoms. Our results suggest that CO_2 concentrations can influence biological carbon cycling in the Southern Ocean, thereby creating potential climate feedbacks.

Zickfeld, K., J. C. Fyfe, M. Eby and A. J. Weaver, 2008, Comment on "Saturation of the Southern Ocean CO_2 sink due to recent climate change", *Science*, **319**(5863), 570b, doi:10.1126/science.1146886

We disagree with the conclusion of Le Quéré *et al*. (Reports, 22 June 2007, p. 1735) that poleward intensifying winds could continue to weaken the Southern Ocean sink in the future. We argue that altered winds, along with rising atmospheric carbon dioxide, will likely increase the efficiency of this sink in the 21st century.

6 Turbulence and Mixing

Mikkelsen, O. A., K. J. Curran, P. S. Hill, and T. G. Milligan, 2007, Entropy analysis of *in situ* particle size, *Estuar. Coast. Shelf Sci.*, **72**: 615-625, doi:10.1016/j.ecss.2006.11.027

Entropy analysis has been used to classify in situ particle (floc) size spectra of suspended particles into groups based on similar distribution characteristics. Results revealed that the in situ spectra sorted into groups that reflected different forcing conditions (e.g. variations in turbulence). The different forcing conditions were not necessarily reflected in other commonly used distribution measures such as median floc diameter. This suggests that entropy analysis may be an effective approach for investigating the effect of changes in forcing conditions on floc size. It is hypothesized that it may be possible to derive the average shape of floc size spectra from measurement of the forcing conditions alone and subsequently derive parameters such as floc fraction, floc density, floc settling velocity and the optical properties of the water column from the average spectra.

Mueller, R. D., W. D. Smyth, B. Ruddick, 2007, Shear and Convective Turbulence in a Model of Thermohaline Intrusions, *J. Phys. Oceanogr.*, **37**(10): 2534–2549, doi:10.1175/JPO3137.1

Thermohaline interleaving is an important mechanism for laterally fluxing salt, heat, and nutrients between water masses. Interleaving is driven by a release of potential energy resulting from the differing diffusivities of heat and salt in seawater. The flows are composed of stacked intrusions that flux more and less buoyant water in opposite directions. In this paper, the role of shear instability caused by this juxtaposed motion is investigated. The model described in Walsh and Ruddick is modified to include both the effects of shear-induced turbulence and an improved convective mixing parameterization. Shear and convective mixing play a similar and significant role in interleaving dynamics. In the absence of either instability, cross-front fluxes are increased by approximately 30%. While in situ observations of horizontal diffusivity resulting from interleaving are not yet precise enough to calibrate the parameterizations independently, parameter values based on independent laboratory and numerical studies lead to diffusivity predictions that are within the error of the observations.

Smyth, W. D., and B. Ruddick, 2010, Effects of Ambient Turbulence on Interleaving at a Baroclinic Front, *J. Phys. Oceanogr.*, **40**(4): 685–712, doi:10.1175/2009JPO4297.1

In this paper the authors investigate the action of ambient turbulence on thermohaline interleaving using both theory and numerical calculations in combination with observations from Meddy Sharon and the Faroe Front. The highly simplified models of ambient turbulence used previously are improved upon by allowing turbulent diffusivities of momentum, heat, and salt to depend on background gradients and to evolve as the instability grows.

Previous studies have shown that ambient turbulence, at typical ocean levels, can quench the thermohaline interleaving in stability on baroclinic fronts. These findings conflict with the observation that interleaving is common in baroclinic frontal zones despite ambient turbulence. Another challenge to the existing theory comes from numerical experiments showing that the Schmidt number for sheared salt fingers is much smaller than previously assumed. Use of the revised value in an interleaving calculation results in interleaving layers that are both weaker and thinner than those observed. This study aims to resolve those paradoxes.

The authors show that, when turbulence has a Prandtl number greater than unity, turbulent momentum fluxes can compensate for the reduced Schmidt number of salt fingering. Thus, ambient turbulence determines the vertical scale of interleaving. In typical oceanic interleaving structures, the observed property gradients are insufficient to predict interleaving growth at an observable level, even when improved turbulence models are used. The deficiency is small, though: gradients sharper by a few tens of percent are sufficient to support instability. The authors suggest that this is due to the efficiency of interleaving in erasing those property gradients.

A new class of mechanisms for interleaving, driven by flow-dependent fluctuations in turbulent diffusivities, is identified. The underlying mechanism is similar to the well-known Phillips layering instability; however, because of Coriolis effects, it has a well-defined vertical scale and also a tilt angle opposite to that of finger-driven interleaving.

6.1 Coastal Mixing Induced by Internal Tides/Waves

Alford, M., R. Lien, H. Simmons, J. Klymak, S. Ramp, Y. Yang, D. Tang, and M. H.-Chang, 2010: Speed and evolution of nonlinear internal waves transiting the South China Sea. *J. Phys. Oceanogr.*, 40(6): 1338-1355, doi:10.1175/2010JPO4388.1

In the South China Sea (SCS), 14 nonlinear internal waves are detected as they transit a synchronous array of 10 moorings spanning the waves' generation site at Luzon Strait, through the deep basin, and onto the upper continental slope 560 km to the west. Their arrival time, speed, width, energy, amplitude, and number of trailing waves are monitored. Waves occur twice daily in a particular pattern where larger, narrower "A" waves alternate with wider, smaller "B" waves. Waves begin as broad internal tides close to Luzon Strait's two ridges, steepening to O(3–10 km) wide in the deep basin and O(200–300 m) on the upper slope. Nearly all waves eventually develop wave trains, with larger–steeper waves developing them earlier and in greater numbers. The B waves in the deep basin

begin at a mean speed of ≈5% greater than the linear mode-1 phase speed for semidiurnal internal waves (computed using climatological and in situ stratification). The A waves travel ≈5%–10% faster than B waves until they reach the continental slope, presumably because of their greater amplitude. On the upper continental slope, all waves speed up relative to linear values, but B waves now travel 8%–12% faster than A waves, in spite of being smaller. Solutions of the Taylor–Goldstein equation with observed currents demonstrate that the B waves' faster speed is a result of modulation of the background currents by an energetic diurnal internal tide on the upper slope. Attempts to ascertain the phase of the barotropic tide at which the waves were generated yielded inconsistent results, possibly partly because of contamination at the easternmost mooring by eastward signals generated at Luzon Strait's western ridge. These results present a coherent picture of the transbasin evolution of the waves but underscore the need to better understand their generation, the nature of their nonlinearity, and propagation through a time-variable background flow, which includes the internal tides.

Garrett, C. and E. Kunze, 2007, Internal tide generation in the deep ocean, *Ann. Rev. Fluid Mech.*, **39**, 57-87, doi:10.1146/annurev.fluid.39.050905.110227

Internal tides are internal gravity waves generated in stratified waters by the interaction of barotropic tidal currents with variable bottom topography. They play a role in dissipating tidal energy and lead to mixing in the deep ocean. Key dimensionless parameters governing their generation include the tidal excursion compared with the scale of the topography, the bottom slope compared with the angle at which rays of internal waves of tidal frequency propagate, and the height of the topography compared with the depth of the ocean. Recent theoretical developments for parts of this parameter space particularly relevant to the deep ocean show that most of the energy flux is associated with low modes that propagate away from the generation region. For isolated features this energy flux is not strongly dependent on the bottom slope. Intense beams of internal tidal energy are expected near "critical slopes," bottom slopes equal to the ray slope, and lead to local mixing.

Garrett, C. and T. Gerkema, 2007, A note On the body-force term in internal-tide generation, *J. Phys. Oceanogr.*, **37**, 2172-2175, doi:10.1175/JPO3165.1

The generation of internal tides can be ascribed to the action of a buoyancy force caused by the flow of the barotropic tide over topographic features. It is commonly assumed that the barotropic flow can be taken as hydrostatic, but it is shown here that this leads to a linearized governing equation for the baroclinic tide that is only valid if the baroclinic tide is also hydrostatic. A governing equation for the baroclinic tide, valid for any situation, is derived here and is shown to be exactly equivalent to a simple transformation of the governing equation for the combined barotropic and baroclinic tides.

Klymak, J. M., R. Pinkel, and L. Rainville, 2008, Direct breaking of the internal tide near topography: Kaena Ridge, Hawaii, *J. Phys. Oceanogr.*, **38**: 380-399, doi:10.1175/2007JPO3728.1

Barotropic to baroclinic conversion and attendant phenomena were recently examined at the Kaena Ridge as an aspect of the Hawaii Ocean Mixing Experiment. Two distinct mixing processes appear to be at work in the waters above the 1100-m-deep ridge crest. At middepths, above 400 m, mixing events resemble their open-ocean counterparts. There is no apparent modulation of mixing rates with the fortnightly cycle, and they are well modeled by standard open-ocean parameterizations. Nearer to the topography, there is quasi-deterministic breaking associated with each baroclinic crest passage. Large-amplitude, small-scale internal waves are triggered by tidal forcing, consistent with lee-wave formation at the ridge break. These waves have vertical wavelengths on the order of 400 m. During spring tides, the waves are nonlinear and exhibit convective instabilities on their leading edge. Dissipation rates exceed those predicted by the open-ocean parameterizations by up to a factor of 100, with the disparity increasing as the seafloor is approached. These observations are based on a set of repeated CTD and microconductivity profiles obtained from the research platform (R/P) *Floating Instrument Platform* (*FLIP*), which was trimoored over the southern edge of the ridge crest. Ocean velocity and shear were resolved to a 4-m vertical scale by a suspended Doppler sonar. Dissipation was estimated both by measuring overturn displacements and from microconductivity wavenumber spectra. The methods agreed in water deeper than 200 m, where sensor resolution limitations do not limit the turbulence estimates. At intense mixing sites new phenomena await discovery, and existing parameterizations cannot be expected to apply.

Klymak, J. M. and S. M. Legg, 2010, A simple mixing scheme for models that resolve breaking internal waves, *Ocean Modell.*, **33**(3-4): 224 - 234, doi:10.1016/j.ocemod.2010.02.005

Breaking internal waves in the vicinity of topography can reach heights of over 100 m and are thought to enhance basin-wide energy dissipation and mixing in the ocean. The scales at which these waves are modelled often include the breaking of large waves (10s of meters), but not the turbulence dissipation scales (centimeters). Previous approaches to parameterize the turbulence have been to use a universally large viscosity, or to use mixing schemes that rely on Richardson-number criteria.

A simple alternative is presented that enhances mixing and viscosity in the presence of breaking waves by assuming that dissipation is governed by the equivalence of the density overturning scales to the Ozmidov scale (, where L_T is the size of the density overturns, and N the stratification). Eddy diffusivities and viscosities are related to the dissipation by the Osborn relation ($K_z=\Gamma\varepsilon N^{-2}$) to yield a simple parameterization, where $\Gamma\approx0.2$ is the flux coefficient. This method is compared to previous schemes for flow over topography to show that, when eddy diffusivity and viscosity are assumed to be proportional, it dissipates the correct

amount of energy, and that the dissipation reported by the mixing scheme is consistent with energy losses in the model. A significant advantage of this scheme is that it has no tunable parameters, apart from the turbulent Prandtl number and flux coefficient. A disadvantage is that the overturning scales of the turbulence must be relatively well-resolved.

Klymak, J. M., S. Legg, and R. Pinkel, 2010, A simple parameterization of turbulent tidal mixing near supercritical topography, *J. Phys. Oceanogr.*, **40**(9): 2059-2074, doi:10.1175/2010JPO4396.1

A simple parameterization for tidal dissipation near supercritical topography, designed to be applied at deep midocean ridges, is presented. In this parameterization, radiation of internal tides is quantified using a linear knife-edge model. Vertical internal wave modes that have nonrotating phase speeds slower than the tidal advection speed are assumed to dissipate locally, primarily because of hydraulic effects near the ridge crest. Evidence for high modes being dissipated is given in idealized numerical models of tidal flow over a Gaussian ridge. These idealized models also give guidance for where in the water column the predicted dissipation should be placed. The dissipation recipe holds if the Coriolis frequency f is varied, as long as $hN/W\ f$, where N is the stratification, h is the topographic height, and W is a width scale. This parameterization is not applicable to shallower topography, which has significantly more dissipation because near-critical processes dominate the observed turbulence. The parameterization compares well against simulations of tidal dissipation at the Kauai ridge but predicts less dissipation than estimated from observations of the full Hawaiian ridge, perhaps because of unparameterized wave–wave interactions.

Klymak, J. M., S. Legg, and R. Pinkel, 2010, High-mode stationary waves in stratified flow over large obstacles, *J. Fluid Mech.*, **644**: 312-336, doi:10.1017/S0022112009992503

Simulations of steady two-dimensional stratified flow over an isolated obstacle are presented where the obstacle is tall enough so that the topographic Froude number, Nh_m/U_o 1. N is the buoyancy frequency, h_m the height of the topography from the channel floor and U_o the flow speed infinitely far from the obstacle. As for moderate Nh_m/U_o (~1), a columnar response propagates far up- and downstream, and an arrested lee wave forms at the topography. Upstream, most of the water beneath the crest is blocked, while the moving layer above the crest has a mean velocity $U_m = U_{oH}/(H-h_m)$. The vertical wavelength implied by this velocity scale, $\lambda_o = 2\pi U_m/N$, predicts dominant vertical scales in the flow. Upstream of the crest there is an accelerated region of fluid approximately λ_o thick, above which there is a weakly oscillatory flow. Downstream the accelerated region is thicker and has less intense velocities. Similarly, the upstream lift of isopycnals is greatest in the first wavelength near the crest, and weaker above and below. Form drag on the obstacle is dominated by the blocked response, and not on the details of the lee wave, unlike flows with moderate Nh_m/U_o.

Directly downstream, the lee wave that forms has a vertical wavelength given by λ_o, except for the deepest lobe which tends to be thicker. This wavelength is small relative to the fluid depth and topographic height, and has a horizontal phase speed $c_{px} = -U_m$, corresponding to an arrested lee wave. When considering the spin-up to steady state, the speed of vertical propagation scales with the vertical component of group velocity $c_{gz} = \alpha U_m$, where α is the aspect ratio of the topography. This implies a time scale = $tN\alpha/2\pi$ for the growth of the lee waves, and that steady state is attained more rapidly with steep topography than shallow, in contrast with linear theory, which does not depend on the aspect ratio.

Legg, S. and J. M. Klymak, 2008, Internal hydraulic jumps and overturning generated by tidal flow over a tall steep ridge, *J. Phys. Oceanogr.*, **38**, 1949–1964, doi:10.1175/2008JPO3777.1

Recent observations from the Hawaiian Ridge indicate episodes of overturning and strong dissipation coupled with the tidal cycle near the top of the ridge. Simulations with realistic topography and stratification suggest that this overturning has its origins in transient internal hydraulic jumps that occur below the shelf break at maximum ebb tide, and then propagate up the slope as internal bores when the flow reverses. A series of numerical simulations explores the parameter space of topographic slope, barotropic velocity, stratification, and forcing frequency to identify the parameter regime in which these internal jumps are possible. Theoretical analysis predicts that the tidally driven jumps may occur when the vertical tidal excursion is large, which is shown to imply steep topographic slopes, such that $dh/dx N/\omega > 1$. The vertical length scale of the jumps is predicted to depend on the flow speed such that the jump Froude number is of order unity. The numerical results agree with the theoretical predictions, with finite-amplitude internal hydraulic jumps and overturning forming during strong offslope tidal flow over steep slopes. These results suggest that internal hydraulic jumps may be an important mechanism for local tidally generated mixing at tall steep topography.

6.2 Island Wake Mixing

Hasegawa, D., M. R. Lewis, and A. Gangopadhyay, 2009, How islands cause phytoplankton to bloom in their wakes, *Geophys. Res. Lett.*, **36**, L20605, doi:10.1029/2009GL039743

The development of phytoplankton blooms in Von Kàrmàn vortex streets in island wakes has been investigated using a coupled bio-physical model which evolves a geostrophically balanced flow past a relatively small (L = 10 km) oceanic island. Three major processes associated with the "island mass effect" are found to occur in series in our numerical experiment. First, increases in phytoplankton were observed in the lee due solely to passive advection from the deep maximum. Second, following the shedding of cyclonic eddies, upwelled nitrate enhances local primary production in the surface euphotic layer resulting in a phytoplankton bloom. The bloom peaks appeared about two weeks downstream from the island. Third, a weaker bloom is also found in the immediate lee of the island, associated with nutrient injection and longer

residence time of upwelled water. The demonstrated detailed features of island mass effect are remarkably consonant with previously observed phenomena in the real ocean.

6.3 Turbulence in the Nearshore Zone

Hay, A. E., 2008, Near-bed turbulence and relict waveformed sand ripples: Observations from the inner shelf, *J. Geophys. Res.*, **113**, C04040, doi:10.1029/2006JC004013

Results are presented from a field investigation of near-bed turbulence above degrading waveformed sand ripples in 17-m water depth on the inner shelf. The heights of the 50-cm wavelength primary ripples were about 5 cm at the start of the observation period, and decreased by a factor of 2 within 15 days. The principal degradation mechanism involved fish making pits in the seafloor. Near-bed turbulent kinetic energy dissipation rates are estimated both from the energy spectrum and from the vertical structure function within the inertial subrange, and ranged from 0.1×10^{-6} to 3×10^{-6} W/kg. The friction velocity, u_*, at the bed ranged from 0.3 to 0.5 cm/s, and the wave friction factor, f_w, from 0.017 to 0.02. The nearbed turbulence intensities and consequently the estimated values of u_*^2 and f_w are likely too small by a factor of 2, partly to satisfy the smooth-wall constraint, and partly to account for the effects of small-scale turbulence within the finite-volume range cells of the coherent Doppler system used to make the turbulence estimates. Finally, the results indicate that the hydraulic roughness of relict ripples is likely a function of both ripple height and steepness, and that the relative roughness should also depend on the near-bed wave orbital excursion. For modeling purposes, Nielsen's ripple roughness formula is recommended, with a reduced proportionality constant to account for the effects of irregular wave forcing and non-equilibrium ripple history.

Newgard, J. P. and A. E. Hay, 2007, Turbulence intensity in the wave boundary layer and bottom friction under (mainly) flat bed conditions, *J. Geophys. Res.*, **112**, C09024, doi:10.1029/2006JC003881

Variations with wave energy of near-bed turbulence and the wave friction factor are investigated in the near-shore zone for bed states spanning low-steepness sand ripples and flat bed, and for wave energies extending well into the sheet flow regime. The measurements were made using a 1.7-MHz pulse-coherent Doppler profiler in ca. 3-m mean water depth. Near-bed turbulence intensities, phase-averaged over the highest-1/3 waves, peak at phases between 10° and 55° after the wave crest, this phase decreasing with increasing wave Reynolds number. Wave friction factors computed from near-bed vertical turbulence intensity fall within the range predicted by existing semi-empirical formulae, and exhibit broadly similar trends. At the higher end of the observed wave energy range (i.e., in the sheet flow regime), however, the measured friction factors increase with sea-and-swell energy faster than the predictions. This anomalous increase is correlated with infragravity wave energy and with mean cross-shore current speed, but not with other forcing parameters including mean long-shore current speed, wave skewness, wave asymmetry and wave breaking frequency. It is argued that the anomaly is partly due to additional near-bed turbulence associated

with infragravity waves, and therefore that these data are not inconsistent with Wilson's (1989) parameterization for bottom roughness in oscillatory sheet flow. Peak near-bed turbulence intensities are independent of wave Reynolds number for $Re \lesssim 1.2 \times 10^6$, but proportional to Re for $Re \gtrsim 1.2 \times 10^6$, this abrupt change possibly indicating a critical dependence on Re of turbulence production in the WBL over flat or nearly flat mobile beds.

Rousseau, S., E. Kunze, R. Dewey, K. Bartlett, and J. Dower, 2010, On Turbulence Production by Swimming Marine Organisms in the Open Ocean and Coastal Waters. *J. Phys. Oceanogr.*, **40**(9): 2107–2121, doi:10.1175/2010JPO4415.1

Microstructure and acoustic profile time series were collected near Ocean Station P in the eastern subarctic North Pacific and in Saanich Inlet at the south end of Vancouver Island, British Columbia, Canada, to examine production of turbulent dissipation by swimming marine organisms. At Ocean Station P, although a number of zooplankton species are large enough to generate turbulence with Reynolds numbers Re > 1000, biomass densities are typically less than 10^3 individuals per cubic meter (<0.01% by volume), and turbulent kinetic energy dissipation rates ε were better correlated with 16-m vertical shear than acoustic backscatter layers. In Saanich Inlet, where krill densities are up to 10^4 individuals per cubic meter (0.1% by volume), no dramatic elevation of dissipation rates ε was associated with dusk and dawn vertical migrations of the acoustic backscatter layer. Dissipation rates are a factor of 2 higher [$\langle\varepsilon\rangle = 1.4 \times 10^{-8}$ W kg^{-1}, corresponding to buoyancy Re = $\langle\varepsilon\rangle/(\nu N^2) \sim 140$] in acoustic backscatter layers than in acoustically quiet waters, regardless of whether they are vertically migrating. The O(1 m) thick turbulence patches have vertical wavenumber spectra for microscale shear commensurate with the Nasmyth model turbulence spectrum. However, the turbulence bursts of $O(10^{-5}$ W kg$^{-1})$ proposed to occur in such dense swarms appear to be rare. Thus far, intense turbulent bursts have been found infrequently, even in very dense aggregations $O(10^4$ individuals per cubic meter) characteristic of coastal and high-latitude environs. Based on sampling to date, this corresponds to a frequency of occurrence of less than 4%, suggesting that turbulence production by the marine biosphere is not efficient.

6.4 Turbulence and Mixing in the Laboratory or Simulated

Bourouiba, L. and P. Bartello, 2007, The intermediate Rossby number range and 2D-3D transfers in decaying rotating homogeneous turbulence, *J. Fluid. Mech.*, **587**: 139-161, doi:10.1017/S0022112007007124

Rotating homogeneous turbulence in a finite domain is studied using numerical simulations, with a particular emphasis on the interactions between the wave and zero-frequency modes. Numerical simulations of decaying homogeneous turbulence subject to a wide range of background rotation rates are presented. The effect of rotation is examined in two finite periodic domains in order to test the effect of the size of the computational domain on the results obtained, thereby testing the accurate sampling of near-resonant interactions. We observe a non-monotonic tendency when Rossby number Ro is varied from large values to the

small-*Ro* limit, which is robust to the change of domain size. Three rotation regimes are identified and discussed: the *large*-, the *intermediate*-, and the *small-Ro* regimes. The intermediate-*Ro* regime is characterized by a positive transfer of energy from wave modes to vortices. The three-dimensional to two-dimensional transfer reaches an initial maximum for $Ro \approx 0.2$ and it is associated with a maximum skewness of vertical vorticity in favour of positive vortices. This maximum is also reached at $Ro \approx 0.2$. In the intermediate range an overall reduction of vertical energy transfer is observed. Additional characteristic horizontal and vertical scales of this particular rotation regime are presented and discussed.

Fellouah, H. and A. Pollard, 2009, The velocity spectra and turbulence length scales distributions in the near to intermediate regions of a round turbulent free jet, *Phys. Fluids*, **21,** 115101, doi:10.1063/1.3258837

Stationary and flying single hot-wire measurements were made to investigate the near to intermediate field in a round free turbulent jet. Measurements were carried out at Reynolds numbers Re_D based on the jet exit mean velocity and the nozzle diameter, between 6000 and 100 000. The objective of this study was to investigate the concept of a mixing transition proposed by Dimotakis ["The mixing transition in turbulent flows," J. Fluid Mech. 409, 69 (2000)]. This was done through the measurement of the velocity spectra and the calculation of Kolmogorov λ_K, Taylor microscale λ_T, the Liepmann–Taylor microscale λ_L, and the viscous length scale λ_v at different positions in the near to intermediate regions of a round free jet. The present results demonstrate the local nature of mixing transition. It is found that the Kolmogorov, Taylor, and viscous length scales all decrease in magnitude with the local Reynolds number Re_δ based on the local center line mean velocity and the local time-averaged diameter of the jet and appear to be only weakly dependent on the radial position, although the ratio $Re_T/Re_\delta^{1/2}$ varies nonlinearly across the jet radius. The ratio of the laminar to viscous length scale exceeds unity beyond the potential core of the jet. Moreover, the skewness of the axial velocity is approximately −0.4 over $30<Re_T<400$.

Fellouah, H., C. G. Ball, and A. Pollard, 2009, Reynolds number effects within the development region of a turbulent round free jet, *Int. J. Heat Mass Trans.*, **52**(17-18): 3943-3954, doi:10.1016/j.ijheatmasstransfer.2009.03.029

In this work, flying and stationary hot-wire measurements were made to investigate the effect of the Reynolds number on the near- and intermediate-fields region (0 6 x/D 6 25) of a round free jet. Measurements were carried out over a range of Reynolds numbers, based on the jet exit mean velocity and the nozzle diameter, that span the mixing transition. The specific Reynolds numbers tested were 6000, 10,000 and 30,000. The objective of this study was to determine what differences there were in mean velocity profiles, turbulence intensity profiles, and velocity spectra. Results revealed a close coupling between the mean velocity distribution and the turbulence intensities and the Reynolds shear stress. From those data obtained, it was concluded that the inertial sub-range frequency span increases with distance downstream from the jet inlet and the mixing transition

seems to occur at the appearance of the inertial sub-range rather than at the transition from the inertial to dissipation range.

Smyth, W. D., J. R. Carpenter, and G. A. Lawrence, 2007, Mixing in Symmetric Holmboe Waves, *J. Phys. Oceanogr.*, **37**(6): 1566–1583

Direct simulations are used to study turbulence and mixing in Holmboe waves. Previous results showing that mixing in Holmboe waves is comparable to that found in the better-known Kelvin–Helmholtz (KH) billows are extended to cover a range of stratification levels. Mixing efficiency is discussed in detail, as are effective diffusivities of buoyancy and momentum. Entrainment rates are compared with results from laboratory experiments. The results suggest that the ratio of the thicknesses of the shear layer and the stratified layer is a key parameter controlling mixing. With that ratio held constant, KH billows mix more rapidly than do Holmboe waves. Among Holmboe waves, mixing increases with increasing density difference, despite the fact that the transition to turbulence is delayed or prevented entirely by the stratification. Results are summarized in parameterizations of the effective viscosity and diffusivity of Holmboe waves.

Sutherland, B. R., A. N. F. Chow, and T. P. Pittman, 2007, The collapse of a mixed patch in stratified fluid, *Phys. Fluids*, **19**, 116602, doi:10.1063/1.2814331

Lock-release laboratory experiments are performed to examine the collapse of a localized mixed patch of fluid in a uniformly stratified ambient with constant buoyancy frequency, N. The intrusion speed is approximately $0.13NH_\ell$, in which H_ℓ is the depth of the mixed patch. This is consistent with the speed of intrusions released from a full-depth lock where $H_\ell = H$ is the depth of the ambient. The vertically propagating waves have frequency set by N ($\omega \simeq 0.7N$) and the horizontal wavelength, λ_x, is set by H_ℓ ($\lambda_x \simeq 1.5H_\ell$). The amplitude is found to scale as the depth of the mixed region cubed at small H_ℓ, and saturates at large $H_\ell \gtrsim 10$ cm due to nonlinear effects.

Tedford, E. W., R. Pieters, and G. A. Lawrence, 2009, Symmetric Holmboe instabilities in a laboratory exchange flow, *J. Fluid Mech.*, 636: 137-153, doi:10.1017/S0022112009007733

Laboratory experiments have been conducted that test the predictions of Holmboe (*Geofys. Publ.*, vol. 24, 1962, pp. 67–112). Symmetric Holmboe instabilities are observed during steady, maximal two-layer exchange flow in a long laboratory channel of rectangular cross-section. Internal hydraulic controls at each end of the channel isolate the subcritical region within the channel from disturbances in the reservoirs. Inside the channel, the instabilities form cusp-like waves that propagate in both directions. The phase speed of the instabilities is consistent with Holmboe's theory and increases along the length of the channel as a result of the gradual acceleration of each layer. This acceleration causes the wavelength of any given instability to increase in the flow direction until it is approximately twice the most amplified wavelength. At this point new waves develop with the result that the average wavelength is almost constant along the length of the channel.

Uddin, M. and A. Pollard, 2007, Self-similarity of Co-Flowing Jets: The virtual origin, *Phys. Fluids*, **19**(6), doi:10.1063/1.2740709

From round and plane jet experimental data, it can be inferred that the existence of the virtual origin can be attributed to variations in thickness of the internal boundary layer at the orifice. Based on this, and further support from large eddy simulations (LES) of axisymmetric coflowing round jets with various inlet conditions, we propose that the local value of the variance in the thickness of the boundary layer and thus the velocity distribution at the jet inlet can be used to predict the location of the virtual origin. This, in turn, indicates the inadequacy of the traditionally used length scale, the jet half-width/radius, and suggests the local variance is a length scale with better physical significance. It appears unlikely that the turbulence intensity distribution at the orifice plays a significant role in the determination of the virtual origin or the axial spread of the effective jet width.

6.5 Eddy Mixing/Flux

Eden, C., R. J. Greatbatch, and D. Olbers, 2007, Interpreting Eddy Fluxes. *J. Phys. Oceanogr.*, **37**(5): 1282–1296

A generalization of the transformed Eulerian and temporal residual means is presented. The new formulation uses rotational fluxes of buoyancy, and the full hierarchy of statistical density moments, to reduce the cross-isopycnal eddy flux to the physically relevant component associated with the averaged water mass properties. The resulting eddy-induced diapycnal diffusivity vanishes for adiabatic, statistically steady flow, and is related to either the growth or decay of mesoscale density variance and/or the covariance between small-scale forcing (mixing) and density fluctuations, such as that associated with the irreversible removal of density variance by dissipation. The relationship between the new formulation and previous approaches is described and is illustrated using results from an eddying channel model. The formalism is quite general and applies to all kinds of averaging and to any tracer (not just density).

Greenan, B. J. W, 2008, Shear and Richardson number in a mode-water eddy, *Deep-Sea Res. Pt. II*, **55**: 1161-1178, doi:10.1016/j.dsr2.2008.01.010

Measurements of stratification and shear were carried out as part of the EDDIES tracer release experiment in mode-water eddy A4 during the summer of 2005. These measurements were accomplished using both shipboard instrumentation and a drifting mooring. A strong relationship between shear intensity and distance from the center of the eddy A4 was observed with the shipboard ADCP. Diapycnal diffusivity at the SF_6 tracer isopycnal prior to and during the release was estimated from the drifting mooring to be 2.9×10^{-6} m^2 s^{-1}. Diffusivity increased by an order of magnitude to 3.2×10^{-5} m^2 s^{-1} during the period of the final tracer survey in early September, which was similar to the value estimated from the tracer analysis for the whole experiment (3.5×10^{-5} m^2 s^{-1}, [Ledwell, J.R., McGillicuddy Jr., D.J., Anderson, L.A., 2008. Nutrient flux into an intense deep chlorophyll layer in a mode-water eddy. Deep-Sea Research II, this issue [doi:10.1016/j.dsr2.2008.02.005]].

Li, M., S. Vagle, D. M. Farmer, 2009, Large Eddy Simulations of Upper-Ocean Response to a Midlatitude Storm and Comparison with Observations*, *J. Phys. Oceanogr.*, **39**(9): 2295–2309

A large eddy simulation (LES) model is used to investigate an upper-ocean response to a fall storm in the open ocean of the North Pacific Ocean. The storm is characterized by rapid increases in wind speed and surface heat loss but a relatively steady wave field. The LES model shows that surface convergence zones or windrows organize into line patterns aligned with the wind direction, evolving from nearly parallel lines to irregular structures featuring Y junctions as the wind speed increases. The downwelling-to-upwelling velocity ratio ranges between 1.2 and 1.6, indicating a moderate level of asymmetry between the downwelling and upwelling plumes in Langmuir circulation. During the storm, the turbulent Langmuir number La_t increases from 0.2 to 0.5 while the vertical turbulence intensity σ_w^2 decreases from 1.4 to 0.7 u_*^2, where u_* is the friction velocity. The order of turbulence intensities in three directions switches from crosswind ≈ vertical > downwind directions to downwind > crosswind > vertical directions. This suggests a transition from Langmuir to shear turbulence as the storm progresses. The Hoennikker number (Ho) remains below 0.1 and the strong evaporative heat loss does not contribute much to the turbulence generation in the ocean mixed layer. The LES results are compared with in situ and acoustic measurements collected during the storm. Patterns of model-predicted near-surface downwelling zones are in good agreement with horizontal distributions of bubble clouds revealed in sidescan sonar images. Striking similarity is also found in the temperature anomalies between the LES model and high-resolution thermistor chain measurements.

6.6 Front Dynamics, Intrusions, and Double Diffusion

Inoue, R., H. Yamazaki, F. Wolk, T. Kono, J. Yoshida, 2007, An Estimation of Buoyancy Flux for a Mixture of Turbulence and Double Diffusion, *J. Phys. Oceanogr.*, **37**(3) 611–624

Microstructure measurements were made in the Mixed Water Region of the Oyashio/Kuroshio/Tsugaru currents system where both turbulence and double diffusion are involved in mixing. While intense turbulence is observed near the front between the Oyashio and the Tsugaru Current, double diffusion occupies a noticeable fraction in both the Tsugaru Water and the Mixed Water between the Oyashio and the Kuroshio. After determining a criterion to distinguish double diffusion from turbulence, vertical diffusivities and buoyancy fluxes are estimated using microstructure data. When turbulence is weak, double diffusion is observed around temperature and salinity anomalies, partly due to interleaving, and dominates the buoyancy flux. Vertical diffusivities due to double diffusion are parameterized as a function of the 10-m-scale density ratio. The 10-m-scale diffusivity estimates are consistent with the microstructure data when an appropriate criterion to reproduce a probability density function for the Turner angle is applied. A weighted-average diffusivity model is proposed to account properly for turbulence and double diffusion simultaneously.

Lavery, A. and T. Ross, 2007, Acoustic scattering from double-diffusive microstructure, *J. Acoustical Soc. America*, **122**(3): 1449-1462, http://dx.doi.org/10.1121/1.2764475

Laboratory measurements of high-frequency broadband acoustic backscattering (200–600 kHz) from the diffusive regime of double-diffusive microstructure have been performed. This type of microstructure, which was characterized using direct microstructure and optical shadowgraph techniques, is identified by sharp density and sound speed interfaces separating well-mixed layers. Vertical acoustic backscattering measurements were performed for a range of physical parameters controlling the double-diffusive microstructure. The echoes have been analyzed in both the frequency domain, providing information on the spectral response of the scattering, and in the time domain, using pulse compression techniques. High levels of variability were observed, associated with interface oscillations and turbulent plumes, with many echoes showing significant spectral structure. Acoustic estimates of interface thickness (1–3 cm), obtained for the echoes with exactly two peaks in the compressed pulse output, were in good agreement with estimates based on direct microstructure and optical shadowgraph measurements. Predictions based on a one-dimensional weak-scattering model that includes the actual density and sound speed profiles agree reasonably with the measured scattering. A remote-sensing tool for mapping oceanic microstructure, such as high-frequency broadband acoustic scattering, could lead to a better understanding of the extent and evolution of double-diffusive layering, and to the importance of double diffusion to oceanic mixing.

Pinheiro, L. M., H. Song, B. Ruddick, J. Dubert, I. Ambar, K. Mustafa, and R. Bezerra, 2009, Detailed 2-D imaging of the Mediterranean outflow and meddies off W. Iberia from multichannel seismic data, *J. Mar. Sys.*, doi:10.1016/j.jmarsys.2009.07.004

Reprocessing of a 326-km long multichannel seismic line acquired in the Tagus Abyssal Plain off W Iberia in 1991 allowed detailed imaging of the thermohaline structure of several mesoscale features within the water column. The interpretation was supported by subsurface float measurements, Sea Level Anomaly (SLA) maps and Sea Surface Temperature (SST) images contemporaneous with the acquisition of the seismic data. Clear images were obtained of the reflective patterns associated with one previously known and one newly discovered meddy, one cyclone, the upper and lower cores of the Mediterranean Undercurrent, and the interface of the high-salinity tongue of the Mediterranean Water with the North Atlantic Central Water. These reveal a complexity and a detail of the lateral variations of the thermohaline structure not easily observed by conventional physical oceanography tools.

The mesoscale structures were imaged via reflections from oceanic fine structures of scale 30 m or less. We compare the characteristics of observed reflections with known mechanisms of fine-structure production. Most of the observed reflections are consistent with internal waves and thermohaline intrusions as previously hypothesized. We postulate a new mechanism to explain the formation of the steeply sloping reflections that outline the meddy and other features, involving frontogenetic isopycnal advection, formation of thermohaline intrusions, and

tilting of the intrusive layers by mesoscale shear flows. The imaging technique therefore shows the relationship between mesoscale features and the fine-scale oceanographic phenomena associated with mixing, including steeply-sloped structures that would otherwise not be tracked using CTD profiles alone.

Ross, T. and A. Lavery, 2009, Laboratory observations of double-diffusive convection using high-frequency broadband acoustics, *Experiments in Fluids*, **46**(2): 355-364, doi:10.1007/s00348-008-0570-9

High-frequency broadband (200–300 kHz) acoustic scattering techniques have been used to observe the diffusive regime of double-diffusive convection in the laboratory. Pulse compression signal processing techniques allow (1) centimetre-scale interface thickness to be rapidly, remotely, and continuously measured, (2) the evolution, and ultimate merging, of multiple interfaces to be observed at high-resolution, and (3) convection cells within the surrounding mixed layers to be observed. The acoustically measured interface thickness, combined with knowledge of the slowly varying temperatures within the surrounding layers, in turn allows the direct estimation of double-diffusive heat and buoyancy fluxes. The acoustically derived interface thickness, interfacial fluxes and migration rates are shown to support established theory. Acoustic techniques complement traditional laboratory sampling methods and provide enhanced capabilities for observing the diffusive regime of double-diffusion in the ocean.

Ruddick, B., H. Song, C. Dong, and L. Pinheiro, 2009, Water column seismic images as smoothed maps of temperature gradient, Oceanography, **22**(1): 192-205

Multichannel seismic imaging of ocean water column features is a new interdisciplinary study that may become an accepted oceanographic tool in coming years. We now know that reflectors are associated with water column thermohaline fine structures such as internal waves and intrusions (on a scale of ~ 10–50 m) associated with ocean mixing, and also that the images outline larger-scale oceanographic features such as currents, water-mass boundaries, eddies, meddies, and fronts. The synopticity and detail showing the relationships between mesoscale and fine-scale features promises improved insight into the processes that cascade energy from mesoscales to mixing scales. In order to trust a new tool, oceanographers require a quantitative understanding of how the new tool acts upon physical properties to yield a final result. We explain the basic principles of multichannel seismics, and show that the imaging process can be viewed as a filtering operation acting on the acoustic impedance field, which, on the scales that matter, is primarily (but not completely) associated with temperature variations. Synthetic seismic images show the derivative of acoustic impedance, averaged over the resolution scale of the acoustic source wavelet—they are, aside from side-lobe effects, essentially smoothed maps of temperature gradient. We use a conductivity-temperature-depth (CTD) trace from the periphery of a meddy to estimate the contribution of thermal (83%) and saline (17%) anomalies to a synthetic seismic trace, and then use multiple CTD traces from the same data set to construct a synthetic seismic image. This synthetic image compares favorably

to a real seismic image of a different meddy with important differences that can be ascribed to the higher lateral resolution of the seismic technique.

Ruddick, B. R., N. S. Oakey, and D. Hebert, 2010, Measuring lateral heat flux across a thermohaline front: A model and observational test, *J. Mar. Res.*, **68**(3-4): 523-539, doi:10.1357/002224010794657146

We develop and test a method to observationally estimate lateral intrusive heat flux across a front. The model combines that of Joyce (1977), in which lateral cross-frontal advection by intrusions creates vertical temperature gradients, and Osborn and Cox (1972) in which vertical mixing of those gradients creates thermal microstructure that is dissipated by molecular conduction of heat. Observations of thermal microstructure dissipation χ_T are then used to estimate the production by intrusions, and hence the lateral heat flux and diffusivity. This method does not depend on the precise mechanism(s) of mixing, or on the dynamical mechanisms driving the frontal intrusions. It relies on several assumptions: (1) lateral cross-frontal advection produces diapycnal temperature gradients that are mixed locally, (2) thermal variance is dissipated locally and not exported, (3) intrusion scales are larger than turbulence scales, and (4) isotropy of temperature microstructure is assumed in order to estimate χ_T.

The method is tested using microstructure observations in Meddy "Sharon," where the erosion rate and associated lateral heat flux are known from successive mesoscale hydrographic observations (Hebert *et al.*, 1990). An expression is developed for the production (lateral heat flux times lateral temperature gradient, expected to equal χ_T) in a front of steady shape that is eroding (detraining) at a steady rate; the production is proportional to the erosion speed and the square of the cross-frontal temperature contrast, both of which are well-known from observations. The qualitative structure and integrated value of the dissipation agree well with model assumptions and predictions: thermal variance produced by lateral intrusive heat flux is dissipated locally, dissipation in intrusive regions dominates total dissipation, and the total dissipation agrees with the observed erosion rate, all of which suggests that microstructure observations can be used to estimate intrusive heat flux. A direct comparison was made between lateral heat flux estimated from mesoscale Meddy structure plus the known rate of erosion, and lateral flux based on microscale temperature dissipation, with excellent agreement in the frontal zone and poorer agreement where lateral temperature gradient is too small to accurately measure.

6.7 Acoustics, Bubbles and Turbulence

Gemmrich, J., 2010, Strong Turbulence in the Wave Crest Region, *J. Phys. Oceanogr.*, **40**(3): 583–595

High-resolution vertical velocity profiles in the surface layer of a lake reveal the turbulence structure beneath strongly forced waves. Dissipation rates of turbulence kinetic energy are estimated based on centered second-order structure functions at 4-Hz sampling. Dissipation rates within nonbreaking wave crests are on average 3 times larger than values found at the same distance to the free

surface but within the wave trough region. This ratio increases to 18 times for periods with frequent wave breaking. The depth-integrated mean dissipation rate is a function of the wave field and correlates well with the mean wave saturation in the wave band $\omega_p \leq \omega \leq 4\omega_p$. It shows a clear threshold behavior in accordance with the onset of wave breaking. The initial bubble size distribution is estimated from the observed distribution of energy dissipation rates, assuming the Hinze scale being the limiting size. This model yields the slope of the size distribution, $\beta \approx -10/3$, consistent with laboratory results reported in the literature, and implies that bubble fragmentation associated with intermittent high dissipation rates is a valid mechanism for the setup of bubble size spectra.

Pratson, L. F., E. W. H. Hutton, A. J. Kettner, J. P. M. Syvitski, P. S. Hill, D. A. George, and T. G. Milligan, 2007, The impact of floods and storms on the acoustic reflectivity of the inner continental shelf: A modeling assessment, *Cont. Shelf Res.*, **27(3-4)**: 542-559, doi:10.1016/j.csr.2005.12.018

Flood deposition and storm reworking of sediments on the inner shelf can change the mixture of grain sizes on the seabed and thus its porosity, bulk density, bulk compressional velocity and reflectivity. Whether these changes are significant enough to be detectable by repeat sub-bottom sonar surveys, however, is uncertain. Here the question is addressed through numerical modeling. Episodic flooding of a large versus small river over the course of a century are modeled with *HYDROTREND* using the drainage basin characteristics of the Po and Pescara Rivers (respectively). A similarly long stochastic record of storms offshore of both rivers is simulated from the statistics of a long-term mooring recording of waves in the western Adriatic Sea. These time series are then input to the stratigraphic model *SEDFLUX2D*, which simulates flood deposition and storm reworking on the inner shelf beyond the river mouths. Finally, annual changes in seabed reflectivity across these shelf regions are computed from bulk densities output by *SEDFLUX2D* and compressional sound speeds computed from mean seafloor grain size using the analytical model of Buckingham [1997. Theory of acoustic attenuation, dispersion, and pulse propagation in unconsolidated granular materials including marine sediments. Journal of the Acoustical Society of America 102, 2579–2596; 1998. Theory of compressional and shear waves in fluidlike marine sediments. Journal of the Acoustical Society of America 103, 288–299; 2000. Wave propagation, stress relaxation, and grain-tograin shearing in saturated, unconsolidated marine sediments. Journal of the Acoustical Society of America 108, 2796–2815]. The modeling predicts reflectivities that change from <12 dB for sands on the innermost shelf to >9 dB for muds farther offshore, values that agree with reflectivity measurements for these sediment types. On local scales of 100 m, however, maximum changes in reflectivity are <0.5 dB. So are most annual changes in reflectivity over all water depths modeled (i.e., 0–35 m). Given that signal differences need to be 2–3 dB to be resolved, the results suggest that grain-size induced changes in reflectivity caused by floods and storms will rarely be detectable by most current sub-bottom sonars.

Ross, T., I. Gaboury, and R. Lueck, 2007, Simultaneous acoustic observations of turbulence and zooplankton in the ocean, *Deep Sea Res. I*, **54**(1): 143-153, doi:10.1016/j.dsr.2006.09.009

Models and laboratory experiments show that zooplankton may locate food more easily in turbulent waters, but whether plankton seek or avoid turbulence in the ocean is an open question. It is difficult to measure turbulence and plankton simultaneously and with the necessary spatial resolution using traditional methods (nets and airfoil shear sensors). Acoustics is commonly used to survey zooplankton abundance and recent studies have shown that stratified turbulence can also be a significant source of sound scatter. This may seem like more of a complication than a boon for those aiming to use acoustics to observe plankton in turbulence. We present acoustic data, however, that show that zooplankton and turbulence can be observed simultaneously with a single 307 kHz sounder. The different natures of the two targets (discrete targets versus a volume effect) allow them to be distinguished. The key is sampling the same targets at multiple ranges. The volume scattering strength of a discrete target will increase as the target nears the sounder, because the volume sampled decreases. Turbulence, as a volume scattering effect, has little range dependence to its volume scattering strength.

Trevorrow, M. V., B. Vasiliev, and S. Vagle, 2008, Directionality and maneuvring effects on a surface ship underwater acoustic signature, *J.Acoust. Soc.Am.*, **124**(2): 767-778, doi:10.1121/1.2939128

This work examines underwater source spectra of a small (560 tons, 40 m length), single-screw oceanographic vessel, focusing on directionality and effects of maneuvers. The measurements utilized a set of four, self-contained buoys with GPS positioning, each recording two calibrated hydrophones with effective acoustic bandwidth from 150 Hz to 5 kHz. In straight, constant-speed runs at speeds up to 6.2 m s(-1), the ship source spectra showed spectral levels in reasonable agreement with reference spectra. The broadband source level was observed to increase as approximately speed to the fourth power over the range of 2.6-6.1 m s(-1), partially biased at low speeds by nonpropulsion machinery signals. Source directionality patterns were extracted from variations in source spectra while the ship transited past the buoy field. The observed spectral source levels exhibited a broadside maximum, with bow and stern aspect reduced by approximately 12-9 dB, respectively, independent of frequency. An empirical model is proposed assuming that spectral source levels exhibit simultaneous variations in aspect angle, speed, and turn rate. After correction for source directionality and speed during turning maneuvers, an excess of up to 18 dB in one-third octave source levels was observed.

7 Numerical Modeling

Ambadan, J. T. and Y. Tang, 2009: Sigma-Point Kalman Filter Data Assimilation Methods for Strongly Nonlinear Systems, *J. Atmos. Sci.*, **66**(2): 261–285, doi:10.1175/2008JAS2681.1

Performance of an advanced, derivativeless, sigma-point Kalman filter (SPKF) data assimilation scheme in a strongly nonlinear dynamical model is investigated. The SPKF data assimilation scheme is compared against standard Kalman filters such as the extended Kalman filter (EKF) and ensemble Kalman filter (EnKF) schemes. Three particular cases —namely, the state, parameter, and joint estimation of states and parameters from a set of discontinuous noisy observations—are studied. The problems associated with the use of tangent linear model (TLM) or Jacobian when using standard Kalman filters are eliminated when using SPKF data assimilation algorithms. Further, the constraints and issues of SPKF data assimilation in real ocean or atmospheric models are emphasized. A reduced sigma-point subspace model is proposed and investigated for higher-dimensional systems.

A low-dimensional Lorenz 1963 model and a higher-dimensional Lorenz 1995 model are used as the test beds for data assimilation experiments. The results of SPKF data assimilation schemes are compared with those of standard EKF and EnKF, in which a highly nonlinear chaotic case is studied. It is shown that the SPKF is capable of estimating the model state and parameters with better accuracy than EKF and EnKF. Numerical experiments showed that in all cases the SPKF can give consistent results with better assimilation skills than EnKF and EKF and can overcome the drawbacks associated with the use of EKF and EnKF.

Greenberg, D. A., F. Dupont, F. H. Lyard, D. R. Lynch, and F. E. Werner, 2007, Resolution issues in numerical models of oceanic and coastal circulation, *Cont. Shelf Res.*, **27**(9): 1317-1343, doi:10.1016/j.csr.2007.01.023

The baroclinic and barotropic properties of ocean processes vary on many scales. These scales are determined by various factors such as the variations in coastline and bottom topography, the forcing meteorology, the latitudinal dependence of the Coriolis force, and the Rossby radius of deformation among others. In this paper we attempt to qualify and quantify scales of these processes, with particular attention to the horizontal resolution necessary to accurately reproduce physical processes in numerical ocean models. We also discuss approaches taken in nesting or down-scaling from global/basin-scale models to regional-scale or shelf-scale models. Finally we offer comments on how vertical resolution affects the representation of stratification in these numerical models.

Huang, A., Y. R. Rao, Y. Lu, and J. Zhao, 2010, Hydrodynamic modeling of Lake Ontario: An intercomparison of three models, *J. Geophys. Res.*, **115**, C12076, doi:10.1029/2010JC006269

The solutions of three lake hydrodynamic models, namely, Princeton Ocean Model (POM), Canadian Version of Diecast Model, and Estuary, Lake, and Coastal Ocean Model, are compared with each other and with observations in Lake Ontario. The models have the same horizontal resolution and are forced with meteorological observations during mid-April to early October of 2006. The three models obtained qualitatively similar results, although they have differences in physical parameters, numerical scheme, and vertical discretization. Comparison

with observations shows that the models can reproduce the time evolution of lake surface temperature reasonably well. All the models produced shallower mixed layers than observations at midlake stations, causing significant errors in simulating the temperatures in the thermocline but performed better near the coast. All the models also reproduced the characteristics of the time variability of the surface currents but quantitatively had substantial errors at subsurface levels. The three models all reproduced the observed spatial pattern of the summer mean near-surface temperatures, with upwelling (colder temperatures) along the north shore and downwelling (warmer temperatures) along the southeastern shore. The models simulated a lake-wide cyclonic circulation occupying a large portion of the lake, consistent with the observed climatology, but showed distinct differences in simulating the smaller gyre in the western corner of the lake. Although POM has half-vertical layers compared to *z* level models, its performance is comparable or slightly better than other models in most of the measures. During a strong easterly wind event, the performances of the models are similar in simulating the upwelling and downwelling processes in the lake and agree with the expected dynamic response to the strong wind forcing.

McGillicuddy Jr., D., B. deYoung B., S. C. Doney, P. M. Gilbert, D. Stammer, D., and F. E. Werner, 2010, Models: Tools for Synthesis in International Oceanographic Research Programs, *Oceanography*, **23**(3), http://www.physics.mun.ca/~bdeyoung/mcg_et_al_2010_IOC_50th.pdf
no abstract; introduction

Through its promotion of coordinated international research programs, the intergovernmental Oceanographic Commission (IOC) has facilitated major progress on some of the most challenging problems in oceanography. Issues of global significance—such as general ocean circulation, the carbon cycle, the structure and dynamics of ecosystems, and harmful algal bloom s—are so large in scope that they require international collaboration to be addressed systematically. International collaborations are even more important when these issues are affected by anthropogenic processes— such as climate change, CO_2 enhancement, ocean acidification, pollution, and eutrophication—whose impacts may differ greatly throughout the global ocean. These problems require an entire portfolio of research activities, including global surveys, regional process studies, time-series observations, laboratory based investigations, and satellite remote sensing. Synthesis of this vast array of results presents its own set of challenges (Hofmann et al., 2010), and models offer an explicit framework for integration of the knowledge gained as well as detailed investigation of the underlying dynamics. Models help us to understand what happened in the past, and to make predictions of future changes—both of which support the development of sound policy and decision making. We review examples of how models have been used for this suite of purposes, focusing on areas where IOC played a key role in organizing and coordinating the research activities.

Pan, S., N. MacDonald, J. Williams, B. A. O'Connor, J. Nicholson, and A. M. Davies, 2007, Modelling the hydrodynamics of offshore sandbanks, *Cont. Shelf Res.*, **27**(9): 1264-1286, doi:10.1016/j.csr.2007.01.007

This paper describes the details of a quasi-three-dimensional model (3DBANK), which has been developed to investigate medium and long-term morphological evolution and development of offshore sandbanks. The model is based on a three-dimensional tidal module using the Galerkin-eigenfunction method, but also includes four sub-modules to compute: the instantaneous bedform characteristics from which the temporal and spatial variations of the shear stresses at the sea bed can be derived; the suspended sediment concentration through the water column; the bed-load and suspended sediment fluxes at a point-in-plan; and the resulting morphological changes, respectively. The model also includes the effects of the wind and waves at the sea surface, as well as the wave–current interaction (WCI), and operates with full hydrodynamic and morphodynamic interaction. The components of the model were tested against laboratory and field data, and the complete model was then applied to Middlekerke Bank off the Flemish coast where extensive field measurements were taken during the European Community (EC) funded Circulation and Sediment Transport Around Banks (CSTAB) Project using various advanced instrumentation including STABLE and HF OSCR. Comparisons of the model results with the field measurements and observations show that the model is capable of reproducing the current and wave-induced bedforms, bed roughness, tidal currents and tidal residuals around the sandbank satisfactorily, and can be used to study the long-term sandbank evolution under various offshore conditions. This paper, however, focuses on the hydrodynamic aspects of the model, while the details of the morphological components will be given in a companion paper.

Sacher, W. and P. Bartello, 2008, Sampling errors in ensemble Kalman filtering. Part I Theory, *Mon. Wea. Rev.*, **13**(8): 3035-3049, doi:10.1175/2007MWR2323.1

This paper discusses the quality of the analysis given by the ensemble Kalman filter in a perfect model context when ensemble sizes are limited. The overall goal is to improve the theoretical understanding of the problem of systematic errors in the analysis variance due to the limited size of the ensemble, as well as the potential of the so-called double-ensemble Kalman filter, covariance inflation, and randomly perturbed analysis techniques to produce a stable analysis—that is to say, one not subject to filter divergence. This is achieved by expressing the error of the ensemble mean and the analysis error covariance matrix in terms of the sampling noise in the background error covariance matrix (owing to the finite ensemble estimation) and by comparing these errors for all methods. Theoretical predictions are confirmed with a simple scalar test case. In light of the analytical results obtained, the expression of the optimal covariance inflation factor is proposed in terms of the limited ensemble size and the Kalman gain.

Sacher, W., and P. Bartello, 2009, Sampling Errors in Ensemble Kalman Filtering. Part II: Application to a Barotropic Model, *Mon. Wea. Rev.*, **137**(5): 1640–1654, doi:10.1175/2008MWR2685.1

In the current study, the authors are concerned with the comparison of the average performance of stochastic versions of the ensemble Kalman filter with and without covariance inflation, as well as the double ensemble Kalman filter. The theoretical results obtained in Part I of this study are confronted with idealized simulations performed with a perfect barotropic quasigeostrophic model. Results obtained are very consistent with the analytic expressions found in Part I. It is also shown that both the double ensemble Kalman filter and covariance inflation techniques can avoid filter divergence. Nevertheless, covariance inflation gives efficient results in terms of accuracy and reliability for a much lower computational cost than the double ensemble Kalman filter and for smaller ensemble sizes.

Shore, J. A., 2009, Modelling the circulation and exchange of Kingston Basin and Lake Ontario with FVCOM, *Ocean Modelling*, **30(**2-3): 106-114, doi:10.1016/j.ocemod.2009.06.007

An unstructured grid, finite-volume, 3-dimensional primitive equation, sigma-coordinate terrain following ocean model (FVCOM) has been applied to Lake Ontario to investigate its monthly climatological circulation with a focus on Kingston Basin. Kingston Basin, in the northeastern end of Lake Ontario, sits between the main body of the lake and the outflowing St. Lawrence River and is adjacent to the Bay of Quinte Area of Concern designated by the International Joint Commission. The focus of this study is to use the unstructured model FVCOM to model the mean circulation in the Basin. Results showed that the FVCOM model can take up to 3 years to spin-up from rest for a wind-forced, almost fully enclosed lake model. The model accurately reproduced the current flow field within the main body of the lake and compared favourably to the flow field observed during the International Field Year for the Great Lakes (IFYGL) in Kingston Basin. Transport stream function results show that the structure of the flow into Kingston Basin from the main body of the lake changes throughout the year.

8 Upwelling

Allen, S. E. and B. M. Hickey, 2010, Dynamics of advection-driven upwelling over a shelf break submarine canyon, *J. Geophys. Res.*, **115**, C08018, doi:10.1029/2009JC005731

The response over a submarine canyon to a several day upwelling event can be separated into three phases: an initial transient response; a later, much longer, "steady" advection-driven response; and a final relaxation phase. For the advection-driven phase over realistically steep, deep, and narrow canyons with near-uniform flow and stratification at rim depth, we have derived scale estimates for four key quantities. Observations from 5 real-world canyon studies and 3 laboratory studies are used to validate the scaling and estimate the scalar constant for each scale. Based on 4 geometric parameters of the canyon, the background stratification, the Coriolis parameter, and the incoming current, we can estimate (1) the depth of upwelling in the canyon to within 15 m, (2) the deep vorticity to

within 15%, and (3) the presence/absence of a rim depth eddy can be determined. Based on laboratory data, (4) the total upwelling flux can also be estimated. The scaling analysis shows the importance of a Rossby number based on the radius of curvature of isobaths at the upstream mouth of the canyon. This Rossby number determines the ability of the flow to cross the canyon isobaths and generate the pressure gradient that drives upwelling in the canyon. Other important scales are a Rossby number based on the length of the canyon which measures the ability of the flow to lift isopycnals and a Burger number based on the width of the canyon that determines the likelihood of an eddy at rim depth. Generally, long canyons with sharply turning upstream isobaths, strong incoming flow, small Coriolis parameter, and weak stratification have the strongest upwelling response.

Dawe, J. T. and S. E. Allen, 2010, Solution convergence of flow over steep topography in a numerical model of canyon upwelling, *J. Geophys. Res.*, **115**, C05008, doi:10.1029/2009JC005597

The convergence as resolution is increased is examined for a numerical model simulation of upwelling over a continental shelf canyon. A series of idealized one- and two-dimensional models are used to plot the dependence of bottom Ekman layer velocity structure and transport on model resolution. Using these results as a guide, a bottom Ekman layer-resolving three-dimensional numerical model is constructed. This model is used to simulate a laboratory model of canyon upwelling. Alongshore velocity, volume of fluid upwelled through the canyon onto the shelf, and change in depth of the canyon water are examined at three grid resolutions. Numerical model particle trajectories are compared with a laboratory model of canyon upwelling to validate the model. The results suggest that current computational cluster power is sufficient to accurately simulate all aspects of upwelling in a steep canyon with the exception of flow separation from the canyon wall.

Ianson, D., R. A. Feely, C. L. Sabine, and L. W. Juranek, 2009, Features of coastal upwelling regions that determine net air-sea CO2 flux, *J Oceanogr.*, **65**(5): 677-687, doi:10.1007/s10872-009-0059-z

The influence of the coastal ocean on global net annual air-sea CO_2 fluxes remains uncertain. However, it is well known that air-sea pCO_2 disequilibria can be large (ocean pCO_2 ranging from ~400 µatm above atmospheric saturation to ~250 µatm below) in eastern boundary currents, and it has been hypothesized that these regions may be an appreciable net carbon sink. In addition it has been shown that the high productivity in these regions (responsible for the exceptionally low surface pCO_2) can cause nutrients and inorganic carbon to become more concentrated in the lower layer of the water column over the shelf relative to adjacent open ocean waters of the same density. This paper explores the potential role of the winter season in determining the net annual CO_2 flux in temperate zone eastern boundary currents, using the results from a box model. The model is parameterized and forced to represent the northernmost part of the upwelling region on the North American Pacific coast. Model results are compared to the few summer data that exist in that region. The model is also used

to determine the effect that upwelling and downwelling strength have on the net annual CO_2 flux. Results show that downwelling may play an important role in limiting the amount of CO_2 outgassing that occurs during winter. Finally data from three distinct regions on the Pacific coast are compared to highlight the importance of upwelling and downwelling strength in determining carbon fluxes in eastern boundary currents and to suggest that other features, such as shelf width, are likely to be important.

Waterhouse, A. F., S. E. Allen, and A. W. Bowie, 2009, Upwelling flow dynamics in long canyons at low Rossby number, *J. Geophys. Res.*, **114**, C05004, doi:10.1029/2008JC004956

Submarine canyons, topographic features incising the continental slope, vary in both shape and size. The dynamics of short canyons have been observed and described in the field, in the laboratory, and with numerical simulations. Flow within long canyons, such as Juan de Fuca canyon, located between Vancouver Island and Washington State in the Pacific Northwest, is less well understood. Physical models of both long and short canyons have been constructed to understand the upwelling dynamics in long canyons and how upwelling changes, as compared with the dynamics of short canyons, at low Rossby number. Stratification and rotation, both important parameters in determining the dynamics in canyons, can be controlled and scaled accordingly for replication of oceanic conditions. The physical model is spun up to an initial rotation rate, and the flow is forced by increasing the rotation rate over the equivalent of several days. Flow visualization is used to determine the strength and location of upwelling, the strength and mechanisms generating vorticity, as well as the differences between the flow within the long and short canyons. The pattern of upwelling between the two canyons is significantly different in the horizontal with upwelling occurring through the canyon head in the short canyon and upwelling occurring close to the mouth along the downstream rim in the long canyon. At high Rossby number, upwelling is similar in both the long and short canyon and is driven by advection. However, as Rossby number decreases, the flow in the long canyon is more strongly affected by the strong convergence of the isobaths near the canyon than by advection alone.

9 Waves in the Ocean

9.1 Wind-generated Waves

Xu, F., W. Perrie, B. Toulany, and P. C. Smith, 2007, Wind-Generated Waves in Hurricane Juan, *Ocean Modelling*, **16**(3-4): 188-205, doi:10.1016/j.ocemod.2006.09.001

We present numerical simulations of the ocean surface waves generated by hurricane Juan in 2003 as it reached its mature stage (travelling from deep waters off Bermuda to Nova Scotia and making landfall near Halifax) using SWAN (v.40.31) nested within WAVEWATCH-III (v.2.22; denoted WW3) wave models, implemented on multiple-nested domains. As for all storm-wave simulations, spectral wave development is highly dependent on accurate

simulations of storm winds during its life cycle. Due to Juan's rapid translation speed (accelerating from 2.28 m s^{-1} on 27 September, 1200 UTC to 20 m s^{-1} on 29 September, 1200 UTC), an interpolation method is developed to blend observed hurricane winds with numerical weather prediction (NWP) model winds accurately. Wave model results are compared to *in situ* surface buoys and ADCP wave data along Juan's track. At landfall, Juan's maximum waves are mainly swell-dominated and peak waves lag the occurrence of the maximum winds. We explore the influence of surface waves on the wind and show that the accuracy of the wave simulation is enhanced by introducing swell and Stokes drift feedback mechanisms to modify the winds, and by limiting the peak drag coefficient under high wind conditions, in accordance with recent theoretical and experimental results.

Xu, F. and W. Perrie, 2008, Spectral Properties of Cyclone-Generated Waves in Deep and Shallow Water, Volume 4: Ocean Engineering; Offshore Renewable Energy, 911-918, doi:10.1115/OMAE2008-57824

Juan is recorded as one of the most damaging storms in the modern history of Nova Scotia, Canada. In this paper, the spectral evolution characteristics of waves generated by hurricane Juan are studied, based on the observed 1D wave spectra along Juan's track in deep open ocean waters (buoy 44137) and the 2D wave spectra in shallow coastal waters at the directional waverider (DWR) location. Valuable results are obtained for cyclone-generated wave spectral properties, in both deep and shallow waters. In deep water, as illustrated at buoy 44137, the spectral variation, spectra pattern development, spectral peak frequency, cut-off frequency coefficient and high frequency spectral tail of the wave spectra are analyzed, before, during and after the cyclone's passing. Thus, the spectral variation characteristics during the entire cyclone processe are obtained. Properties of the high frequency spectral tail are discussed, using average frequency and peak frequency as the cut-off frequency parameters under different cut-off coefficient conditions, respectively. We suggest reasonable values for the cut-off frequency parameter. Cyclone-generated 2D wave spectra in shallow water (at DWR location) are investigated, shoaling effects, 2D spectral pattern variations, swell and wind waves spectral evolution. Our study shows the invalidity of presently accepted spectral formulae, in describing cyclone-generated waves.

9.2 Breaking Waves

Chen, Z., C. S. Zhan, K. Lee, Z. Li, and M. Boufadel, 2008, Modelling of Oil Droplet Kinetics Under Breaking Waves, *Oil Spill Response: A Global Perspective*, **4**: 221-236, doi:10.1007/978-1-4020-8565-9_30

A research program was initiated to develop numerical models to describe oil droplet formation and behaviour following oil spills at sea. Specifically, suitable models have been examined to quantify the energy requirement for the formation of oil droplets and their subsequent mixing and resurfacing. Wave energy dissipation rate (ε) is a critical parameter governing the evolution of spilled oil including its droplet size distribution, break-up, coalescence, dispersion, and

resurfacing. Four parameters influencing energy dissipation rate were considered, and one was selected for detailed study of oil droplet kinetics including related mixing and transport. Since previous experiments illustrated the evolution of oil droplets maintained under a constant wave energy level, a population model was used to account for the change of droplet size and distribution with time. It is expected that these study results will provide a fundamental understanding of the natural oil dispersion process and the exact nature of the fluid mechanics involved. This information will be used to formulate a standard procedure for testing available and new oil spill countermeasures.

Chen, Z., C.-S. Zhan, K. Lee, Z. Li, and M.C. Boufadel, 2009, Modeling oil droplet formation and evolution under breaking waves, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **31**(5): 438-448, doi:10.1080/15567030701531295

A research program was initiated to develop numerical models to describe oil droplet formation and behavior following oil spills at sea. Specifically, suitable models have been examined to quantify the energy requirement for the formation of oil droplets and their subsequent mixing and resurfacing. Wave energy dissipation rate is a critical parameter governing the evolution of spilled oil including its droplet size distribution, breakup, coalesce, and dispersion. Methods of computing the energy dissipation rate were researched, and one was selected for a detailed study of oil droplet kinetics. Additionally, a population model was developed to account for the evolution of oil droplets under typical wave energy levels. Preliminary validation of the proposed models, using a full-scale computer-controlled wave tank facility at the Centre for Offshore Oil and Gas Environmental Research (COOGER), showed good agreement between experimental data and predictions for mean oil droplet diameter under breaking wave conditions for time intervals of 1, 10, 60, and 300 min after the spill. A similar correlation was observed for oil concentration in the aqueous phase. Comparisons were also made to evaluate the influence of energy on oil droplet behavior in the presence of chemical dispersants. The study results will be used to formulate a standard procedure for developing new oil spill countermeasures.

Chen, Z., C. S. Zhan, and K. Lee, 2009, Formation and vertical mixing of oil droplets resulting from oil slick under breaking waves - a modeling study, *Environ. Forensics*, **10**: 347-353, doi:10.1080/15275920903347438

Oil spilled at sea can be dispersed by a variety of natural processes, of which the influence of breaking waves is dominant. In this study, formation and the subsequent vertical mixing of oil droplets with respect to low and high wave energy quantities are investigated through a coupled modeling approach. Methods of computing the energy dissipation rate for the field waves were extended to support the modeling of oil droplet kinetics, including related vertical mixing and transport. The developed method was first examined with literature data including an agreement with results reported in Delvigne and Sweeney (1988). Preliminary experimental validation was then conducted using a full-scale automated wave tank facility at the Centre for Offshore Oil and Gas Environmental Research

(COOGER, Dartmouth Canada); consistency has been observed between experimental data and model predictions for the mean oil droplet diameter under breaking wave conditions for time intervals of 1, 10, 60, and 300 minutes after the spill. Outputs of this research will be used to improve existing oil spill modeling tools and to formulate effective oil spill countermeasures.

Gemmrich, J. R., M. L. Banner and C. Garrett, 2008, Spectrally resolved energy dissipation and momentum flux of breaking waves, *J. Phys. Oceanogr.*, **38**: 1296-1312, doi:10.1007/978-3-540-36906-6_9

Breaking waves dissipate energy in the oceanic surface layer (top few meters) and also support the air-sea momentum flux. Spectrally resolved energy dissipation and momentum flux are extracted from open ocean observations of the breaking crest length distribution $\Lambda(c)$. This concept, first introduced by Duncan and Phillips more than 2 decades ago, includes an unknown proportionality factor b. Independent estimates of direct turbulence measurements are used to evaluate this proportionality factor.

Hwang, P. A., B. Zhang, J. V. Toporkov, and W. Perrie, 2010, Comparison of composite Bragg theory and quad-polarization radar backscatter from RADARSAT-2: With applications to wave breaking and high wind retrieval, *J. Geophys. Res.*, **115**, C08019, doi:10.1029/2009JC005995

Depolarized (de-pol) radar backscatter is now produced by many spaceborne satellites. Analysis of RADARSAT-2 (R2) quad-polarization (quad-pol) data with collocated in situ ocean wind measurements reveals that the de-pol radar backscatter does not saturate in high winds. This is a significant development for radar wind sensing, because wind retrieval with copolarized (co-pol) backscatter suffers from problems of incidence- and-azimuth-angle-dependent signal saturation and dampening in high winds. We present a study comparing satellite quad-pol measurements with the composite surface Bragg (CB) theory of radar backscattering from the ocean surface. The co-pol data are in good agreement with the CB theory. De-pol data are more sensitive to wind speed compared to theoretical prediction, thus retrieval of high winds is more accurate using the de-pol return. The cubic wind speed dependence of de-pol returns in high winds reflects the significant breaking wave contributions. The relationship can be used to obtain wave-breaking properties from space.

Hwang, P. A., B. Zhang, J. V. Toporkov, and W. Perrie, 2010, Correction to "Comparison of composite Bragg theory and quad-polarization radar backscatter from RADARSAT-2: With applications to wave breaking and high wind retrieval", *J. Geophys. Res.*, **115**, C11099, doi:10.1029/2010JC006653

no abstract; correction

In the paper "Comparison of composite Bragg theory and quad-polarization radar backscatter from RADARSAT-2: With applications to wave breaking and high wind retrieval" by P. A. Hwang et al. (*Journal of Geophysical Research*, *115*, C08019, doi:10.1029/2009JC005995) the coefficients in equation (11) are in

error. The correct equation for wind speed inversion from the depolarized radar return should be

$$U_{10} = \begin{cases} 5.1178 \times 10^{-3} q^2 + 1.6664 q + 54.235, & 20^\circ \le \theta \le 30^\circ \\ -2.6444 \times 10^{-2} q^2 - 1.3433 \times 10^{-2} q + 33.106, & 30^\circ < \theta \le 40^\circ \end{cases}, \quad (11)$$

where U_{10} is reference wind speed at 10 m elevation, q the C band depolarized radar return in dB, $q = \sigma_{0HV}^{dB}$, and θ the radar incidence angle.

Lamb, K. G., O. Polukhina, T. Talipova, E. Pelinovsky, W. Xiao, and A. Kurkin, 2007, Breather Generation in Fully Nonlinear Models of a Stratified Fluid, *Phys. Rev. E.*, **75**(4), doi:10.1103/PhysRevE.75.046306

Nonlinear wave motion is studied in a symmetric, continuously stratified, smoothed three-layer fluid in the framework of the fully nonlinear Euler equations under the Boussinesq approximation. The weakly nonlinear limit is discussed in which the governing equations can be reduced to the fully integrable modified Korteweg–de Vries equation. For some choices of the layer thicknesses the cubic nonlinear term is positive and the modified Korteweg–de Vries equation has soliton and breather solutions. Using such a stratification, the Euler equations are solved numerically using a sign-variable, initial disturbance. Breathers were generated for several forms of the initial disturbance. The breathers have moderate amplitude and to a good approximation can be described by the modified Korteweg–de Vries equation. As far as we know this is the first presentation of a breather in numerical simulations using the full nonlinear Euler equations for a stratified fluid.

Lamb, K. G., 2008, On the calculation of the available potential energy of an isolated perturbation in a density stratified fluid, *J. Fluid Mech.* **597**: 415-427, doi:10.1017/S0022112007009743

Two methods for calculating the available potential energy (APE) of an isolated feature in a density-stratified fluid, such as an internal solitary wave or an eddy, are compared. The first formulation calculates the APE by integrating the perturbation potential energy density E_w. The second uses an available potential energy density E_a. Both formulations are based on the reference density obtained by adiabatically rearranging the density field to a state of minimum energy. It is shown, under more general conditions than used previously, that (i) the integrals of E_w and E_a over a finite domain are identical; and (ii) that for an isolated feature in an unbounded domain, the far-field density $\bar{\rho}(z)$ can be used as the reference density if E_a is used to find the APE. This is not the case when E_w is used, hence use of the available potential energy density formulation is simpler in this situation.

Rojas, G., and M. R. Loewen, 2010, Void fraction measurements beneath plunging and spilling breaking waves, *J. Geophys. Res.*, **115**, C08001, doi:10.1029/2009JC005614

The temporal and spatial variations of the void fraction fields beneath deepwater breaking waves were investigated in the laboratory. There were a total of 13 measurement positions along the plunging wave; the peak void fractions

measured varied from 0.024 to 0.96 and the time-averaged void fractions varied from 0.012 to 0.37. For the spilling wave, there were four measurement positions, and the mean void fractions varied from 0.17 to 0.29. It was found that an energetic spilling breaker may entrain approximately the same volume of air as a steeper, larger-amplitude plunging breaker. The speed of advance of the air cavity entrained beneath the plunging wave was estimated to be 70% of the phase speed of the breaking wave. The speed of the third bubble cloud entrained by the splash-up was found to be approximately 90% of the phase speed. Beneath the spilling breaker, the speed of advance of the bubble cloud was estimated to be 100% of the phase speed. These measurements have lead to the identification of four significant events during the breaking of a plunging wave: the plunging water jet impacting the forward face of the wave, the air cavity collapse, the splash-up impact on the forward wave face, and the location and timing of the peak void fraction in the splashing zone. Numerical models of plunging breakers should be able to accurately predict the timing and nature of these events.

9.3 Rogue Waves

Garrett, C. and J. Gemmrich, 2009, Rogue waves, (Quick study), *Physics Today*, **62**(6): 57-59, http://ptonline.aip.org/journals/doc/PHTOAD-ft/vol_62/iss_6/62_1.shtml?bypassSSO=1

no abstract

Rich and challenging physics lies behind the gigantic ocean waves that seem to appear without warning to damage ships or sweep people off rocky shores.

Media accounts often portray rogue, or freak, waves in dramatic terms. *New Scientist* proclaimed on 30 June 2001, "It came from nowhere, snapping giant ships in two." Tales of such monsters of the deep give the impression that the waves are huge and unpredictable. In this Quick Study, we address two basic questions. First, what causes rough seas with large ocean waves? Second, for a given sea state (a general term used to describe the surface roughness), do extra-large waves occur more frequently than random superposition of different wave trains would predict?

Gemmrich, J. and C. Garrett, 2008, Unexpected waves, *J. Phys. Oceanogr.*, **38**: 2330-2336, doi:10.1175/2008JPO3960.1

Extreme, or "rogue," waves are those in the tail of the probability distribution and are a matter of great concern and considerable research. They may be partly associated with non-Gaussian behavior caused by resonant nonlinear interactions. Here it is shown that even in a Gaussian sea, "unexpected" waves, in the sense of, for example, waves twice as large as any in the preceding 30 periods, occur with sufficient frequency to be of interest and importance. The return period of unexpected waves is quantified as a function of the height multiplier and prior quiescent interval for various spectral shapes, and it is shown how the return period is modified if allowance is made for nonlinear changes in wave shape and/or a buildup of one or more waves prior to the unexpected wave. The return

period of "two-sided" unexpected waves, with subsequent as well as prior quiescence, is also evaluated.

Gemmrich, J. and C. Garrett, 2010, Unexpected waves: Intermediate depth simulations and comparison with observations, *Ocean Eng.*, **37**(2-3): 262-267 doi:10.1016/j.oceaneng.2009.10.007

In an earlier study, we defined an "unexpected wave" as, for example, a wave twice as high as any of the preceding 30 waves. Here we extend earlier deep water simulations to allow for the greater crest enhancement in water of finite depth and find that the predicted frequency of unexpected waves increases significantly. We also analyze data obtained by wave buoys off the east and west coasts of Canada. In both deep and intermediate depth water, the occurrence of unexpected waves is in reasonable accord with our simulations, supporting our assumption of random superposition of waves though with local crest enhancement by the non-resonant second harmonic.

9.4 Nonlinear Internal Waves

Ansong, J. K. and B. R. Sutherland, 2010, Internal gravity waves generated by convective plumes, *J. Fluid Mech.*, **648**: 405-434, doi:10.1017/S0022112009993193

We present experimental results of the generation of internal gravity waves by a turbulent buoyant plume impinging upon the interface between a uniform density layer of fluid and a linearly stratified layer. The wave field is observed and its properties are measured non-intrusively using axisymmetric Schlieren. In particular, we determine the fraction of the energy flux associated with the plume at the neutral buoyancy level that is extracted by the waves. On average, this was found to be approximately 4%. Within the limits of the experimental parameters, the maximum vertical displacement amplitude of waves were found to depend linearly upon the maximum penetration height of the plume beyond the neutral level. The frequency of the waves was found to lie in a narrow range relative to the buoyancy frequency. The results are used to interpret the generation of waves in the atmosphere by convective storms impinging upon the tropopause via the mechanical oscillator effect.

Boegman, L. and G. N. Ivey, 2009, Flow separation and resuspension beneath shoaling nonlinear internal waves, *J. Geophys. Res.*, **114**, C02018, doi:10.1029/2007JC004411

Laboratory observations are presented showing the structure and dynamics of the turbulent bottom boundary layer beneath nonlinear internal waves (NLIWs) of depression shoaling upon sloping topography. The adverse pressure gradient beneath the shoaling waves causes the rear face to steepen, flow separation to occur, and wave-induced near-bottom vortices to suspend bed material. The resuspension is directly attributed to the near-bed viscous stress and to near-bed patches of elevated positive Reynolds stress generated by the vortical structures. These results are consistent with published field observations of resuspension events beneath shoaling NLIWs. Elevated near-bed viscous stresses are found throughout the domain at locations that are not correlated to the resuspension events. Near-bed viscous stress is thus required for incipient sediment motion but

is not necessarily a precursor for resuspension. Resuspension is dependent on the vertical velocity field associated with positive Reynolds stress and is also found to occur where the mean (wave-averaged) vertical velocity is directed away from the bed. The results are interpreted by analogy to the eddy-stress and turbulent bursting resuspension models developed for turbulent channel flows.

Brown, G. L. and B. R. Sutherland, 2007, Internal Wave Tunnelling Through Non-uniformly Stratified Shear Flow, *Atmos.-Ocean*, **45**(1): 47–56, doi:10.3137/ao.v450104

We examine the transmission of internal gravity waves through a non-uniformly stratified fluid with vertically varying background shear. To quantify wave transmission we show that the appropriate measure is the ratio of the flux of transmitted to incident pseudoenergy, T. We derive an analytic prediction of T for the transmission of waves through a piecewise-linear shear flow in two cases. In both, the fluid is unstratified over the depth of the shear and uniformly stratified elsewhere. In one study, the density profile is continuous. Such a basic state is unstable but with vanishingly small growth rate as the bulk Richardson number, Ri, becomes large. In the limit of an infinitely large Richardson number (no shear), we recover the tunnelling prediction of Sutherland and Yewchuk (2004). In weak shear, incident waves can transmit weakly, even if the phase speed matches the flow speed within the shear layer (a critical level). However, no transmission occurs when the phase speed of incident waves exactly matches the flow speed on the opposite flank of the shear. In strong shear, with Ri $\approx$ 1, a transmission peak occurs where the incident wavenumber and frequency are close to, but different from, those associated with unstable modes. In a second study, the background density profile is discontinuous and representative of a well-mixed patch within a once uniformly stratified fluid. In this case, no transmission occurs for incident waves with phase speed matching the speed of the flow within the shear layer. However, a transmission spike occurs if the incident waves are resonant with interfacial waves that flank the shear.

Fouli, H. and D. Z. Zhu, 2008, Transition of Two-Layer Stratified Flow from the Slope of Bottom Topography to a Horizontal Channel, *Atmos.-Ocean*, **46**(4): 391–404 doi:10.3137/AO928.2008

An experimental study was conducted to investigate the transition of two-layer stratified flow from the slope of bottom topography to a horizontal channel. Three experiments, with a reduced gravity of $g' = 1.64$, 6.47 and 18.0 cm s–2, were performed. Particle image velocimetry and planar laser-induced fluorescence were used to obtain the measurements of velocity and concentration fields. The flow rate, obtained from the measured velocity field, increases significantly toward the toe of the topography by almost 40% from that at the sill crest due to the interfacial wave activities. In the horizontal channel, however, the flow rate only increases marginally. Estimates of the composite Froude number indicate that the supercritical flow on the slope of the topography goes through the transition to the subcritical flow in the horizontal channel. The transition is mainly due to the increase in the lower-layer thickness because of increasing interfacial friction caused by the breaking of interfacial waves, and no internal hydraulic

jumps are observed. The measured mean concentration field showed the formation of an intermediate layer of medium density, which increased its thickness with g' and helped to suppress turbulence. Spectral analysis of the density interfacial fluctuations indicated that the interfacial waves that developed on the slope of the topography broke up downstream of the toe into smaller amplitude waves at larger frequencies. The waves at several channel cross-sections were also examined.

Gregory, K. D. and B. R. Sutherland, 2010, Transmission and reflection of internal wave beams, *Phys. Fluids*, **22**(10), 106601, doi:10.1063/1.3486613

An existing method for predicting the partial transmission of plane internal gravity waves across a weakly stratified region is adapted so as to predict the transmission of internal wave beams having finite horizontal and vertical extent. The results are compared with laboratory experiments in which internal waves generated by an oscillating cylinder are incident upon a mixed region of varying depth and stratification. The results are in good agreement except when the characteristic frequency of the beam is close to the minimum buoyancy frequency of the weakly stratified mixed region. In this case, the predicted transmission coefficient varies rapidly with frequency and so is sensitive to small measurement errors. Applications of this method to atmospheric and oceanic internal waves are discussed.

Holdsworth, A. M., S. Décamp, and B. R. Sutherland, 2010, The axisymmetric collapse of a mixed patch and internal wave generation in uniformly stratified fluid, *Phys. Fluids*, **22**(10), doi:10.1063/1.3489124

Laboratory experiments are used to investigate the axisymmetric collapse of a localized mixed region in uniformly stratified ambient. The collapsing fluid forms an intrusion and generates vertically propagating internal gravity waves in the stratified ambient. The speed of the intrusion is found to be $(0.085\pm0.001)\ N_0H_m$ where H_m is the depth of the mixed patch and N_0 is the buoyancy frequency. Internal wave frequencies are set by the buoyancy frequency, ($\omega \simeq 0.8N_0$), and the effective horizontal wavenumber is set by the radius of the cylinder so that $k_r \simeq 2R_c$. Vertical displacement amplitudes scale with the depth of the mixed patch according to $|\xi|/(H_m/2) = 0.032\pm0.002$ and we find that about 2% of the available potential energy of the mixed region is extracted by the internal waves. Extrapolation of these results to oceanic circumstances of mixed region collapse beneath a hurricane gives a conservative estimate of the power extracted by internal waves during the lifecycle of the storm is estimated to range from 6×10^{10} to 4×10^{12}W. The corresponding power from all hurricanes averaged over the course of a year can range from 1×10^{9} to 8×10^{9}W.

Korobov, A. and K. G. Lamb, 2008, Interharmonics in internal gravity waves generated by tide-topography interaction, *J. Fluid Mech.* **611**: 61-95, doi:10.1017/S0022112008002449

The dynamics and spectrum of internal gravity waves generated in a linearly stratified fluid by tidal flow over a flat-topped ridge are investigated at five

different latitudes using an inviscid two-dimensional numerical model. The resulting wave field includes progressive freely propagating waves which satisfy the dispersion relation, and forced waves which are trapped non-propagating oscillations with frequencies outside the internal wave band. The flow is largely stable with respect to shear instabilities, and, throughout the runs, there is a negligibly small amount of overturning which is confined to the highly nonlinear regions along the sloping topography and where tidal beams reflect from the boundaries. The wave spectrum exhibits a self-similar structure with prominent peaks at tidal harmonics and interharmonics, whose magnitudes decay exponentially with frequency. Two strong subharmonics are generated by an instability of tidal beams which is particularly strong for near-critical latitudes where the Coriolis frequency is half the tidal frequency. When both subharmonics are within the free internal wave range (as in cases 0°–20° N), they form a resonant triad with the tidal harmonic. When at least one of the two subharmonics is outside of the range (as in cases 30°–40° N) the observed instability is no longer a resonant triad interaction. We argue that the two subharmonics are generated by parametric subharmonic instability that can produce both progressive and forced waves. Other interharmonics are produced through wave–wave interactions and are not an artefact of Doppler shifting as assumed by previous authors. As the two subharmonics are, in general, not proper fractions of the tidal frequency, the wave–wave interactions are capable of transferring energy to a continuum of frequencies.

Lamb, K. G., 2007, Energy and pseudoenergy flux in the internal wave field generated by tidal flow over topography, *Cont. Shelf Res.*, **27**(9): 1208-1232, doi:10.1016/j.csr.2007.01.020

The mechanical energy and pseudoenergy budgets in the internal wave field generated by tidal flow over topography is considered using a nonlinear, two-dimensional numerical model. The Boussinesq and rigid lid approximations are made, viscosity and diffusion are ignored and the flow is treated as incompressible. Both ridge and bank edge topographies are considered. The nonlinear energy equation and an equation for pseudoenergy (kinetic energy plus available potential energy) are satisfied to within less than 1%. For a uniform stratification (constant buoyancy frequency N) the available potential energy density is identical to the linear potential energy density $\frac{1}{2}(g^2/N^2)\tilde{\rho}_d^2$ where $\tilde{\rho}_d$ is the density perturbation. For weak tidal flow over a ridge in the deep ocean, using a uniform stratification, the generated waves are small, approximately 2% of the water depth, and the traditional expression for the energy flux, $\langle \tilde{u}\tilde{p}_d \rangle$ accurately gives the pseudoenergy flux. For a case with strong tidal flow across a bank edge, using a non-uniform stratification, large internal solitary waves are generated. In this case, the linear form of the potential energy is very different from the available potential energy and the traditional energy flux term $\langle \tilde{u}\tilde{p}_d \rangle$ accounts for only half of the pseudoenergy flux. Fluxes of kinetic and available potential energy are comparable to the traditional energy flux term and hence must be included when estimating energy fluxes in the internal wave field.

Mirshak, R. and D. E. Kelley, 2009, Inferring propagation direction of nonlinear internal waves in a vertically sheared background flow, *J. Atmos. Oceanic Technol.,* **26**: 615–625, doi:10.1175/2008JTEC0632.1

Internal waves heave the background flow through which they propagate. If the background flow is vertically sheared, the high-pass-filtered velocity field will thus contain signals of both the wave velocity and the heaved flow. Under conditions of large wave amplitude and large background shear—a common situation for nonlinear internal waves in coastal waters—the velocity fluctuations caused by wave heaving of the background flow can be comparable to the wave velocity itself. This complicates the inference of wave properties such as energy flux and propagation direction. The present study deals with methods to infer propagation direction in such situations. Attention is given to three methods that may be applied to acoustic Doppler current profiler measurements: a "filtering" method that estimates wave signals from high-pass-filtered time series, a "beamwise" method that infers wave direction from lagged correlations of echo intensity between the spatially separated acoustic beams of the profiler, and a "modal" method that separates background and wave signals by regressing the high-pass-filtered velocity field onto a normal-mode wave model. The methods are tested using synthetic datasets. The results suggest that the filtering method is biased by wave heaving of the background shear, while the beamwise and modal methods are resistant to heaving. The beamwise method provides accurate predictions of wave propagation angle for cases in which the measurements have high temporal resolution and the environment exhibits no depth-averaged background flow. The limitation on depth-averaged flow is relaxed for the modal method, but it requires the measurement of stratification. These issues are illustrated, and the applicability of these methods is explored with a series of sensitivity tests, and it is found that the different methods perform well under different circumstances.

Munroe, J. R. and B. R. Sutherland, 2008, Generation of internal waves by sheared turbulence: experiments, *Env. Fluid Mech.,* **8**(5-6): 527-534, doi:10.1007/s10652-008-9094-3

A series of experiments is presented that model the generation of internal gravity waves in the ocean by the forcing of turbulent eddies in the surface mixed layer. The experimental setup consists of a shallow mixed upper layer and a deep continuously stratified lower layer. A source of turbulence is dragged through the upper layer. Internal waves can freely propagate in the lower layer. The internal waves are measured using synthetic schlieren to determine the frequencies of the generated waves. Consistent with other studies, it is found that the characteristic frequencies of internal waves generated by turbulence are an approximate constant fraction of the buoyancy frequency.

Nault, J. T. and B. R. Sutherland, 2007, Internal wave transmission in nonuniform flows, *Phys. Fluids*, **19**(1), 016601, doi:10.1063/1.2424791

We compute transmission coefficients for internal waves propagating in a fluid with continuously varying stratification and background shear. In stationary fluid

the transmission is characterized by the ratio of transmitted to incident energy. More generally, transmission across the shear is appropriately characterized by the ratio of transmitted to incident pseudoenergy flux. First, we examine the transmission and reflection of internal waves incident upon a weakly stratified layer in stationary fluid focusing upon the opposing limits of piecewise-linear theory and a heuristic application of Wentzel-Kramers-Brillouin (WKB) theory. We find the WKB prediction is reasonably accurate if the distance of transition from strong to weak stratification is as small as one sixth the vertical wavelength of the transmitted waves. In the limit of infinitesimally small transition distances the prediction of piecewise-linear theory is reproduced. Second, we consider the transmission of internal waves across a shear layer which initially is uniformly stratified. In particular, we show that significant transmission is possible across critical layers if the minimum gradient Richardson number is less than 1/4. Finally, we show that internal waves can partially transmit across a mixed region that results from the evolution of an unstable shear layer. Transmission across critical layers occurs for waves whose horizontal phase speed matches the background flow speed at levels where the gradient Richardson number is less than 1/4.

Clark, H. and B. Sutherland, 2009, Schlieren measurements of internal waves in non-Boussinesq fluids, *Exp. Fluids*, **47**(2): 183-193, doi:10.1007/s00348-009-0648-z

Previous experiments that have examined the generation of internal gravity waves by a monochromatic source have been restricted to small amplitude forcing in Boussinesq stratified fluids. Here we present measurements of internal waves generated by a circular cylinder oscillating at large amplitude in a non-Boussinesq fluid. The `synthetic schlieren' optical measurement technique (Sutherland et al. in J Fluid Mech 390:93-126, 1999) is extended to stratifications in which the index of refraction of the fluid may vary nonlinearly with density. The method is applied to examine disturbances in approximately uniformly stratified ambient fluids consisting either of sodium chloride (NaCl) or sodium iodide (NaI) solutions whose concentrations increase to near-saturation at the bottom of the tank. In particular, we report upon the first extensive measurements of the optical properties of NaI solutions as they depend upon concentration and density. Applying the results to experiments, we find that large amplitude forcing generates a patch of oscillatory turbulence surrounding the cylinder, thereby increasing the effective cylinder size and decreasing the amplitude of the waves in comparison with the predictions of linear theory. We parameterize the influence of the turbulent boundary layer in terms of an effective cylinder radius and forcing amplitude.

Stastna, M. and K. G. Lamb, 2008, Sediment resuspension mechanisms associated with internal waves in coastal waters, *J. Geophys. Res.*, **113**, C10016, doi:10.1029/2007JC004711

Large-amplitude, vertically trapped internal waves can induce sizable velocities and trigger hydrodynamic instabilities in the bottom boundary layer, thereby contributing to the resuspension of sediments and the maintenance of sediment

concentration in the water column. We discuss numerical simulations of several different situations in which the boundary layer in the wave footprint undergoes hydrodynamic instability, with a resultant increase in the incidence of spatiotemporal structures that could facilitate sediment resuspension. For the case of internal solitary waves we provide bounds in parameter space separating regions in which internal waves can be expected to efficiently resuspend sediment from those in which the boundary layer in the wave footprint is both laminar and stable. A notable finding is that the onset of instability is a strong function of the background current. The Lagrangian transport of passive particles due to the instability is explored, and some quantitative measures of the efficiency of the particle transport process are provided. We subsequently discuss the evolution of the power spectra of the bottom shear stress with time and find that while the general characteristics of the instability are robust, lowering either the Reynolds number or the strength of the background current leads to an increase in the typical length scales associated with the mature instability. Finally, we discuss instabilities during the internal wave generation process and alternative instability mechanisms when the bottom is not flat.

9.5 Remote Sensing of Waves

Cheel, R. A. and A. E. Hay, 2008, Cross-ripple patterns and wave directional spectra, *J. Geophys. Res.*, **113**, C10009, doi:10.1029/2008JC004734

Rotary sonar images of the seafloor during SandyDuck97 are used to investigate the geometry of the cross-rippled bed state relative to the directional properties of the incident waves. The sonar imagery indicates that the cross-ripple pattern is a quasi-regular diamond-shaped lattice constructed of variable length ladder-like tiles, each with shorter-wavelength ripples residing within the troughs of the longer-wavelength component. The longer-wavelength crests were oriented at approximately ±30° with respect to the incident wave direction. Most wave directional spectra were not bimodal in direction and, for the small number (17%) which were, the distribution of the angular separations of the two peaks was very broad and indicated no preferred value. Thus, contrary to some previous suggestions in the literature, these results indicate not only that cross ripples do not require waves propagating from two different directions for their formation but also that for most of the occurrences during this experiment, cross ripples formed when the incident wave field was unimodal in direction. Finally, the orientation angles of the long-crested ripple components exhibit no dependence on mean current velocity.

Maier, I. and A. E. Hay, 2009, Occurrence and orientation of anorbital ripples in near-shore sands, *J. Geophys. Res.*, **114**, F04022, doi:10.1029/2008JF001126

The orientation of linear transition ripples (LTRs) relative to incident wave direction is studied using rotary fan beam sonar images and wave and current data from electromagnetic flowmeters in ~3 m water during SandyDuck97. LTR occurrence is determined objectively with an automatic recognition algorithm. LTRs occurred for RMS wave orbital velocities between 0.15 and 0.35 m s^{-1}. The

ripples were highly two dimensional, and of the anorbital type (λ_0/D_{50} = 524 to 535, d_0/D_{50} = 4300 to 25,000) with 7.6 cm mean wavelength in 150 μm median diameter sand. The ripple crests were typically aligned perpendicular to the incident sea-and-swell direction: specifically, about 60% of the normals to the crests differ from wave direction by less than 5° and more than 90% by less than 10°. During rapid changes in wave direction, however, ripple orientation adjustment lagged the wave direction by O(1 h). Ripple reorientation occurred piecewise along the crests, with new crest segments sometimes bridging two or more old segments. The 1 h reorientation time scale is longer by several orders of magnitude than the adjustment time based on theoretical bed load transport rate and the ripple volume. As a possible explanation, we suggest that a significant fraction of the transport, more than 90%, bypasses the ripples during orientation adjustment through large angles.

Zhang, B., W. Perrie, and Y. He, 2009, Remote sensing of ocean waves by along-track interferometric synthetic aperture radar, *J. Geophys. Res.*, **114**, C10015, doi:10.1029/2009JC005310

A new wave retrieval method for the Along-Track Interferometric Synthetic Aperture Radar (AT-InSAR) phase image is presented. The new algorithm, named parametric retrieval algorithm (PRA), uses the full nonlinear mapping relations. It differs from previous retrieval algorithms in that it does not require a priori information about the sea state or the wind vector from scatterometer data. Instead, it combines the observed AT-InSAR phase spectrum and assumed wind vector to estimate the wind sea spectrum. The method has been validated using several C-band and X-band HH-polarized AT-InSAR observations collocated with spectral buoy measurements. In this paper, X-band and C-band HH-polarized AT-InSAR phase images of ocean waves are first used to study AT-InSAR wave imaging fidelity. The resulting phase spectra are quantitatively compared with forward-mapped in situ directional wave spectra collocated with the AT-InSAR observations. Subsequently, we combine the parametric retrieval algorithm (PRA) with X-band and C-band HH-polarized AT-InSAR phase images to retrieve ocean wave spectra. The results show that the ocean wavelengths, wave directions, and significant wave heights estimated from the retrieved ocean wave spectra are in agreement with the buoy measurements.

Zhang, B., W. Perrie, and Y. He, 2010, Validation of RADARSAT-2 fully polarimetric SAR measurements of ocean surface waves, *J. Geophys. Res.*, **115**, C06031, doi:10.1029/2009JC005887

C band RADARSAT-2 fully polarimetric (fine quad-polarization mode, HH+VV+HV+VH) synthetic aperture radar (SAR) images are used to validate ocean surface waves measurements using the polarimetric SAR wave retrieval algorithm, without estimating the complex hydrodynamic modulation transfer function, even under large radar incidence angles. The linearly polarized radar backscatter cross sections (RBCS) are first calculated with the copolarization (HH, VV) and cross-polarization (HV, VH) RBCS and the polarization orientation angle. Subsequently, in the azimuth direction, the vertically and

linearly polarized RBCS are used to measure the wave slopes. In the range direction, we combine horizontally and vertically polarized RBCS to estimate wave slopes. Taken together, wave slope spectra can be derived using estimated wave slopes in azimuth and range directions. Wave parameters extracted from the resultant wave slope spectra are validated with colocated National Data Buoy Center (NDBC) buoy measurements (wave periods, wavelengths, wave directions, and significant wave heights) and are shown to be in good agreement.

9.6 Miscellaneous Wave Studies

Carpenter, J. R. , E. W. Tedford, M. Rahmani, and G. A. Lawrence, 2010, Holmboe wave fields in simulation and experiment, J. Fluid Mech., **648**: 205-223 doi:10.1017/S002211200999317X

The basic wave field resulting from Holmboe's instability is studied both numerically and experimentally. Comparisons between the direct numerical simulations (DNS) and laboratory experiments result in Holmboe waves that are similar in their appearance and phase speed. However, different boundary conditions result in mean flows that display gradual variations either temporally (in the simulations) or spatially (in the experiments). These differences are found to affect the evolution of the dominant wavenumber and amplitude of the wave field. The simulations exhibit a nonlinear 'wave coarsening' effect, whereby the energy is shifted to lower wavenumbers in discrete merging events. This process is typically found to result from either ejections of mixed fluid away from the density interface or vortex pairing. In the experiments, energy is transferred to lower wavenumbers by the 'stretching' of the wave field by a gradually varying mean velocity. This stretching results in a reduction of wave amplitude compared with the DNS.

Carton, X., F. J. Poulin, and M. Pavec, 2010, Linear baroclinic and parametric instabilities of boundary currents in a two-layer model, *Geophys. Astrophys. Fluid Dyn.*, doi:10.1080/03091929.2010.490556

The linear baroclinic and parametric instabilities of boundary currents with piecewise-constant potential vorticity are studied in a two-layer quasi-geostrophic model. The growth rates of both the exponential modes and of the optimal perturbations are calculated for the baroclinic instability of steady coastal currents. We show that the growth rates of the exponential modes are maximal for a vertically symmetric flow. Furthermore, the vertical asymmetries induced by different layer thicknesses, the presence of a barotropic potential vorticity or bottom topography, all act to dampen the growth rates and favor growth at shorter wavelengths. It is shown that this behavior can be predicted from the conditions for vertical resonance of Rossby waves on the two potential vorticity fronts. Also, the baroclinic instability of the optimal perturbations has larger growth rates at shorter wavelengths and shorter time scales. As well, the presence of a sloping bottom of moderate amplitude favors the growth of these optimal perturbations. Finally, we compute the growth rates of parametric instability of oscillatory coastal flows. We show that subharmonic resonance is the most unstable mode of growth. In addition, a second region of parametric instability is found (for the first

time) away from marginality of exponential-mode baroclinic instability. It is shown that the functional dependency of the growth rates of parametric instability, for optimal excitation, are similar to that of the optimal perturbations of baroclinic instability. To explain this a mechanism for parametric instability, involving the rapid growth of short-wave optimal perturbations, is proposed.

Mullarney, J. C., A. E. Hay, and A. J. Bowen, 2008, Resonant modulation of the flow in a tidal channel, *J. Geophys. Res.*, **113**, C10007, doi:10.1029/2007JC004522

The coupling between a quarter-wave resonance in a coastal bay and a Helmholtz mode in an adjacent cove (connected to the bay through a narrow channel) is investigated by comparing field measurements to analytical and numerical model predictions. Pressure and velocity spectra from locations throughout the bay reveal an oscillation with a period of approximately 1 hour, consistent with a quarter-wave seiche mode. The associated sea surface displacements throughout the bay are small (less than 5 cm RMS, i.e., only 10% of the tidal elevation). Velocities within the channel are significantly modulated in the 1-hour band, with amplitudes up to 40% of the peak tidal current. The analytical model shows that the modulation of the channel flow results from the interaction between the quarter-wave mode in the main basin and a Helmholtz resonance in the cove, also with a period near 1 hour. The amplitude and phase of the 1-hour oscillation varies through the tidal cycle because of the change in Helmholtz frequency with tidal elevation. Good quantitative agreement between the data and the model predictions is obtained if a drag coefficient approximately 3–4 times larger than the classical value of 3×10^{-3} is used in the channel and cove.

Mulligan, R. P., A. E. Hay, and A. J. Bowen, 2010, A wave-driven jet over a rocky shoal, *J*. Geophys. Res., **115**, C10038, doi:10.1029/2009JC006027

Field observations and model simulations are presented of flow generated by waves breaking over a shoal at the entrance to a shallow bay. The shoal is composed of a series of steep and narrow bedrock ridges with depths of 2–8 m at the ridge crests. Observations from instruments on the shoal indicated peak significant wave heights during a storm event were 2.4–4.0 m across the observation sites; this spatial variability is due to wave breaking over the ridges. The 2-D depth-averaged hydrodynamic model Delft3D, coupled to the wave model SWAN, was used to simulate the waves and wave-driven flow over the shoal and throughout the entire bay with a nested fine grid (5 m resolution) to resolve the shoal bathymetry. The model predicts a well-defined jet behind the shoal, with mean axial speeds of 0.4–0.7 m/s. The observations indicate maximum speeds behind the shoal of 0.3–0.4 m/s, exceeding the maximum tidal current speed by more than a factor of 4, that are consistent in timing and direction with the model predictions. The model overpredicts wave breaking over the steep slopes and as a result the current speeds are overestimated.

Perrie, W. and D. T. Resio, 2009, A Two-Scale Approximation for Efficient Representation of Nonlinear Energy Transfers in a Wind Wave Spectrum. Part II:

Application to Observed Wave Spectra, *J. Phys. Oceanogr.*, **39**, 2451–2476, doi:10.1175/2009JPO3947.1

In Part I of this series, a new method for estimating nonlinear transfer rates in wind waves, based on a two-scale approximation (TSA) to the full Boltzmann integral (FBI) for quadruplet wave–wave interactions, was presented, and this new method was tested for idealized spectral data. Here, the focus is on comparisons of the TSA and the discrete interaction approximation (DIA) with the FBI for observed wave spectra from field measurements. Observed wave spectra are taken from a wave gauge array in Currituck Sound and a directional waverider off the coast near the Field Research Facility at Duck, North Carolina. Results show that the TSA compares much more favorably to the FBI than does the DIA, even for cases in which the parametric component of the formulation does not capture the spectral energy distribution very well. These results remain valid for the TSA estimates when the FBI results are significantly affected by the directional distribution of energy. It is also shown that although nonlinear transfers are substantially weaker in swell portions of the spectrum these interactions contribute significantly to the spectral evolution and net energy balance in long-distance swell propagation.

Perrie, W., A. Susilo, and B. Toulany, 2010, A new approximation for nonlinear wave–wave interactions, *Ocean Modelling*, **33**(1-2): 159-176, doi:10.1016/j.ocemod.2009.12.009

Modern wave models require an accurate computation of the nonlinear wave–wave interactions. This is because nonlinear wave–wave interactions play an important role in the evolution of wind waves, accounting for nonlinear transfer of wave energy to lower and higher frequencies within the spectrum. Presently, in almost all operational state-of-the-art wave models, nonlinear transfer due to wave–wave interactions are evaluated by the discrete interaction approximation (DIA), which was developed by pioneering studies led by Hasselmann more than two decades ago. Although many efforts have tried to develop new methodologies to improve DIA, its basic formulation has not changed. In this study, we present a new computational method by evaluating the dominant nonlinear wave transfer along the wavenumber and the wave directional axes, and by approximating the contributions along the resonance loci. The new method is denoted the Advanced Dominant Interaction (AvDI) method. We show that AvDI is sufficiently efficient that it can be implemented within an operational wave model. As a validation of the approach, we compare simulations of hurricane Juan with observed wave data.http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VPS-4Y4PVTM-1&_user=10&_coverDate=12%2F31%2F2010&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_searchStrId=1680246764&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=fde1e5d4e6c9ce0bc063afdb21a9cfa5&searchtype=a - aff1

Resio, D. and W. Perrie, 2008, A two-scale approximation for efficient representation of nonlinear energy transfers in a wind wave spectrum. Part 1: Theoretical Development, *J. Phys. Oceanogr.*, **38**(12): 2801-2816, doi:10.1175/2008JPO3713.1

A new method for estimating the transfer rates in wind wave spectra is derived and tested, based on a two-scale approximation (TSA) to the total integral for quadruplet wave–wave interactions. Comparisons of this new estimation method to the full integral are given for several idealized spectra, including Joint North Sea Wave Project spectra with different peakednesses, a finite depth case, and cases with perturbations added to underlying parametric spectra. In particular, these comparisons show that the TSA is a significant improvement over the discrete interaction approximation (DIA) in deep water and an even greater improvement in shallow water.

Wang, X. L., V. R. Swail, F. W. Zwiers, X. Zhang, and Y. Feng, 2009, Detection of external influence on trends of atmospheric storminess and northern ocean wave heights, *Clim. Dyn.*, **32**: 189–203, doi:10.1007/s00382-008-0442-2

The atmospheric storminess as inferred from geostrophic wind energy and ocean wave heights have increased in boreal winter over the past half century in the high-latitudes of the northern hemisphere (especially the northeast North Atlantic), and have decreased in more southerly northern latitudes. This study shows that these trend patterns contain a detectable response to anthropogenic and natural forcing combined. The effect of external influence is found to be strongest in the winter hemisphere, that is, in the northern hemisphere in January–March and in the southern hemisphere in July–September. However, the simulated response to anthropogenic and natural forcing combined, which was obtained directly from climate models in the case of geostrophic wind energy and indirectly via an empirical downscaling procedure in the case of ocean wave heights, is significantly weaker than the magnitude of the observed changes in these parameters.

Yong, H., Y. Baoshu, W. Perrie, and H. Yijun, 2008, Responses of summertime extreme wave heights to local climate variations in the East China Sea, *J. Geophys. Res.*, **113**, C09031, doi:10.1029/2008JC004732

We detected the responses of summertime extreme wave heights (H_{top10}, average of the highest 10% of significant wave heights in June, July and August) to local climate variations in the East China Sea by applying an empirical orthogonal function analysis to H_{top10} derived from the WAVEWATCH-III wave model driven by 6 hourly sea surface wind fields from ERA-40 reanalysis over the period 1958–2002. Decreases in H_{top10} in the northern East China Sea (Yellow Sea) correspond to attenuation of the East Asian Summer Monsoon, while increases in the south are primarily due to enhancement of tropical cyclone activities in the western North Pacific.

9.7 Rossby Waves

Poulin, Francis J., Kristopher Rowe, 2008: On "A Consistent Theory for Linear Waves of the Shallow-Water Equations on a Rotating Plane in Midlatitudes". *J. Phys. Oceanogr.*, **38**(9): 2111–2117, doi:10.1175/2007JPO3932.1

Recently, Paldor et al. provided a consistent and unified theory for Kelvin, Poincaré (inertial–gravity), and Rossby waves in the rotating shallow-water equations (SWE). Unfortunately, the article has some errors, and the effort is made to correct them in this note. Also, the eigenvalue problem is rewritten in a dimensional form and then nondimensionalized in terms of more traditional nondimensional parameters and compared to the dispersion relations of the old and new theories. The errors in Paldor et al. are only quantitative in nature and do not alter their major results: Rossby waves can have larger phase speeds than what is predicted from the classical theory, and Rossby and Poincaré waves can be trapped near the equatorward boundary.

Poulin, F. J., 2009, Can Long Meridional Length Scales Yield Faster Rossby Waves? *J. Phys. Oceanogr.*, **39**(2): 472–478

There is much interest in better understanding the westward-propagating subinertial signal in the ocean basins because it influences many aspects of the ocean's circulation. One explanation for the origin of this signal is that it is predominantly composed of Rossby waves. Chelton and Schlax assumed the observations were Rossby waves and compared their phase speeds with those predicted from nondispersive linear quasigeostrophic wave speeds. They concluded that the theory underestimated the observed wave speeds. Recently, in the context of the shallow-water model, Paldor, Rubin, and Mariano found that by including the full meridional variation of the Coriolis parameter, the Rossby waves have faster phase speeds. Here, their analysis is extended to derive a general dispersion relation for stratified Rossby waves that is suitable for both mesoscale and synoptic length scales. Then, realistic profiles of the buoyancy frequency are used to compare the phase speeds from the Ocean Topography Experiment (TOPEX)/Poseidon data with the new theory. It is found that the new theory does not yield any significant increase in Rossby wave speeds.

9.8 Solitary Waves

Aghsaee, P., L. Boegman, and K. G. Lamb, 2010, Breaking of shoaling internal solitary waves, *J. Fluid Mech.*, **659**: 289-317, doi:10.1017/S002211201000248X

The breaking of fully nonlinear internal solitary waves of depression shoaling upon a uniformly sloping boundary in a smoothed two-layer density field was investigated using high-resolution two-dimensional simulations. Our simulations were limited to narrow-crested waves, which are more common than broad-crested waves in geophysical flows. The simulations were performed for a wide range of boundary slopes $S \in [0.01, 0.3]$ and wave slopes extending the parameter range to weaker slopes than considered in previous laboratory and numerical studies. Over steep slopes ($S \geq 0.1$), three distinct breaking processes

were observed: surging, plunging and collapsing breakers which are associated with reflection, convective instability and boundary-layer separation, respectively. Over mild slopes ($S \leq 0.05$), nonlinearity varies gradually and the wave fissions into a train of waves of elevation as it passes through the turning point where solitary waves reverse polarity. The dynamics of each breaker type were investigated and the predominance of a particular mechanism was associated with a relative developmental time scale. The breaking location was modelled as a function of wave amplitude (a), characteristic wave length and the isopycnal length along the slope. The breaker type was characterized in wave slope ($S_w = a/L_w$, where L_w is a measure of half of the wavelength) versus S space, and the reflection coefficient (R), modelled as a function of the internal Iribarren number, was in agreement with other studies. The effects of grid resolution and wave Reynolds number (Re_w) on R, boundary-layer separation and the evolution of global instability were studied. High Reynolds numbers ($Re_w \sim 10^4$) were found to trigger a global instability, which modifies the breaking process relative to the lower Re_w case, but not necessarily the breaking location, and results in a ~ 10 % increase in R, relative to the $Re_w \sim 10^3$ case.

Bourgault, D. and C. Richards, 2007, A laboratory experiment on internal solitary waves, *American Journal of Physics*, **75**(4): 1-5, doi:10.1119/1.2437749

A simple laboratory experiment is designed to show the properties of internal solitary waves. The procedure and analysis are suited for a senior undergraduate laboratory course, though the techniques described may also be used for demonstration purposes in a fluid mechanics course. The measurements collected can be compared to the weakly nonlinear Korteweg–deVries (KdV) theory for the wave shape, lengthscale-amplitude relationship, and phase speed. The experiment provides a good introduction to internal solitary waves in the ocean, along with an exploration of error analysis and the limits of applicability of a theory.

Bourgault, D., M. D. Blokhina, R. Mirshak, and D. E. Kelley, 2007, Evolution of a shoaling internal solitary wavetrain, *Geophys. Res. Lett.*, **34**, L03601, doi:10.1029/2006GL028462

Field observations of an internal solitary wavetrain impacting a shoaling bottom are presented. Measurements of the spatio-temporal characteristics of the shoaling waves are given, as well as estimations of the mixing they may have caused upon impact. The observations are discussed in the context of numerical simulations, laboratory experiments, and hypotheses recently raised on the origin and evolution of internal solitary waves in coastal environments.

Bourgault, D. and D. E. Kelley, 2007, On the Reflectance of Uniform Slopes for Normally Incident Interfacial Solitary Waves, *J. Phys. Oceanogr.*, **37**(5): 1156–1162

The collision of interfacial solitary waves with sloping boundaries may provide an important energy source for mixing in coastal waters. Collision energetics have been studied in the laboratory for the idealized case of normal incidence upon uniform slopes. Before these results can be recast into an ocean parameterization, contradictory laboratory findings must be addressed, as must the possibility of a

bias owing to laboratory sidewall effects. As a first step, the authors have revisited the laboratory results in the context of numerical simulations performed with a nonhydrostatic laterally averaged model. It is shown that the simulations and the laboratory measurements match closely, but only for simulations that incorporate sidewall friction. More laboratory measurements are called for, but in the meantime the numerical simulations done without sidewall friction suggest a tentative parameterization of the reflectance of interfacial solitary waves upon impact with uniform slopes.

Carr, M., M. Stastna, and P. A. Davies, 2010, Internal solitary wave-induced flow over a corrugated bed, *Ocean Dyn.*, **60**(4): 1007-1025, doi:10.1007/s10236-010-0286-2

A combined numerical and experimental study of the propagation of an internal solitary wave (ISW) over a corrugated bed is presented, in which the amplitude and the wavelength of the corrugated bed, together with the wave amplitude and wave speed of the ISW, have been varied parametrically. Both ISWs of elevation and depression have been considered. The wave-induced currents over the corrugated bed cause flow separation at the apex of the corrugations and a sequence of lee vortices forms as a result. These vortices develop fully after the main wave has passed over the topographic feature, resulting in deformation of the overlying pycnocline and, in some instances, significant vertical mixing. It is found that the intensity of the vortex formation is dependent on both the amplitude and wavelength of the bottom topography. In the case of an ISW of depression, the generation of vertically (upward)-propagating vortices is seen to result in entrainment of fluid from a bottom boundary jet (Carr and Davies, Phys Fluids 18:016601, *2006*), while, in the elevation case, a second mechanism is present to induce significant turbulent mixing in the water column. It occurs when the bottom corrugations reach into, or are very near, the pycnocline at rest. Large waves of elevation that are stable on approach to the corrugations exhibit evidence of a spatio-temporally developing shear instability as they interact with the bottom corrugation. The shear instability takes the form of billows that have a vertical extent that can reach 50% of the wave amplitude.

Chin-Bing, S. A., A. Warn-Varnas, D. B. King, J. Hawkins, and K. Lamb, 2009, Effects on acoustics caused by ocean solitons, Part B: Acoustics, *Nonlinear Analysis: Theory, Methods & Applications*, **71**(12): e2194-e2204, ISSN 0362-546X, doi:10.1016/j.na.2009.04.069

Large amplitude internal solitary waves in the ocean can interfere with underwater acoustic signals. For certain acoustic parameters (source depth, receiver depth, and frequency) a redistribution of acoustical energy to higher-order acoustic modes can occur as the acoustic signal propagates through the solitary wave train. Depending on the ocean bottom composition, this can result in a significant loss in acoustical signal intensity. In order to simulate and understand this phenomena, it is necessary to generate a solitary wave train that is realistic and contains the spectral components that will interact with the acoustic signal. This requires a primitive equation nonhydrostatic ocean model. Part A [A.C. Warn-Varnas, S.A. Chin-Bing, D. King, J. Hawkins, K. Lamb, Effects on

acoustics caused by ocean solitons: Part A. Oceanography, Nonlinear Anal., in press (doi:10.1016/j.na.2009.02.104)] of this two-part article addressed that issue. In this work we use acoustic model simulations to demonstrate the mode linkage between the solitary wave train and the acoustic signal that can result in a large signal loss. Understanding the linkage allows for pre-examination of the solitary wave characteristics to determine if they could affect propagating acoustic signals. The procedure has the advantage that only a few computer runs are required from the ocean model and no lengthy computer runs are required from acoustic propagation models. Only a quick calculation of the acoustic mode eigenvalues is needed.

Lamb, K. G. and V. T. Nguyen, 2009, Calculating Energy Flux in Internal Solitary Waves with an Application to Reflectance, *J. Phys. Oceanogr.*, **39**(3): 559–580

The energetics of internal solitary waves (ISWs) in continuous, quasi-two-layer stratifications are explored using fully nonlinear, nonhydrostatic numerical simulations. The kinetic energy of an internal solitary wave is always greater than the available potential energy, by as much as 30% for the stratifications considered. Because of different spatial distributions of the kinetic and available potential energy densities, however, the fluxes are quite different. The available potential energy flux is found to always exceed the kinetic energy flux, by as much as a factor of 5. The sizes of the various fluxes in the wave pseudoenergy (kinetic plus available potential energy) equation are compared, showing that, while the linear flux term (velocity–pressure perturbation) dominates the fluxes, the fluxes of available potential and kinetic energy are significant for large ISWs. Past work on estimating the reflectance (ratio of reflected to incident pseudoenergy flux) associated with internal solitary waves incident on a linearly sloping bottom in laboratory experiments and numerical simulations has incorrectly assumed that the available potential energy flux was equal to the kinetic energy flux. Hence, the sensitivity of reflectance estimates to the way the flux is calculated is investigated. For these low Reynolds number situations, it is found that a correct account of the available potential energy flux reduces the reflectance by as much as 0.1 when the pycnocline is close to the surface.

Lamb, K. G., 2010, Energetics of internal solitary waves in a background sheared current, *Nonlin. Processes Geophys.*, **17**: 553-568, doi:10.5194/npg-17-553-2010

The energetics of internal waves in the presence of a background sheared current is explored via numerical simulations for four different situations based on oceanographic conditions: the nonlinear interaction of two internal solitary waves; an internal solitary wave shoaling through a turning point; internal solitary wave reflection from a sloping boundary and a deep-water internal seiche trapped in a deep basin. In the simulations with variable water depth using the Boussinesq approximation the combination of a background sheared current, bathymetry and a rigid lid results in a change in the total energy of the system due to the work done by a pressure change that is established across the domain. A final simulation of the deep-water internal seiche in which the Boussinesq approximation is not invoked and a diffuse air-water interface is added to the

system results in the energy remaining constant because the generation of surface waves prevents the establishment of a net pressure increase across the domain. The difference in the perturbation energy in the Boussinesq and non-Boussinesq simulations is accounted for by the surface waves.

Marsden, R. F., 2007, Tracking solitary waves below land-fast ice, *J. Geophys. Res.*, **112**, C08002, doi:10.1029/2006JC004004

Data from two acoustic Doppler current profilers, separated by 76 m and deployed through land-fast ice in the Canadian Arctic Archipelago in May 2002, are examined. The three velocity components were sampled intermittently at 1-minute intervals over a 3-week period to 19 m below the ice-water interface. The vertical structure was resolved using empirical orthogonal functions (EOF), while the shallow water Korteweg de Vries (KdV) and deep water Benjamin-Ono (BO) theoretical solutions were used to guide a pseudo- wavelet analysis of the horizontal structure. Numerous instances of near-simultaneous spikes were detected in the empirical mode 1 time series. A 3.5-hour period on 21 May 2002 containing two disturbances was examined in detail. Wavelet scalograms suggested that there was a 20-minute lag in the first disturbance and 16 minutes in the second. The scalogram values indicated that KdV was more consistent with the waveshapewave shapes than BO theory. The character of the two events was very different. The first had a broader spatial distribution than the second, and the measured translational speed was reasonably consistent with that of a mode 1 KdV solitary wave. The second event had a much slower propagation speed and a near surface maximum in the vertical velocity eigenvector, suggesting a mode 2 wave. It is suggested that ice keels from a nearby pressure ridge could be the source.

McMillan, J. M. and B. R Sutherland, 2010, The Lifecycle of axisymmetric internal solitary waves, *Nonlin. Proc. Geophys.*, **17**: 443-453, doi:10.5194/npg-17-443-2010

The generation and evolution of solitary waves by intrusive gravity currents in an approximate two-layer fluid with equal upper- and lower-layer depths is examined in a cylindrical geometry by way of theory and numerical simulations. The study is limited to vertically symmetric cases in which the density of the intruding fluid is equal to the average density of the ambient. We show that even though the head height of the intrusion decreases, it propagates at a constant speed well beyond 3 lock radii. This is because the strong stratification at the interface supports the formation of a mode-2 solitary wave that surrounds the intrusion head and carries it outwards at a constant speed. The wave and intrusion propagate faster than a linear long wave; therefore, there is strong supporting evidence that the wave is indeed nonlinear. Rectilinear Korteweg-de Vries theory is extended to allow the wave amplitude to decay as r^{-p} with p=½ and the theory is compared to the observed waves to demonstrate that the width of the wave scales with its amplitude. After propagating beyond 7 lock radii the intrusion runs out of fluid. Thereafter, the wave continues to spread radially at a constant speed, however, the amplitude decreases sufficiently so that linear dispersion dominates and the amplitude decays with distance as r^{-1}.

Stastna, M. and F. Poulin, 2007, On the Existence of Solitary Wave Solutions to the Shallow-Water Equations on the f Plane, *J. Phys. Oceanogr.*, **37**(3) 794–798

In a recent paper Li argued that the inviscid shallow-water equations on the *f* plane exhibit a class of zonally propagating solitary wave solutions, referred to by the author as "geosolitary waves." These solutions have propagation speeds that are slower than the shallow-water speed $(gH)^{1/2}$, and as constructed by Li, have a cusp in the height and zonal velocity field at the origin. The meridional velocity is found to be discontinuous at the origin, though its magnitude is much smaller than the magnitude of the zonal velocity. The authors reconsider the existence of geosolitary waves from the point of view of dynamical system theory and demonstrate that the cusp discontinuity at the origin is an unavoidable property of the solutions. Moreover, it is shown that, in contrast to suggestions made by Li, adding viscosity and diffusivity does not yield smooth, bounded solitary wave solutions. Last, the reason why geosolitary waves cannot be expected to exist in a continuously stratified fluid is discussed.

Stastna, M., F. J. Poulin, K. Rowe, and D. Subich, 2009, On fully nonlinear, vertically trapped wave packets in a stratified fluid on the f-plane, *Physics of Fluids,* **21**, 106604, doi:10.1063/1.3253400

The ubiquity of solitary and solitarylike internal waves in the coastal ocean has been recognized for some time. Recent theoretical studies of a strongly nonlinear, weakly nonhydrostatic set of layer-averaged model equations have predicted that rotation, for example, on the f-plane, can lead to the decay and subsequent reemergence of internal solitary waves. We reconsider this problem using high resolution numerical simulations of the rotating stratified Euler equations. We find that in certain cases the initial disturbances indeed fission into nonlinear wave packets, with the constituent waves making up the wave packet being, in themselves, nonlinear. However, for typical coastal ocean parameters this only occurs at rotation rates higher than those on Earth on the time scales we are able to simulate. We confirm, using the Dubreil–Jacotin–Long equation, that the vertical structure of the wave-induced currents is well predicted by the fully nonlinear theory of nonrotating internal solitary waves and that weakly nonlinear Korteweg–de Vries equation-based theory fails to describe this structure accurately. Subsequently, we consider flat-crested solitary waves that allow us to fix the wave amplitude while varying the horizontal wavelength. We find that as the waves' horizontal extent nears the baroclinic Rossby radius more energy is deposited into the wave tail. However, no wave overtaking is observed, and an explanation for this fact is proposed. Finally, we discuss the effects of the horizontal component of the rotation vector and derive an exact equation for rotation modified waves near the equator. This equation demonstrates that in this situation, rotation modifies the structure of the fully nonlinear waves but does not lead to solitary wave decay.

Sutherland, B. R. and J. T. Nault, 2007, Intrusive gravity currents propagating along thin and thick interfaces, *J. Fluid Mech.*, **586**: 109-118, doi:10.1017/@002112007007288

Inviscid gravity currents released from a finite-length lock are known to propagate at a constant speed to a predicted finite distance before decelerating. By extension this should occur in a two-layer fluid with equal upper- and lower-layer depths for an intrusion having the average density of the ambient. The experiments presented here show this is not necessarily the case. The finite-depth thickness of the interface non-negligibly influences the evolution of the intrusion so that it propagates well beyond the predicted constant-speed limit; it propagates without decelerating beyond 22 lock lengths in a rectilinear geometry and beyond 6 lock radii in an axisymmetric geometry. Experiments and numerical simulations demonstrate that the intrusion speed decreases to half the two-layer speed in the circumstance in which the interface spans the domain. The corresponding long mode-2 interfacial wave speed increases rapidly with interfacial thickness, becoming comparable with the intrusion speed when the interfacial thickness is approximately one-quarter the domain height. For somewhat thinner interfacial thicknesses, the intrusion excites solitary waves that move faster than the long-wave speed. The coupling between intrusions and the waves they excite, together with reduced mixing of the current head, result in constant-speed propagation for longer times.

Swaters, G. E., 2007, Perturbations of soliton solutions to the unstable nonlinear Schrödinger and sine-Gordon equations, *Stud. Appl. Math.* **118**, 99-116, doi:10.1111/j.1467-9590.2007.00365.x

The adiabatic evolution of soliton solutions to the *unstable* nonlinear Schrödinger (UNS) and sine-Gordon (SG) equations in the presence of small perturbations is reconsidered. The transport equations describing the evolution of the solitary wave parameters are determined by a direct multiple-scale asymptotic expansion and by phase-averaged conservation relations for an arbitrary perturbation. The evolution associated with a dissipative perturbation is explicitly determined and the first-order perturbation fields are also obtained.

Turnbull, M. R. and G. E. Swaters, 2007, Evolution of solitary marginal disturbances in baroclinic frontal geostrophic dynamics with dissipation and time-varying background flow, *Proc. R. Soc. A*, **463**(2083): 1749-1769, doi:10.1098/rspa.2007.1850

A two-layer frontal geostrophic flow corresponds to a dynamical regime that describes the low-frequency evolution of baroclinic ocean currents with large amplitude deflections of the interface between the layers on length-scales longer than the internal deformation radius within the context of a thin upper layer overlying a dynamically active lower layer. The finite-amplitude evolution of solitary disturbances in baroclinic frontal geostrophic dynamics in the presence of time-varying background flow and dissipation is shown to be governed by a two-equation extension of the *unstable* nonlinear Schrödinger (UNS) equation with variable coefficients and forcing. The soliton solution of the unperturbed UNS equation corresponds to a saturated isolated coherent anomaly in the baroclinic instability of surface-intensified oceanographic fronts and currents. The adiabatic evolution of the propagating soliton and the uniformly valid first-order perturbation fields are determined using a direct perturbation approach together

with phase-averaged conservation relations when both dissipation and time variability are present. It is shown that the soliton amplitude parameter decays exponentially due to the presence of the dissipation but is unaffected by the time variability in the background flow. On the other hand, the soliton translation velocity is unaffected by the dissipation and evolves only in response to the time variability in the background flow. The adiabatic solution for the induced mean flow exhibits a dissipation-generated 'shelf region' in the far field behind the soliton, which is removed by solving the initial-value problem.

Warn-Varnas, A., S. A. Chin-Bing, D. B. King, J. Hawkins, and K. Lamb, 2009, Effects on acoustics caused by ocean solitons, Part A. Oceanography, *Nonlinear Analysis.* **71**(12): e1807-e1817, doi:10.1016/j.na.2009.02.104

Our work addresses the link between internal solitary waves and acoustics. The location of the study is in the Yellow Sea south of the Shandong peninsula. Previously in this region, we have performed internal solitary wave generation and propagation simulations with the Lamb nonhydrostatic model [K. Lamb, Numerical experiments of internal waves generated by strong tidal flow across a finite amplitude bank edge, J. Geophys. Res. 99 (c1) (1994) 848–864; A. Warn-Varnas, S.A. Chin-Bing, D.B. King, J.A. Hawkins, K.G. Lamb, M. Teixeira, Yellow Sea ocean-acoustic solitary wave modeling studies, J. Geophys. Res. 110 (2005) C08001, doi:10.1029/2004JC002801]. The model parameters were tuned to SAR data. Here, we consider variations of solitary wave characteristics in parameter space. We introduce scaling parameters for a two-layer analogue configuration. This analogue is applied to predicted numerical solutions with the full nonlinear nonhydrostatic Lamb model in the first of the above-mentioned references. Variations of density difference across the pycnocline, tidal forcing and topographic height are considered. Characteristics of solitary waves are analyzed as the parameters deviate from a tuned case to data. Changes of solitary wave functional form, amplitude, wavelength, and phase speed are tracked. We consider oceanographic and acoustical parameters that describe the physical ocean–acoustic environment and its associated variability. For certain source, receiver, and acoustical frequency configurations, a redistribution of acoustical energy to higher modes can occur and result in acoustical intensity loss in the presence of solitary wave trains [A. Warn-Varnas, S.A. Chin-Bing, D.B. King, J. A. Hawkins, K.G. Lamb, M. Teixeira, Yellow Sea internal solitary wave variability, in: N.G. Pace, Finn B. Jensen (Eds.), Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002]. This will be considered in part B.

Warn-Varnas, A., S. Chin-Bing, D. King, J. Hawkins, K G. Lamb, and J. Lynch. 2007. Winter Primer 4 ocean-acoustic solitary wave studies, *IEEE J. Ocean. Eng.* **32**: 436-452, doi:10.1109/JOE.2006.875273

In this paper, we present results from a joint oceanographic-acoustic study of solitary waves and their effects during the 1997 winter PRIMER4 experiment on the shelfbreak south of Cape Cod, MA. The study addresses the acoustic effects induced by solitary waves and associated oceanographic phenomena. Solitary

wave generation and propagation simulations are produced by the Lamb model [J. Geophys. Res., vol. 99, pp. 848-864, 1994]. The model is nonhydrostatic and is formulated in 2.5 dimensions using terrain following coordinates. Acoustic field calculations are performed with a parabolic equation acoustic model along the path of solitary wave train propagation. The oceanographic model is initialized from density profiles derived from conductivity-temperature-depth (CTD) casts using analytical functions. The model is forced with a prescribed semidiurnal tidal velocity. An ocean background current is introduced. Simulations based on parameters derived from measurements show the following: 1) internal solitary waves of elevation propagate onto the shelfbreak region; 2) opposing ocean currents enhance the formation of solitary waves at the shelfbreak; 3) deepening of the winter mixed layer results in less penetration of the solitary waves on to the shelf; 4) density structure, mixed-layer depth, tidal forcing, and ocean currents control the formation of solitary waves of elevation at the shelfbreak; 5) energy conversion, from semidiurnal barotropic to semidiurnal barcoclinic tides and to internal solitary waves, occurs; 6) amplitudes and periods of modeled solitary waves are in the range of thermistor chain measurements; and 7) lower mixed-layer densities increase the phase speed of simulated solitary waves. Acoustic field calculations are coupled to the propagation of the solitary wave packets through the sound-speed changes that are derived from the oceanographic simulations. Acoustic model predictions show signal intensity fluctuations similar to the anomalous losses in acoustic energy observed in the Yellow Sea data taken by Zhou [J. Acoust. Soc. Amer., vol. 90, pp. 2042-2054, 1991]. In some cases, the presence of solitary waves on the shelf enhances the propagation of acoustic energy onto the shelf. This was observed for acoustic simulations where the acoustic source was located beyond the shelfbreak and at a depth greater than the shelf depth.

Warn-Varnas, A., J. Hawkins, K. G. Lamb, S. Piacsek, S. Chin-Bing, D. King, and G. Burgos, 2010, Solitary wave generation dynamics at Luzon Strait, *Ocean Modelling*, **31**(1-2): 9-27, doi:10.1016/j.ocemod.2009.08.002

A high resolution modeling study is undertaken, with a 2.5-dimensional nonhydrostatic model, of the generation of internal waves induced by tidal motion over the ridges in Luzon Strait. The model is forced by the barotropic tidal components K1, M2, and O1. These tidal components, along with the initial density field, were extracted from data and models. As the barotropic tide moves over the Luzon Strait sills, there is a conversion of barotropic tidal energy into baroclinic tidal energy. Depressions are generated that propagate towards the Asian Seas International Acoustics Experiment (ASIAEX) test site on the Chinese continental shelf. Nonlinear effects steepen the depressions, frequency and amplitude dispersion set in, and disintegration into large amplitude solitary waves occurs. The effects of varying the initial density field, tidal component magnitudes, as well as adding a steady background current to represent the occasional excursions of the Kuroshio Current into the strait, are considered.

Depressions are generated at each of the two sills in Luzon Strait which radiate away, steepening and evolving into internal solitary wave trains. Baroclinic fluxes of available potential energy, kinetic energy and linear are calculated for various parameter combinations. The solitary wave trains produced in the simulations generally consist of large amplitude wave trains alternating with small amplitude wave trains. During strong tidal flow, Kelvin–Helmholtz type instabilities can develop over the taller double-humped sill. The solitary waves propagating towards the ASIAEX test site have been observed to reach amplitudes of 120–250 m, depending on the tidal strength. ASIAEX observations indicate amplitudes up to 150 m and the Windy Island Experiment (WISE) measurements contain magnitudes over 200 m. The model results yield solitary wave amplitudes of 70–300 m and half widths of 0.60–3.25 km, depending on parameter values. These are in the range of observations. Measurements by Klymak et al. (2006), in the South China Sea, exhibit amplitudes of 170 m, half widths of 3 km and phase speeds of 2.9 m s^{-1}. Model predictions indicate that the solitary waves making up the wave packet each experience different background currents with strong near surface shear.

The energy in the leading soliton of the large amplitude wave trains ranges between 1.8 and 9.0 GJ m^{-1}. The smaller value, produced using barotropic tidal currents based on the Oregon State University data base, is the same as the energy estimated to be in a solitary wave observed by Klymak et al. (2006). Estimates of the conversion of barotropic tidal energy into radiating internal wave energy yield conversion rates ranging between 3.6% and 8.3%.

10 Density Currents, Baroclinic and Shear Flows

Inoue, R. and W. D. Smyth, 2009, Efficiency of Mixing Forced by Unsteady Shear Flow, *J. Phys. Oceanogr.*, **39**(5): 1150–1166, doi:10.1175/2008JPO3927.1

The dependence of mixing efficiency on time-varying forcing is studied by direct numerical simulation (DNS) of Kelvin–Helmholtz (KH) instability. Time-dependent forcing fields are designed to reproduce a wavelike oscillation by solving the equations of motion in a tilted coordinate frame and allowing the tilt angle to vary in time. Mixing efficiency Γ_c is defined as the ratio of potential energy gain to dissipation, both averaged over one forcing cycle and first examined via parameters characterizing waves: the minimum Richardson number Ri_{min} and the normalized frequency of the forcing ω/N. The effect of Reynolds number Re_0 and the initial random disturbance amplitude b are also examined. In the experiments presented, Γ_c varies between 0.21 and 0.36 and is controlled by the timing of two events: the emergence of KH billows and the arrival of the deceleration of the mean shear by the wavelike forcing. Here, Γ_c is higher than a canonical value of 0.2 when the deceleration phase of the forcing suppresses the less efficient turbulence after breakdown of KH billows. However, when Ri_{min} and ω/N are small, KH billows start to develop before Ri_{min} is achieved. Therefore, the forcing accelerates the mean shear and thereby sustains turbulence after the breakdown of KH billows. The canonical value is then reproduced in the

DNS. Although larger values of Re_0 and b intensify the development of KH billows and modify Γ_c, this effect is less significant when forcing fields act to sustain turbulence. The time-averaged Thorpe scale and Ozmidov scale are also used to see how mixing is modified by forcing fields and compared with past microstructure measurements. It is found that DNS also corresponds to past observations if the forcing accelerates the mean shear to sustain turbulence.

Poulin, F. J., G. R. Flierl, and J. Pedlosky, 2010, The Baroclinic Adjustment of Time-Dependent Shear Flows, *J. Phys. Oceanogr.*, **40**(8):1851–1865, doi:10.1175/2010JPO4217.1

Motivated by the fact that time-dependent currents are ubiquitous in the ocean, this work studies the two-layer Phillips model on the beta plane with baroclinic shear flows that are steady, periodic, or aperiodic in time to understand their nonlinear evolution better. When a linearly unstable basic state is slightly perturbed, the primary wave grows exponentially until nonlinear advection adjusts the growth. Even though for long time scales these nearly two-dimensional motions predominantly cascade energy to large scales, for relatively short times the wave–mean flow and wave–wave interactions cascade energy to smaller horizontal length scales. The authors demonstrate that the manner through which these mechanisms excite the harmonics depends significantly on the characteristics of the basic state. Time-dependent basic states can excite harmonics very rapidly in comparison to steady basic states. Moreover, in all the simulations of aperiodic baroclinic shear flows, the barotropic component of the primary wave continues to grow after the adjustment by the nonlinearities. Furthermore, the authors find that the correction to the zonal mean flow can be much larger when the basic state is aperiodic compared to the periodic or steady limits. Finally, even though time-dependent baroclinic shear on an f plane is linearly stable, the authors show that perturbations can grow algebraically in the linear regime because of the erratic variations in the aperiodic flow. Subsequently, baroclinicity adjusts the growing wave and creates a final state that is more energetic than the nonlinear adjustment of any of the unstable steady baroclinic shears that are considered.

Poulin, F. J., 2010, The Linear Stability of Time-Dependent Baroclinic Shear, *J. Phys. Oceanogr.*, **40**(3): 568–581

This article aims to advance the understanding of inherent randomness in geophysical fluids by considering the particular example of baroclinic shear flows that are spatially uniform in the horizontal directions and aperiodic in time. The time variability of the shear is chosen to be the Kubo oscillator, which is a family of time-dependent bounded noise that is oscillatory in nature with various degrees of stochasticity.

The author analyzed the linear stability of a wide range of temporally periodic and aperiodic shears with a zero and nonzero mean to get a more complete understanding of the effect of oscillations in shear flows in the context of the two-layer quasigeostrophic Phillips model. It is determined that the parametric mode,

which exists in the periodic limit, also exists in the range of small and moderate stochasticities but vanishes in highly erratic flows. Moreover, random variations weaken the effects of periodicity and yield growth rates more similar to that of the time-averaged steady-state analog. This signifies that the periodic shear flows possess the most extreme case of stabilization and destabilization and are thus anomalous. In the limit of an *f* plane, the linear stability problem is solved exactly to reveal that individual solutions to the linear dynamics with time-dependent baroclinic shear have growth rates that are equal to that of the time-averaged steady state. This implies that baroclinic shear flows with zero means are linearly stable in that they do not grow exponentially in time. This means that the stochastic mode that was found to exist in the Mathieu equation does not arise in this model. However, because the perturbations grow algebraically, the aperiodic baroclinic shear on an *f* plane can give rise to nonlinear instabilities.

Swaters, G. E., 2010, Modal Interpretation for the Ekman Destabilization of Inviscidly Stable Baroclinic Flow in the Phillips Model, *J. Phys. Oceanogr.*, **40**(4): 830–839, doi:10.1175/2009JPO4311.1

Ekman boundary layers can lead to the destabilization of baroclinic flow in the Phillips model that, in the absence of dissipation, is nonlinearly stable in the sense of Liapunov. It is shown that the Ekman-induced instability of inviscidly stable baroclinic flow in the Phillips model occurs if and only if the kinematic phase velocity associated with the dissipation lies outside the interval bounded by the greatest and least neutrally stable Rossby wave phase velocities. Thus, Ekman-induced destabilization does not correspond to a coalescence of the barotropic and baroclinic Rossby modes as in classical inviscid baroclinic instability. The differing modal mechanisms between the two instability processes is the reason why subcritical baroclinic shears in the classical theory can be destabilized by an Ekman layer, even in the zero dissipation limit of the theory.

Wells, M. and P. Nadarajah, 2009, The Intrusion Depth of Density Currents Flowing into Stratified Water Bodies, *J. Phys. Oceanogr.*, **39**(8) 1935–1947

Theory and laboratory experiments are presented describing the depth at which a density current intrudes into a linearly stratified water column, as a function of the entrainment ratio E, the buoyancy flux in the dense current B, and the magnitude of the stratification N. The main result is that $Z \sim E^{-1/3}B^{1/3}/N$. It is shown that the depth of the intrusion scales as $Z \sim (3 \pm 1)B^{1/3}/N$ for laboratory experiments, and as $Z \sim (3 \pm 1)\, B_{\mathrm{geo}}^{1/3}/N$ for oceanic density currents. The velocity of a large-scale density current is controlled by a geostrophic balance defined as $U_{\mathrm{geo}} = 0.25g's/f$, where s is the slope and f is the Coriolis parameter. The geostrophic buoyancy flux is then defined by $B_{\mathrm{geo}} = g'U_{\mathrm{geo}}h$, with g' the reduced gravity and h the thickness of the current. The scaling $Z \propto B_{\mathrm{geo}}^{1/3}/N$ herein implies that the depth of an oceanic intrusion is relatively insensitive to changes in source water properties but is very sensitive to changes in the stratification of the water column, consistent with the previous scaling of Price and Baringer. For example, if the buoyancy flux of a dense current were to double while the stratification remained constant, then there

would only be a 25% increase in the intrusion depth, whereas doubling the stratification would result in a 50% decrease of the intrusion depth.

11 Laboratory Studies

Afanasyev, Y. D. and V. N. Korabel, 2008, Wakes and vortex streets behind a localized force: numerical simulations, *Comm. in Nonlin. Sci. and Num. Sim.,* **13**(6): 1101-1111, doi:10.1016/j.cnsns.2006.10.001

Two-dimensional wakes behind a body force acting inside a small circular area are investigated using direct numerical simulations. The flows induced by a single force are asymptotically related to the far-field wakes of a bluff body but belong to a wider class of flows because the problem contains an extra control parameter. Stable (almost parallel) wakes as well as regular vortex streets similar to those observed in the wakes of bluff bodies were obtained in our simulations. The behavior of the frequency of vortex shedding in the unstable wakes is described in detail for different values of the main control parameters of the flow, namely the amplitude of the forcing, the velocity of the stream, the size of the forcing area and the kinematic viscosity of fluid. Two different regimes of vortex shedding were observed in the space of these control parameters. Transition between the regimes is characterized by a rapid drop in frequency. The relation between the flows generated by a force and those past a circular cylinder is identified.

Afanasyev, Y. D., P. B. Rhines, and E. G. Lindahl, 2008a, Emission of inertia-gravity waves by baroclinically unstable flows: laboratory experiments with Altimetric Imaging Velocimetry, *J. Atmosp. Sci.,* **65**: 250-262, doi:10.1175/2007JAS2336.1

Results from new experiments on baroclinic instability of a coastal jet demonstrate that this almost balanced flow spontaneously emits inertial waves when the Rossby radius of deformation is relatively small such that the characteristics of baroclinic meanders match the dispersion relation for the inertial waves. The energy of the waves is small compared to the energy of the flow. A single event of wave emission is identified in the experiment with larger radius of deformation and is interpreted in terms of vorticity dynamics. The flows are generated on a laboratory polar β-plane where the Coriolis parameter varies quadratically with latitude. A new method for imaging the rotating flows, which the authors call "altimetric imaging velocimetry," is employed. Optical color coding of slopes of the free-surface elevation field allows the authors to derive the fields of pressure, surface elevation, geostrophic velocity, or the "gradient wind" velocity with very high spatial resolution (typically several million vectors) limited largely by the pixel resolution of the available imaging sensors. The technique is particularly suited for the investigations of small-amplitude waves, which are often difficult to detect by other methods.

Afanasyev, Y. D., P. B. Rhines and E. G. Lindahl, 2008b, Laboratory experiments with Altimetric Imaging Velocimetry: Cylinder wakes on the polar beta-plane, *Phys. Fluids,* **20**(8), 086604, doi:10.1063/1.2968451

Intense vortices in the wake of a circular cylinder are investigated in a rotating parabolic (polar) β-plane fluid. This system has a background potential vorticity (PV) field that supports Rossby waves and causes vortices to migrate and radiate. A method for imaging rotating flows, which we call "altimetric imaging velocimetry" is employed. Optical color coding of slopes of the free-surface elevation field yields the pressure, geostrophic and gradient wind velocity, and potential vorticity fields with very high spatial resolution, limited largely by the pixel resolution of the available imaging sensors. Cylinder wakes on the polar β-plane exhibit strikingly different regimes as it is translated azimuthally, eastward or westward. Self-arrangement of vortices after the cylinder was stopped drives an intense eastward jet formed by the rows of anticyclones and cyclones on its flanks. In agreement with the idea of a PV staircase, this jet has a strong PV gradient at its center, while PV is homogenized by the vortices on either side. A slowly translating cylinder generates Rossby waves with phase propagation locked to the cylinder, and intermediate cases show a widespread vortex/wave interaction.

Afanasyev, Y. D. and V. Jewtoukoff, 2009, Dipolar gyres generated by continuous forcing on a polar beta-plane, *Phys. Fluids,* **21,** 066602, doi:10.1063/1.3156007

Dipolar vortices generated by a force applied to an area of finite size are investigated in a rotating, polar β-plane fluid. The laboratory polar β-plane is dynamically equivalent to the polar regions of the ocean or the atmosphere where the Coriolis parameter varies quadratically with latitude. Both forced and unforced evolution of the flow is observed. The altimetric imaging velocimetry method is employed for imaging the rotating flows and measuring the velocity and surface elevation fields. The forced dipoles were observed to rotate in the anticyclonic direction from their initial orientation where the axis of the dipole is aligned with the direction of the force toward some steady state where the axis of the dipole is at an angle to the direction of the force. The theoretical prediction of the rotation angle is found to be in good agreement with the experimental results. Asymptotic solutions for limiting cases when forced dipoles are affected either by the Ekman-type bottom friction or by the γ-effect are found. The experiments also demonstrate that the unforced free dipoles rotate anticyclonically with almost steady rate and emit basin-scale Rossby waves.

Afanasyev, Y. D., P. B. Rhines, and E. G. Lindahl, 2009, Velocity and Potential Vorticity fields measured by Altimetric Imaging Velocimetry in the rotating fluid, *Exps. Fluids*, **47**(6): 913-926, doi:10.1007/s00348-009-0689-3

An optical method of altimetric imaging velocimetry (AIV) for measuring the slope of the surface elevation in the rotating fluid with free surface is described. This method allows one to obtain the major dynamical fields in the fluid layer including velocity, vorticity and surface elevation. When used in combination with the Optical Thickness method the AIV can be used to render the full dynamical characteristics of a two-layer flow. Both methods allow one to achieve very high spatial resolution by rendering a velocity vector in each pixel of the image. An example of the two-layer source-driven flow on a c-plane (also called

polar b-plane) is offered to demonstrate the application of these methods. This ‘‘b-plume’ is a gyre-like response to a point source of fluid, including intense jets, eddies and Rossby waves.

Derzho, O. G. and Y. D. Afanasyev, 2008, Rotating dipolar gyres on a gamma-plane, *Phys Fluids*, **20**(3), 036603, doi:10.1063/1.2890083

Nonlinear dipolar vortices/gyres on a γ-plane are investigated both experimentally and theoretically. The solutions describe a fundamental dipolar mode of large scale barotropic motion of the polar ocean or atmosphere on the rotating planet. The entire dipolar gyre is predicted to rotate anticyclonically with a specific angular velocity. The existence and stability of the theoretically predicted flow are confirmed in a laboratory experiment on a rotating platform. The laboratory flows are induced by an electromagnetic method and are observed using the nonintrusive optical method of altimetric imaging velocimetry. The rotation rate of the experimental flow is in good agreement with that predicted theoretically. Detailed measurements of the velocity field and surface elevation demonstrate that an assumption of linearity of the relation between the relative vorticity and the stream function is valid.

Munroe, J. R., B. R. Sutherland, C. Voegeli, V. Birman, and E. H. Meiburg, 2009, Intrusive gravity currents from finite-length locks in a uniformly stratified fluid, *J. Fluid Mech.*, **635**: 245-273, doi:10.1017/S0022112009007563

Gravity currents intruding into a uniformly stratified ambient are examined in a series of finite-volume full-depth lock-release laboratory experiments and in numerical simulations. Previous studies have focused on gravity currents which are denser than fluid at the bottom of the ambient or on symmetric cases in which the intrusion is the average of the ambient density. Here, we vary the density of the intrusion between these two extremes. After an initial adjustment, the intrusions and the internal waves they generate travel at a constant speed. For small departures from symmetry, the intrusion speed depends weakly upon density relative to the ambient fluid density. However, the internal wave speed approximately doubles as the waves change from having a mode-2 structure when generated by symmetric intrusions to having a mode-1 structure when generated by intrusions propagating near the bottom. In the latter circumstance, the interactions between the intrusion and internal waves reflected from the lock-end of the tank are sufficiently strong and so the intrusion stops propagating before reaching the end of the tank. These observations are corroborated by the analysis of two-dimensional numerical simulations of the experimental conditions. These reveal a significant transfer of available potential energy to the ambient in asymmetric circumstances.

12 Instrumentation

Bishop, C., R. Bachmayer, and B. deYoung, 2009, Underwater Glider Research at Memorial University, *J. Oceanic Tech.*, **4**(1), http://www.physics.mun.ca/~bdeyoung/GliderResearch.pdf

no abstract; first paragraph

Autonomous Underwater Gliders (AUGs) are becoming the tool of choice for oceanographers to collect in-situ data on the world's oceans. Since the summer of 2006, the National Research Council-Institute for Ocean Technology (NRC-IOT) and Memorial University (MUN) have been exploring the potential for AUGs to gather oceanographic information with application to the Newfoundland Shelf. Our group has now collected over a month's worth of deployment data, and has flown over 700 km with AUGs. Preliminary work has involved testing these vehicles in our local environment and also the integration of new sensors into the platform.

Hurley, J., B. deYoung, and C. Williams, 2007, Reducing drag and oscillation of spheres used for buoyancy in oceanographic moorings. *J. Atmos. Oceanic Tech.*, **25**: 1823-1833, doi:10.1175/2006JTECHO472.1

Numerical and laboratory results of the drag characteristics are presented for different configurations of an underwater buoyancy package. It is shown that the drag and oscillation of an underwater sphere can be reduced substantially with the addition of a shaped cowling. The influence of several different cowling shapes on the drag and lift are determined. The results from a numerical fluid dynamical calculation are compared and laboratory measurements are scaled. Both the dynamic and static components of drag and lift are presented. The drag force for an underwater sphere can be reduced by more than 80% for a full teardrop-shaped cowling. A truncated teardrop, more practical for real applications, will still reduce the drag by 60%–70%. In addition to the drag, the amplitude of oscillations driven by eddy shedding is similarly reduced.

Williams, C. D., R. Bachmayer, and B. deYoung, 2008, Progress in predicting the performance of ocean gliders from at-sea measurements, *OCEANS 2008*, 15-18 Sept. 2008:1-8, doi:10.1109/OCEANS.2008.5152068

With over 100 commercially-available ocean gliders being used by researchers around the world, there is strong evidence that these platforms have become the tool of choice for those who require continuous sampling of ocean properties over a range of user-controllable depths. Researchers continue to add new sensors to these vehicles usually on the external surfaces where a sensor can work in an essentially unobstructed flow condition. These added sensors change the behaviour of the glider. For the purpose of improving our predictions of the behaviour of a glider during steady-state glides and course-changing manoeuvres, it is useful to have a simple analytical hydrodynamic model which can be validated quickly using at-sea measurements during several descending and ascending glides. The purpose of this paper is twofold: (i) to show how the hydrodynamic properties which govern steady-state gliding can be extracted from measurements made with on-board sensors, and, (ii) to show how these hydrodynamic properties can be used to predict the performance of ocean gliders (e.g. glide angle, glide speed, duration of voyage etc.). We describe a three-parameter model which has proved useful in representing the behaviour of an ocean glider during straight-line descents and ascents. This parametric model has

been validated with at-sea measurements during multiple glides. Estimates for these parameters can be obtained from the measurements of four quantities on-board a Slocum ElectricTM glider, namely (i) the fore-and-aft position of the pitch-control battery, (ii) the volume of seawater which is ingested or expelled by the buoyancy engine, (iii) the glider pitch angle, and, (iv) the glider depth. We describe briefly a method for obtaining estimates for three of these parameters and show some results in terms of the glider drag and lift coefficients over a wide range of operating conditions. Additional work is outlined to obtain estimates for the parameters which determine the pitching moment behaviour of this ocean glider.

Zedel, L., 2008, Modeling Pulse-to-pulse Coherent Doppler Sonar, *J. Atmos. Oceanic Tech.*, **25**: 1834-1844, doi:10.1175/2008JTECHO585.1

Coherent Doppler sonar provides a powerful tool for probing boundary layer flows under field and laboratory conditions. However, velocity profiling applications of this technique are complicated by characteristic velocity and range ambiguities. Proper implementation for any application requires careful design so that performance can be accurately predicted. In this paper, a computer model capable of simulating coherent Doppler operation is presented. The point scatterer model operates in three dimensions and accommodates bistatic transducer geometries. Excellent agreement is demonstrated between model simulations and laboratory trials. Some simple model applications are presented. The model has been developed for profiling applications but is equally suited to modeling point measurement acoustic Doppler velocimeters.

Zedel, L. and F. Y. Cyr-Racine, 2009, Extracting Fish and Water Velocity from Doppler Profiler Data *ICES J. Mar. Sci.,* **66**(9): 1846-1852, doi:10.1093/icesjms/fsp168

Doppler current profilers are optimized for measuring water velocities, but have the demonstrated capability to measure fish swimming speeds. This is possible when fish form schools that are large enough for all multiple Doppler sonar beams to sample the fish speeds at the same time. In situations where fish are not present in at least three acoustic beams, it is impossible to extract fish velocity with the data-processing algorithms normally used to extract water velocity. We present an alternative method of analysing Doppler sonar data that treats data from individual acoustic beams independently, so that velocities can be extracted when fish appear intermittently in the sonar beams. The method determines the variance for each velocity estimate so that data averaging can be adjusted to achieve the desired accuracy. The algorithm is applied to extract both water and fish velocities from Doppler profiler observations of overwintering Atlantic cod (*Gadus morhua*) in Smith Sound, Newfoundland. Currents in this enclosed coastal area are slow (~10 cm s^{-1}), and the fish appear to move passively with the water much of the time. However, there are times when the fish have velocities different from those of the water, and profiles averaged over 20 d show clear differences in fish and water velocities.

13 Remote Sensing

Bélanger, S., M. Babin, and P. Larouche, 2008, An empirical ocean color algorithm for estimating the contribution of chromophoric dissolved organic matter to total light absorption in optically complex waters, *J. Geophys. Res.*, **113**, C04027, doi:10.1029/2007JC004436

To estimate the depth-integrated rate of photochemical processes involving chromophoric dissolved organic matter (CDOM) in coastal waters, the contribution of CDOM to the total absorption coefficient must be known from UV to green. At 307 sites sampled in various coastal marine environments, the ratio between CDOM and the total absorption coefficient ([a_{CDOM}/a_t]) at 412 nm was found to vary over a wide range, from 0.20 to 0.95. An empirical algorithm was developed to retrieve [a_{CDOM}/a_t](412) from satellite remote sensing reflectance. The absolute uncertainty on the [a_{CDOM}/a_t] retrieval was 0.14. As exemplified with the data from the Baltic and North Seas, the algorithm provides a means to distinguish the contribution of CDOM to the absorption coefficient of colored detrital material (i.e., CDM = CDOM + nonalgal particles) at the regional scale. The implications of the variability in the magnitude and spectral shape of [a_{CDOM}/a_t] for the assessment of depth-integrated production of any photoproducts involving CDOM photolysis are discussed in details. We applied the algorithm to a Sea-viewing Wide Field-of-View Sensor (SeaWiFS) image of the Southeastern Beaufort Sea where terrestrial inputs are abundant. The spatial variability in the [a_{CDOM}/a_t] reaches as much as threefold over the continental shelf and beyond. These results clearly show that it is necessary to account for the spatial variability of [a_{CDOM}/a_t] when quantifying CDOM-related photochemical processes in the ocean.

Choisnard, J. and S. Laroche, 2008, Properties of variational data assimilation for synthetic aperture radar wind retrieval, *J. Geophys. Res.*, **113**, C05006, doi:10.1029/2007JC004534

The quality of marine wind vector retrieved from variational data assimilation (VAR) of Synthetic Aperture Radar (SAR) backscatter observation is assessed. It is found that the observation is most sensitive to wind speed. The retrieved wind direction from VAR is largely influenced by background wind direction and most of the SAR observation variability is assigned to wind speed. Non-linearity of the Geophysical Model Function (GMF) introduces wind speed bias, modulated by wind direction anisotropy (up-downwind/crosswind difference). The examination of the background wind vector departure from observation reveals two regimes: a quasi-linear response to wind direction for high background wind speed; and a rather monotonic response with two sharp transitions located at crosswind directions for low background wind speed. Information content of SAR observation is estimated using the entropy reduction approach, both analytically and from Monte-Carlo simulations. Crosswind directions have the lowest information content and correspond to those where non-linearity introduces largest discrepancies between analytic and Monte-Carlo estimations. The linear approximation of the GMF needed in the incremental VAR formulation is

examined. The retrieved winds using the incremental formulation are in good agreement with those using the non-linear GMF. Monte-Carlo simulations reveal specific situations, around sharp transitions at crosswind directions, where both linear and non-linear VAR formulations may produce more noise than extract information form observations.

Danielson, R. E., M. Dowd, and H. Ritchie, 2008, Objective analysis of marine winds with the benefit of the Radarsat-1 synthetic aperture radar: A nonlinear regression framework, *J. Geophys. Res.,* **113**, C05019, doi:10.1029/2007JC004413

Surface wind analyses are constructed from spaceborne synthetic aperture radar (SAR) measurements along coastal regions of eastern and western North America and collocated operational marine wind forecasts. Each analysis minimizes the error sum of squares of the wind forecast, the SAR backscatter, and wind direction that is inferred from the SAR backscatter gradient. The relative importance of the SAR wind information is defined by its expected error covariances. Parameters that define these covariances are postulated for half the analyses by comparison with an independent set of buoy observations. The remaining analyses are found to compare better with buoy observations than conventional analysis approaches. It is suggested that SAR wind information generally be weighted strongly in an analysis and that an error covariance length scale of O[10 km] is appropriate.

Devred E., S. Sathyendranath, and T. Platt, 2007, Relationship between the Q factor and inherent optical properties: Relevance to ocean-colour inversion algorithms, *Geophys. Res. Lett.* **34**, L18601, doi:10.1029/2007GL030764

Conversion between upwelling irradiance and radiance at the sea surface, essential for some aspects of remote sensing of ocean colour, requires knowledge of the *Q* factor. The *Q* factor depends on solar zenith angle, satellite viewing angle and the optical properties of the water. For simulated data for two fixed solar zenith angles, we express the *Q* factor as a function of total absorption and backscattering coefficients. The new parameterisation is used in an algorithm to retrieve total water backscattering from in situ ocean-colour data. The algorithm performs better than those in which the *Q* factor is expressed as a function of chlorophyll-a concentration alone.

Forget, M.-H., S. Sathyendranath, T. Platt, J. Pommier, and C. Fuentes-Yaco, 2007, Computation of primary production from remote-sensing of ocean colour of the Lagrangian site of C-SOLAS, Mar. Ecol. Prog. Ser., 352: 27–38, doi:10.3354/meps07223

At the C-SOLAS Lagrangian Study site, the phytoplankton community was dominated by diatoms in declining bloom conditions, which were characterised by a decrease in primary production over time. Measurements of primary production were performed using photosynthesis-light experiments and simulated *in situ* incubations. Several methods were used to assign photosynthetic parameters for estimation of primary production from remote-sensing of ocean colour: (1) the nearest-neighbour method (NNM), (2) a temperature-dependent model, (3) an iterative approach to retrieve photosynthetic parameters from *in situ*

measurements of phytoplankton production, and (4) average values of measured parameters. Owing to the declining status of the diatom population and its patchy distribution, the magnitude of primary production measured from *in situ* incubations was highly variable. Under bloom conditions, all methods underestimated production compared with results of simulated *in situ* measurements; however, the NNM provided the closest estimates to the *in situ* measurements. In the declining bloom phase, the NNM overestimated primary production, whereas the iterative method returned estimates of production in good agreement with the *in situ* observations. In conditions characterized by mixed-phytoplankton populations, the NNM returned estimates in agreement with the observations. A new method is proposed for classifying image pixels using criteria accessible to remote sensing, according to the phase of the diatom bloom (bloom versus declining conditions) and according to community composition (diatom versus mixed population). Upon separating the database used for parameter assignment into 2 parts, one representing the general phytoplankton community and the other representing declining diatom conditions, estimates of chlorophyll *a*-normalised water-column production were in good agreement with *in situ* observations.

Forget, M.-H., S. Sathyendranath, T. Platt, J. Pommier, C. Vis, M. Kyewalyanga, and C. Hudon, 2007, Extraction of photosynthesis-irradiance parameters from phytoplankton production data: Demonstration in various aquatic systems, *J. Plankton Res.*, **29**(3): 249-262, doi:10.1093/plankt/fbm012

A method is presented for extraction of the photosynthesis-response parameters from profiles of phytoplankton production. The procedure, previously proposed but not tested, is implemented here in various types of aquatic system and a protocol is established for its use. Values of daily primary production integrated over the photic zone were estimated from in situ or simulated in situ incubations in four coastal and open-ocean marine systems, and from photosynthesis-irradiance (*P–E*) curves in the afore-mentioned marine systems, as well as in two freshwater systems. The slope of the measured daily water-column production (normalised to water-column chlorophyll *a* biomass) plotted against the daily incident irradiance was variable from system to system (0.09 to 0.60), showing a broader range than previously reported values. Using an iterative procedure, we estimated the photosynthetic parameters from this linear relationship. Generally, estimated values lie within the 95% confidence interval of the photosynthetic parameters obtained from the *P–E* curves, showing that the estimates agree well with measurements. The new method, based on the photophysiological response of the phytoplankton community, provides a way to enhance our ability to compute primary production from remote sensing of ocean colour.

Gower, J. and S. King, 2007, An Antarctic ice-related "superbloom" observed with the MERIS satellite imager, *Geophys. Res. Lett.*, **34**, L15501, doi:10.1029/2007GL029638

MERIS (Medium Resolution Imaging Spectrometer) satellite imagery for early March 2006 shows streaks and patches of what appears to be an intense plankton bloom among broken ice off Ronne Entrance, Antarctica, near 73 S, 83 W. The

streaks are 2 to 10 km wide and up to 100 km long, extending across open water between land and the ice edge. We interpret these streaks as an example of a previously reported type of "superbloom," in which very high surface concentrations of chlorophyll occur in water containing ice platelets. Spectral bands of the MERIS satellite imager in the visible and near-infrared allow computation of an index suitable for detection of surface blooms containing high concentrations of chlorophyll, especially blooms associated with high-scattering from suspended sediment or ice. The images presented here suggest a new way in which MERIS images can contribute to the study of primary productivity in polar regions.

Huot, Y., C. A. Brown, and J. J. Cullen, 2007, Retrieval of phytoplankton biomass from simultaneous inversion of reflectance, the diffuse attenuation coefficient, and Sun-induced fluorescence in coastal waters, *J. Geophys. Res.*, **112**, C06013, doi:10.1029/2006JC003794

A model has been developed to retrieve phytoplankton absorption, a proxy for phytoplankton biomass, from observations of reflectance (R) and the diffuse attenuation coefficient (K_d) collected by moored radiometers in coastal waters, where high concentrations of chromophoric dissolved organic matter (CDOM) confound conventional ocean color algorithms. The inversion uses simultaneously two forward models: (1) a look-up table (LUT) that accounts for instrument geometry and the effect of the solar angle on both R and K_d and (2) an analytical function describing the effects of Sun-induced fluorescence (SIF) of chlorophyll on R. Estimates of phytoplankton biomass (mostly from SIF), the absorption by colored matter, and the particulate backscattering coefficients (mostly from the LUT) are obtained by optimizing the amplitude and shape of the absorption and backscattering coefficients in the forward model to best match the observations. An equation describing the quantum yield of fluorescence (photons fluoresced/photons absorbed) as a function of incident irradiance constrains the model and allows estimates of phytoplankton absorption. Innovations include: the utilization of both R and K_d, providing good separation of the effects of backscattering from absorption; avoidance of reflectance bands between 400 and 600 nm, thereby avoiding interference from bottom reflection and CDOM fluorescence; utilization of the full emission band of SIF; and accounting for the irradiance-dependence of its quantum yield. The model effectively retrieved chlorophyll concentration from an independent data set — $r = 0.76$, n = 93, with a mean absolute percent error (MAPE) of 24%; this is better than a modern ocean color algorithm (OC4V4) on its validation data set, when restricted to the same range of chlorophyll ($r = 0.67$, n = 384, MAPE = 51%).

Lee, Z., S. Shang, C. Hu, M. Lewis, R. Arnone, Y. Li, and B. Lubac, 2010, Time series of bio-optical properties in a subtropical gyre: Implications for the evaluation of interannual trends of biogeochemical properties, *J. Geophys. Res.*, **115**, C09012, doi:10.1029/2009JC005865

With a validated Quasi-Analytical Algorithm, an 11 year (1998–2008) monthly time series of the primary optical properties of waters in the center of the South

Pacific gyre was developed from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS). Also derived are chlorophyll *a* (Chl *a*) concentrations with the operational empirical algorithms for SeaWiFS and MODIS. The optical properties include the absorption coefficient (at 443 nm) of phytoplankton (a_{ph}) and that of the combination of detritus and gelbstoff (a_{dg}). From these time series, we further derived their annual background (summer low) and seasonal intensity (the difference between winter high and summer low). These time series show that (1) the optical properties have different seasonal and interannual variations, indicating different dynamics of these properties in the subtropical gyre; (2) there is a decreasing trend ($r^2 = 0.24$) of the background a_{ph} in the 1998–2008 period and an increasing trend of the a_{ph} seasonal intensity ($r^2 = 0.11$) for this period, and both trends are not statistically significant; (3) the a_{ph} time series agrees with the Chl *a* time series at the seasonal scale, but differs with respect to interannual variations; and (4) different interannual trends could be inferred with different time frames. These results emphasize that it is difficult to draw unequivocal conclusions about long-term trends of biogeochemical properties in the oceans with the current relatively short bio-optical records. To clarify and predict such trends, it is critical to get a full account of the forces that are responsible for the seasonal and interannual variations of these properties.

Moore, C., A. Barnard, P. Fietzek, M. R. Lewis, H. M. Sosik, S. White, and O. Zielinski, 2008, Optical tools for ocean monitoring and research, *Ocean Sciences*, **5**: 661-684**,** doi:10.5194/osd-5-659-2008

Requirements for understanding the relationships between ocean color and suspended and dissolved materials within the water column, and a rapidly emerging photonics and materials technology base for performing optical based analytical techniques have generated a diverse offering of commercial sensors and research prototypes that perform optical measurements in water. Through inversion, these tools are now being used to determine a diverse set of related biogeochemical and physical parameters. Techniques engaged include measurement of the solar radiance distribution, absorption, scattering, stimulated fluorescence, flowcytometry, and various spectroscopy methods. Selective membranes and other techniques for material isolation further enhance specificity, leading to sensors for measurement of dissolved oxygen, methane, carbon dioxide, common nutrients and a variety of other parameters. Scientists are using these measurements to infer information related to an increasing set of parameters and wide range of applications over relevant scales in space and time.

Nair, A., S. Sathyendranath, T. Platt, J. Morales, V. Stuart, M.-H. Forget, E. Devred, E., and H. Bouman, 2008, Remote sensing of phytoplankton functional types, *Remote Sens. Environ.*, **112**(8): 3366–3375, doi:10.1016/j.rse.2008.01.021

The principal goal in early missions of satellite-borne visible spectral radiometry (ocean colour) was to create synoptic fields of phytoplankton biomass indexed as concentration of chlorophyll-a. In the context of climate change, a major application of the results has been in the modelling of primary production and the

ocean carbon cycle. It is now recognised that a partition of the marine autotrophic pool into a suite of phytoplankton functional types, each type having a characteristic role in the biogeochemical cycle of the ocean, would increase our understanding of the role of phytoplankton in the global carbon cycle. At the same time, new methods have been emerging that use visible spectral radiometry to map some of the phytoplankton functional types. Here, we assess the state of the art, and suggest paths for future work.

Pimentel, S., K. Haines, and N. K. Nichols, 2008a, The assimilation of satellite-derived sea surface temperatures into a diurnal cycle model, *J. Geophys. Res.*, **113**, C09013, doi:10.1029/2007JC004608

Satellite sea surface temperature (SST) observations available from infrared and microwave radiometers derive a skin and sub-skin temperature measurement from very near the ocean surface. These measurements, particularly those taken during the day under clear calm conditions, are often seen to have a diurnal warming signal. These diurnal SST signals can result in errors and aliasing when observations collected at different times of the day and from a variety of observation sources are merged together to obtain "foundation" or bulk SST observation products. A similar problem occurs when SST observations are assimilated into ocean models, which typically do not resolve a diurnal cycle. In this article, a novel data assimilation method is developed and implemented that explicitly utilizes diurnal signal information in SST observations. The technique assimilates SST observations taken over the day into a diurnal cycle model by making corrections, within uncertainty bounds, to the surface boundary forcing of the model. In particular, the surface wind speeds and the fractional cloud cover parameter, which are typically poorly known over the oceans, are tuned in the process. This method is shown to improve the estimate of diurnal SST variability, and it has the potential to reduce uncertainties in estimates of foundation or bulk SST. As such, the procedure can be viewed as a dynamic observation operator.

Platt, T. and S. Sathyendranathhttp://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6V-4SRDFF3-2&_user=10&_coverDate=08%2F15%2F2008&_rdoc=1&_fmt=high&_orig=gateway&_origin=gateway&_sort=d&_docanchor=&view=c&_searchStrId=1676567305&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=aa0720f50bf63cc900c1c87e06b802bf&searchtype=a - aff2, 2008, Ecological indicators for the pelagic zone of the ocean from remote sensing, *Remote Sensing Env.* **112**(8): 3426-3436, doi:10.1016/j.rse.2007.10.016

It is generally accepted that responsible stewardship of the ocean implies ecosystem-based management. A requirement then arises for ecosystem indicators that can be applied in serial fashion with a view to detection of ecosystem change in response to environmental perturbations such as climate change or overfishing. The status of ecological indicators for the pelagic ecosystem is reviewed. The desirable properties of such indicators are listed and it is pointed out that remote sensing (ocean colour, supplemented by sea-surface temperature) is an important

aid to achieving them . Some ecological indicators that can be developed from remotely-sensed data on ocean colour are tabulated. They deal with the seasonal cycle of phytoplankton biomass, production and loss terms, annual production, new production, ratio of production to respiration, spatial variances in phytoplankton biomass and production, spatial distribution of phytoplankton functional types, delineation of ecological provinces and phytoplankton size structure.

Platt, T. and S. Sathyendranath, 2008, Ecological indicators for the pelagic zone of the ocean, *Remote Sens. Environ.*, **112**(8): 3426-3436, doi:10.1016/j.rse.2007.10.016

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Platt, T., S. Sathyendranath, M.-H. Forget, G. N. White, C. Caverhill, H. Bouman, E. Devred, and S. Son, 2008, Operational mode estimation of primary production at large geographical scales, *Remote Sens. Environ.*, **112**(8): 3437–3448, doi:10.1016/j.rse.2007.11.018

A protocol is developed for calculation of phytoplankton production from remotely-sensed data in the operational mode. The key element is an objective assignment, on a pixel-by-pixel basis, of the parameters required to implement a primary production model (parameters of the photosynthesis-response function and of the vertical distribution of pigment biomass). In a regional context, the assignment is made by searching the archived data on these parameters according to the (remotely-sensed) chlorophyll concentration and surface temperature. We refer to this approach as the Nearest-Neighbour Method. The procedure is justified on the basis of the known variation of bio- optical properties of phytoplankton with chlorophyll and temperature as well as through consideration of the seasonal variation of watercolumn stratification and its effect on the vertical pigment profile. We illustrate the method, and its justification, using data from the Northwest Atlantic Ocean. Using data from an oceanographic expedition not included in the archive, we find that the parameters estimated in this way are not significantly different from those obtained by direct measurement. We estimate the error associated with parameter assignment on the calculated phytoplankton

production to be about 27%. Some potential limitations of the method are discussed.

Platt, T., S. Sathyendranath, M.-H. Forget, G. N. White III, C. Caverhill, H. Bouman, E. D., and S.-H. Son, 2008, Operational estimation of primary production at large geographical scales, *Remote Sensing of Env.*, **112**(8): 3437-3448, doi:10.1016/j.rse.2007.11.018

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Platt, T., G. N. White III, L. Zhai, S. Sathyendranath, and S. Roy, 2009, The phenology of phytoplankton blooms: Ecosystem indicators from remote sensing, *Ecological Modelling*, **220**(21): 3057-3069, doi:10.1016/j.ecolmodel.2008.11.022

Remote sensing offers many advantages in the development of ecosystem indicators for the pelagic zone of the ocean. Particularly suitable in this context are the indicators arising from time series that can be constructed from remotely sensed data. For example, using ocean-colour radiometry, the phenology of phytoplankton blooms can be assessed. Metrics defined in this way show promise as informative indicators for the entire pelagic ecosystem. A simple phytoplankton–substrate model, with forcing dependent on latitude and day number is used to explore the qualitative features of bloom phenology for comparison with the results observed in a suite of 10-year time series of chlorophyll concentration, as assessed by remote sensing, from the Northwest Atlantic Ocean. The model reveals features of the dynamics that might otherwise have been overlooked in evaluation of the observational data.

Platt, T., S. Sathyendranath, G. N. White, C. Fuentes-Yaco, L. Zhai, E. Devred, and C. Tang, 2009, Diagnostic Properties of Phytoplankton Time Series from Remote Sensing, *Estuaries and Coasts*, **33**: 428-439, doi:10.1007/s12237-009-9161-0

Remote sensing provides our only window into the phytoplankton community on synoptic scales, permitting the construction of spatially distributed time series of biomass indexed as chlorophyll concentration. Data from the SeaWiFS mission have accumulated to the point where they meet the criterion of a 10-year series. The seasonal phytoplankton cycle is the dominant mode of temporal variability. The time series can be used to construct a variety of ecological indicators of the pelagic system useful in ecosystem-based management. These are reviewed and examples of their implementation are presented. Phenology of phytoplankton blooms is given particular attention. Interannual variation in some of the indicators is strong, presumably a response to variation in large-scale forcing. Examination of the results in the context of a simple phytoplankton-nutrient model enhances the interpretation. Remote sensing imagery also lends itself to the retrieval of information on community structure, in addition to biomass. More information will be recovered from satellite imagery if the remote-sensing program is coupled closely to a ship program on which appropriate bio-optical observations are made. The data series can be distilled to yield concise descriptions of the unfolding of ecosystem characteristics through time.

Platt, T., S. Sathyendranath, G. N. White, C. Fuentes-Yaco, L. Zhai, E. Devred, and C. Tang, 2010, Diagnostic Properties of Phytoplankton Time Series from Remote Sensing, *Estuaries and Coasts*, **33**(2): 428-439, doi:10.1007/s12237-009-9161-0

Remote sensing provides our only window into the phytoplankton community on synoptic scales, permitting the construction of spatially distributed time series of biomass indexed as chlorophyll concentration. Data from the SeaWiFS mission have accumulated to the point where they meet the criterion of a 10-year series. The seasonal phytoplankton cycle is the dominant mode of temporal variability. The time series can be used to construct a variety of ecological indicators of the pelagic system useful in ecosystem-based management. These are reviewed and examples of their implementation are presented. Phenology of phytoplankton blooms is given particular attention. Interannual variation in some of the indicators is strong, presumably a response to variation in large-scale forcing. Examination of the results in the context of a simple phytoplankton-nutrient model enhances the interpretation. Remote sensing imagery also lends itself to the retrieval of information on community structure, in addition to biomass. More information will be recovered from satellite imagery if the remote-sensing program is coupled closely to a ship program on which appropriate bio-optical observations are made. The data series can be distilled to yield concise descriptions of the unfolding of ecosystem characteristics through time.

Sathyendranath, S. and T. Platt, 2007, Spectral effects in bio-optical control on the ocean system, Oceanologia, **49**(1): 5-39

The influence of phytoplankton on the spectral structure of the submarine irradiance field is reviewed. The implications for the ocean system of the spectral response by phytoplankton to the ambient light field are discussed. For example, it provides the basis for retrieval of phytoplankton biomass by visible spectral radiometry (ocean-colour remote sensing). In the computation of primary

production, the results of spectral models differ in a known and systematic manner from those of non-spectral ones. The bias can be corrected without risk of incurring additional random errors. The models in use for phytoplankton growth, whether based on available light or absorbed light, whether expressed in terms of chlorophyll or carbon, are shown all to conform to the same basic formalism with the same parameters. Residual uncertainty lies less with the models than with the parameters required for their implementation. The submarine light field and the spectral characteristics of phytoplankton carry latent information on phytoplankton community structure. Differences in spectral response by different functional types of phytoplankton are small but significant. Optical considerations limit the maximum phytoplankton biomass that can be sustained in a given surface mixed layer. Moreover, the upper bound on the biomass depends on the spectral response of the dominant phytoplankton taxa. As a result, an optical control exists in the mixed layer that tends to resist extreme excursions of the biomass and also to maintain biodiversity in the phytoplankton.

Son, S., T. Platt, C. Fuentes-Yaco, H. Bouman, E. Devred, Y. Wu, and S. Sathyendranath, 2007, Possible biogeochemical response to the passage of Hurricane Fabian observed by satellites, *J. Plankton Res.*, **29**(8): 687-697, doi:10.1093/plankt/fbm050

Physical and biogeochemical changes induced by the Hurricane Fabian in the Northwest Atlantic in early September 2003 were observed using composite satellite images. After the passage of the hurricane, the mean sea surface temperature (SST) along the track decreased on average by about 1.3°C with maximum decrease of 10°C. At the same time, the mean Chl a concentration increased by about 42%. Entrainment of cold, nutrient-rich waters by vertical mixing induced by the hurricane seems to have enhanced the phytoplankton production. Asymmetric distribution of changes in SST and Chl a (strong intensity on the right side of the storm track) was observed from the satellite data. The storm-induced nitrate increase estimated from the satellite SST, using a local relationship between nitrate and temperature measurements was about 40% on average along the track of the storm. A numerical model study and climatological nutrient profile showed an increase in mixed-layer depth of 26 m and nitrate increase of about 0.2 μmol L^{-1} after the storm passage. In addition to altering the physicochemical conditions of the water column, physical forcing by the hurricane also changed the taxonomic composition of phytoplankton. It is inferred that the dominance of diatoms after the storm is a result of the increase in nutrient concentration within the mixed layer due to the wind forcing of the storm.

Voss, K. J., S. McLean, M. Lewis, C. Johnson, S. Flora, M. Feinholz, M. Yarbrough, C. Trees, M. Twardowski, and D. Clark, 2010, An example crossover experiment for testing new vicarious calibration techniques for satellite ocean color radiometry, *J. Ocean Atmos. Technol.*, **27**: 1747-1759, doi:10.1175/2010JTECH0737.1

Vicarious calibration of ocean color satellites involves the use of accurate surface measurements of water-leaving radiance to update and improve the system calibration of ocean color satellite sensors. An experiment was performed to

compare a free-fall technique with the established Marine Optical Buoy (MOBY) measurement. It was found in the laboratory that the radiance and irradiance instruments compared well within their estimated uncertainties for various spectral sources. The spectrally averaged differences between the National Institute of Standards and Technology (NIST) values for the sources and the instruments were <2.5% for the radiance sensors and <1.5% for the irradiance sensors. In the field, the sensors measuring the above-surface downwelling irradiance performed nearly as well as they had in the laboratory, with an average difference of <2%. While the water-leaving radiance L_w calculated from each instrument agreed in almost all cases within the combined instrument uncertainties (approximately 7%), there was a relative bias between the two instrument classes/techniques that varied spectrally. The spectrally averaged (400–600 nm) difference between the two instrument classes/techniques was 3.1%. However, the spectral variation resulted in the free-fall instruments being 0.2% lower at 450 nm and 5.9% higher at 550 nm. Based on the analysis of one matchup, the bias in L_w was similar to that observed for L_u(1 m) with both systems, indicating the difference did not come from propagating L_u(1 m) to L_w.

Zhai, L., T. Platt, C. Tang, M. Dowd, S. Sathyendranath, and M.-H. Forget, 2008, Estimation of phytoplankton loss rate by remote sensing, *Geophys. Res. Lett.*, **35**, L23606, doi:10.1029/2008GL035666

A method is presented for estimation of seasonally-varying, total loss rate of phytoplankton from time series of satellite-derived phytoplankton biomass data. The loss is calculated as the difference between the (modelled) rate of photosynthesis and the observed, realized rate of change of phytoplankton biomass. A Monte Carlo procedure is used to recover the loss rates. The (biomass-normalized) total loss rate shows a seasonal cycle with values ranging from 0.5 to 3 mg C (mg Chl)$^{-1}$ h^{-1} and shows an abrupt shift during the spring bloom. On the other hand, the absolute loss rate increases during blooms, a consequence of the increase in the biomass. The normalized total loss rate can be further expressed as a time-varying fraction of the assimilation number. The fraction lies in the range from 0.2 to 0.8. During the increasing (decreasing) phase of phytoplankton blooming, the ratio of growth to total loss increases (decreases), such that this ratio may have value as an ecological indicator for blooms.

14 Tsunami Research

Bornhold, B. D., J. R. Harper, D. McLaren, and R. E. Thomson, 2007, Destruction of the First Nations Village of Kwalate by a Rock Avalanche-generated Tsunami, *Atmos.-Ocean*, **45**(2): 123–128, doi:10.3137/ao.450205

The First Nations (Da'naxda'xw) village of Kwalate, Knight Inlet, British Columbia was located along the shore of a funnel-shaped bay. Archaeological investigations show that this was a major village that stretched 90 m along the shoreline and was home to possibly 100 or more inhabitants. Oral stories indicate that the village was completely swept away by a tsunami that formed when an 840-m high rock avalanche descended into the water on the opposite side of the

fjord. Shipboard geological mapping, combined with empirical tsunami modelling, indicate that the tsunami was likely 2 to 6 m high prior to run-up into the village. Radiocarbon dates reveal that the village was occupied from the late 1300s CE until the late 1500s CE when it was destroyed by the tsunami.

Candella, R., A. B. Rabinovich, and R. E. Thomson, 2008, The 2004 Sumatra tsunami as recorded on the Atlantic coast of South America, *Advances in Geosciences,* **14**: 117-128, doi:10.5194/adgeo-14-117-2008

The 2004 Sumatra tsunami propagated throughout the World Ocean and was clearly recorded by tide gauges on the Atlantic coast of South America. A total of 17 tsunami records were found and subsequently examined for this region. Tsunami wave heights and arrival times are generally consistent with numerical modeling results. Maximum wave heights of more than 1.2 m were observed on the coasts of Uruguay and southeastern Brazil. Marked differences in tsunami height from pairs of closely located tide gauge sites on the coast of Argentina illustrate the importance that local topographic resonance effects can have on the observed wave response. Findings reveal that, outside the Indian Ocean, the highest waves were recorded in the South Atlantic and not in the Pacific as has been previously suggested.

Cherniawsky, J. Y. , V. V. Titov, K. Wang and J.-Y. Li, 2007, Numerical Simulations of Tsunami Waves and Currents for Southern Vancouver Island from a Cascadia Megathrust Earthquake, *Pure and Applied Geophysics*, **164**(2-3): 465-492, doi:10.1007/s00024-006-0169-0

The 1700 great Cascadia earthquake (M = 9) generated widespread tsunami waves that affected the entire Pacific Ocean and caused damage as distant as Japan. Similar catastrophic waves may be generated by a future Cascadia megathrust earthquake. We use three rupture scenarios for this earthquake in numerical experiments to study propagation of tsunami waves off the west coast of North America and to predict tsunami heights and currents in several bays and harbours on southern Vancouver Island, British Columbia, including Ucluelet, located on the west coast of the island, and Victoria and Esquimalt harbours inside Juan de Fuca Strait. The earthquake scenarios are: an 1100-km long rupture over the entire length of the subduction zone and separate ruptures of its northern or southern segments. As expected, the southern earthquake scenario has a limited effect over most of the Vancouver Island coast, with waves in the harbours not exceeding 1 m. The other two scenarios produce large tsunami waves, higher than 16 m at one location near Ucluelet and over 4 m inside Esquimalt and Victoria harbours, and very strong currents that reach 17 m/s in narrow channels and near headlands. Because the assumed rupture scenarios are based on a previous earthquake, direct use of the model results to estimate the effect of a future earthquake requires appropriate qualification.

Fine, I. V., J. Y. Cherniawsky, A. B. Rabinovich and F. E. Stephensen, 2009, Numerical modeling and observations of tsunami waves in Alberni Inlet and Barkley Sound, British

Columbia, *Pure and Applied Geophysics,* **165**(11-12): 2019–2044, doi:10.1007/s00024-008-0414-9

Alberni Inlet is a long and narrow fjord adjacent to Barkley Sound on the Pacific Coast of Vancouver Island, Canada. Port Alberni, at the head of the inlet, was affected in 1964 by the largest Pacific tsunami waves in Canadian history. We use observations and results from two numerical models to investigate the resonant characteristics of the region and amplification of tsunami waves in Barkley Sound and Alberni Inlet. The first model (A) was forced at its open boundary with a stationary autoregressive signal, similar to the observed background noise. The second model (B) used an initial sea-level deformation from a potential earthquake off California in the southern segment of the Cascadia Subduction Zone, producing transient tsunami waves. Spectral, cross-spectral and frequency-time (f-t) analyses of the observations were used to examine the resonant properties and topographic response of the local area. The respective results show large admittance functions over a wide 0.5–0.9 cph frequency band, implying a low Q factor but high amplification of arriving waves. This unusual behavior is a result of two effects: A quarter-wave resonance of the system for its fundamental Helmholtz mode and amplification due to the narrowing of the channel cross section from Barkley Sound to Alberni Inlet. The model A numerical results agree favorably with the observations, indicating an energetic resonant mode at frequency of *0.53 cph (112 min), with its nodal line located near the entrance to Barkley Sound and amplification factor value close to 12. The results from the tsunami propagation model (B) yield spectral characteristics similar to those from the model A and from the observations. The maximum tsunami current speed for this scenario is 2.4 m s-1 in Sproat Narrows, which divides Alberni Inlet into two parts, while the largest computed wave height is 1.6 m in the northern Alberni Inlet, in the area of Port Alberni.

Gower, J., 2007, The 26 December 2004 tsunami measured by satellite altimetry, *Int. J. Rem. Sens.*, **28**(13-14): 2897-2913, doi:10.1080/01431160601094484

The 26 December 2004 magnitude 9 earthquake off Sumatra provided the first examples of travelling tsunami waves in mid-ocean clearly detected by satellite altimetry. The earthquake was the largest since satellite altimetry started in the 1970s and gave peak-to-trough wave heights in mid-ocean of over a metre. The tsunami was detected by three of the four altimeters presently giving sea surface height information. Each detected the spreading front twice, as it moved south-westwards into the Indian Ocean and as it moved northwards into the Bay of Bengal. They also detected the disturbed region closer to the epicentre that expands with the slower velocities of higher-frequency waves. Although the plate rupture is estimated to extend over about 1300 km in a north/south direction, the satellite observations appear consistent with a smaller generation area towards the south of this rupture zone. Fronts observed in the Indian Ocean show a positive first crest. Those observed in the Bay of Bengal are of smaller amplitude and appear to show a first negative first crest (trough). The structure in the Indian Ocean front observed by Jason-1 suggests the possible presence of a shorter-wavelength negative component superimposed on the positive crest.

Laverov, N. P., L. I. Lobkovsky, B. W. Levin, A. B. Rabinovich, E. A. Kulikov, I. V. Fine and R. E. Thomson, 2009, The Kuril Tsunamis of November 15, 2006, and January 13, 2007: Two Trans-Pacific Events, *Doklady Earth Sciences*. **426**(4): 658–664, doi:10.1134/S1028334X09040333

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GEOPHYSICS

The Kuril Tsunamis of November 15, 2006, and January 13, 2007: Two Trans-Pacific Events

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On December 26, 2004, a catastrophic earthquake (M_w = 9.3) occurred near the northwestern coast of Sumatra Island in the Indian Ocean. The tsunami generated by this event caused unprecedented destruction (with more than 226 000 casualties) and was one of the worst natural disasters in human history [15]. Analysis of this event performed at the Institute of Oceanology, RAS immediately after this event, revealed firstly, that the source of the earthquake of December 26, 2004, was located in a large seismic gap region where strong earthquakes had not been observed for more than 150 years; and secondly, that a similar seismic gap is located in the central part of the Kuril Kamchatka Subduction Zone [1, 4].

The possibility that a catastrophic earthquake and associated tsunami could occur within this gap was estimated to be extremely high and, correspondingly, this region requires thorough study and permanent geophysical monitoring. To examine this seismic gap, the Russian Academy of Sciences carried out two geophysical expeditions onboard the R/V *Akademik Lavrentiev* in August and September 2005 and 2006. During these expeditions, the structure of the subduction zone in the region of the Central Kuril gap was studied in detail and the region of the expected earthquake was located more precisely. The results of the research expeditions were used for prognostic tsunami calculations under different scenarios of a possible earthquake source [2, 5]. In 2006, a precise geodesic basis was developed to estimate the velocities of tectonic motions on the Kuril Islands and to determine coseismic effects needed for future geodynamic investigations in the conjunction zone between the Pacific and North American (Okhotsk) lithospheric plates. The arc of the Kuril Islands was instrumented with a network of GPS sensors along its entire extension. This network includes five permanent observational sites (on Shikotan, Kunashir, Iturup, Paramushir, and Urup islands) and six temporary observational sites (on Urup, Ketoi, Matua, Harimkotan, Paramushir, and Tanfilieva islands) [12].

On November 15, 2006, at 11:14 UTC, a strong earthquake occurred in the region of the Central Kuril Islands (M_w = 8.3) exactly where it had been predicted [6–8, 13]. The earthquake epicenter was located on the continental slope of the Kuril–Kamchatka Trench approximately 90 km southeast of Simushir Island. Two months later, on January 13, 2007, a second earthquake with similar magnitude (M_w = 8.1) to the 2006 earthquake occurred in the same region. The epicenter of the main shock was located on the oceanic side of the trench 100 km to the east of the epicenter of the first earthquake (Fig. 1a) [6, 7, 13]. Both earthquakes caused transoceanic tsunamis that were recorded over the entire Pacific basin including the coasts of Japan, Hawaii, Alaska, Canada, Peru, Chile, New Zealand, and the West Coast of the United States [7, 11, 13]. The first tsunami was stronger. It damaged several towns on the Pacific coast of the United States, with the severest damage in Crescent City (California) located in 6300 km from the earthquake epicenter [9].

The authors of [6, 7, 11] analyzed the properties of the Kuril tsunamis of 2006 and 2007 in the near-field zone, i.e., in the region of the Central Kuril Islands and North Japan. According to coastal tide gauge data, the maximum tsunami wave heights in 2006 were recorded at Malokurilsk on Shikotan Island (155 cm) and at the Japanese stations Urakawa (118.3 cm) and Hachinohe (106.3 cm). In 2007, significant tsunami waves were

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Lobkovskii, L. I., A. B. Rabinovich, E. A .Kul ikov, A. I. Ivashchenko, I. V. Fine, R. E. Thomson, T. N. Ivel' skaya, and G. S. Bogdanov, 2009, The Kuril Earthquakes and Tsunamis of Nove mber 15, 2006 and January 13, 2007: Observations, Analysis, and Numerical Modeling, *Oceanology*, **49**(2): 166-181, doi:10.1134/S0001437009020027

Major earthquakes occurred in the regi on of the Central Kuril Islands on November 15, 2006 (M_w = 8.3) and January 13, 2007 (M_w = 8.1). These earthquakes generated strong tsunam is recorded throughout the entire Pacific Ocean. The first was the strongest trans-Pacific tsunami of the past 42 years (since the Alaska tsunami in 1964). The high probability of a strong earthquake ($M_w \geq$ 8.5) and associated destructive tsunam i occurring in this re gion was predicted earlier. The most probable earthquake source region was investigated and possible scenarios for the tsunam i generation were modeled. Investigations of the event s that occurred on November 15, 2006, a nd January 13, 2007, enabled us to estimate the validity of the forecast and compare the parameters of the forecasted and observed earthquakes and tsunam is. In this paper, we disc uss the concept of "seismic gaps," which form ed the basis for the forecast of these events, and put forward further assumptions about the expected seismic activity in the region. We investigate the efficien cy of the tsuna mi warning services and estim ate the statistical parameters for the observed tsunami waves that s truck the Far Eastern coast of Russia and Northern Jap an. The propagation and transform ation of the 2006 and 2007 tsunam is are studied using num erical hydrodynamic modeling. The spatial characteristics of the two events are compared.

Mecking, J. V., C. T. Fogarty, R. J. Great batch, J. Sheng, and D. Mercer (2009), Using atmospheric model output to sim ulate the m eteorological tsunami response to Tropical Storm Helene, 2009, *J. Geophys. Res.*, **114**, C10005, doi:10.1029/2009JC005290

In the fall of both 1999 and 2000, unexpect ed "rapid tides" occurred along the coast of the Avalon Penins ula of Newfoundla nd. These rapid tides have been linked to the passing of Tropical Storm Jose (1999) and Tropical Storm Helene (2000) over the Grand Banks. Here we examine the dynam ic ocean response to Tropical Storm Helene (2000) using a barotropic shallow water ocean m odel forced by atmospheric p ressure and surf ace winds derived from a si mulation of Helene using a dynam ical model of the atm osphere. The ocean m odel is able to capture the main features of the observe d response at the coast of Newfoundland as seen in the available tide gauge data. Results show that the sim ulated sea level response at the coast is driven by a co mbination of wind stress and atmospheric pressure forcing, the form er generally dominating. An exception is C onception Bay, Newfoundland, where the response is captured mainly by atmospheric pressure forcing. Offshore near the edge of the Grand Banks, atmospheric pressure and wind stress forcing are equa lly important. The wind-forced response depends on the divergence of the surface wind stress and hence on the structure of the storm in the atm ospheric model simulation. Sensitivity studies show the importance of having a sm all time interval (on the order of m inutes) at which the atmospheric forcing is supplied to the o cean model and show the im portance of the location of the storm track.

Mosher, D.C., 2009, Submarine landslides and consequent tsunamis in Canada, *Geoscience Canada*, **36**(4): 179-190

Canada has the longest coastline and largest continental margin of any nation in the World. As a result, it is more likely than other nations to experience marine geohazards such as submarine landslides and consequent tsunamis. Coastal landslides represent a specific threat because of their possible proximity to societal infrastructure and high tsunami potential; they occur without warning and with little time lag between failure and tsunami impact. Continental margin landslides are common in the geologic record but tare on human timescales. Some ancient submarine landslides are massive but more recent events indicate that even relatively small slides on continental margins can generate devastating tsunamis. Tsunami impact can occur hundreds of km away from the source event, and with less than 2 hours warning. Identification of high-potential submarine landslide regions, combined with an understanding of landslide and tsunami processes and sophisticated tsunami propagation models, are required to identify areas at high risk of impact.

Mosher, D.C. , Z. Xu, and J. Shimeld, 2010, The Pliocene Shelburne mass-movement and consequent tsunami, western Scotian Slope. Submarine Mass Movements and Their Consequences. Advances in Natural and Technological Hazards Research, **28**(IV): 765-775, doi:10.1007/978-90-481-3071-9_62

Submarine mass-movement is a significant process along continental margins, even along passive margin slopes. Interpretation of seismic reflection profiles along the Scotian margin, for example, indicates the Cenozoic section is dominated by mass transport deposits (MTD) at a spectrum of scales. Occasional exceptionally large MTDs are observed which seem particularly foreign in a passive continental margin setting. The Shelburne MTD was recognized from exploration industry seismic reflection data along the western Scotian Slope. It is a buried Plio/Pleistocene feature that extends in excess of 100 km from the upper slope to the abyssal plain and maps to an area in excess of 5,990 km^2 and a volume >862 km^3. Its features demonstrate that it is a frontally-emergent MTD with a slump portion and a debris flow/run-out portion. Tsunami simulations were generated for this event, one assuming the slump portion generated the tsunami, the other, both the slump and debris flow contributed. For a mass movement comparable in scale to the Shelburne MTD, these simulations demonstrate that the city of Halifax, Nova Scotia, would be impacted within 70 to 80 minutes by a 13–25 m high wave, depending on the MTD source volume (slump or slump and debris field).

Rabinovich, A. B. and R. E. Thomson, 2007, The 26 December 2004 Sumatra tsunami: analysis of tide gauge data from the World Ocean. Part 1. Indian Ocean and South Africa, *Pure Appl. Geophys.*, **164**(2-3): 261-308, doi:10.1007/s00024-006-0164-5

The M_w = 9.3 megathrust earthquake of December 26, 2004 off the northwest coast of Sumatra in the Indian Ocean generated a catastrophic tsunami that was recorded by a large number of tide gauges throughout the World Ocean. Part 1 of our study of this event examines tide gauge measurements from the Indian Ocean

region, at sites located from a few hundred to several thousand kilometers from the source area. Statistical characteristics of the tsunami waves, including wave height, duration, and arrival time, are determined, along with spectral properties of the tsunami records.

Rabinovich, A. B., R. E. Thomson, and F. E. Stephenson, 2007, The 26 December 2004 Sumatra Tsunami: Analysis of Tide Gauge Data from the World Ocean Part 1. Indian Ocean and South Africa, *Surveys in Geophysics*, **27**(6): 647-677, doi:10.1007/s10712-006-9000-9

The M_w=9.3 megathrust earthquake of December 26, 2004 off the coast of Sumatra in the Indian Ocean generated a catastrophic tsunami that caused widespread damage in coastal areas and left more than 226,000 people dead or missing. The Sumatra tsunami was accurately recorded by a large number of tide gauges throughout the world's oceans. This paper examines the amplitudes, frequencies and wave train structure of tsunami waves recorded by tide gauges located more than 20,000 km from the source area along the Pacific and Atlantic coasts of North America.

Rabinovich, A. B., R. E. Thomson, V. V. Titov, F. E. Stephenson, and G. C. Rogers, 2008, Locally Generated Tsunamis Recorded on the Coast of British Columbia, *Atmos.-Ocean*, **46**(3): 343–360, doi:10.3137/ao.460304

This study presents analyses and numerical simulations of local tsunamis generated by two recent earthquakes off the coast of British Columbia. The Queen Charlotte Islands earthquake (Mw = 6.1) on 12 October 2001 generated waves that were recorded by tide gauges at Bamfield, Tofino, Winter Harbour and Port Hardy on the coast of Vancouver Island, with maximum measured wave heights of 11.3, 18.2, 22.7 and 14.5 cm, respectively. The Explorer Plate earthquake off Vancouver Island (Mw = 6.6) on 2 November 2004 generated waves recorded only at Bamfield and Tofino, with lower heights of 7.5 cm and 10.8 cm, respectively. The generation of tsunamis by these moderate, Mw = 6.1–6.6, local earthquakes suggests the possibility of destructive tsunamis from local sources other than the Cascadia Subduction Zone. This, in turn, has implications for tsunami hazards for this seismically active region of coastal North America.

Rabinovich, A. B., L. I. Lobkovsky, I. V. Fine, R. E. Thomson, T. N. Ivelskaya, and E. A. Kulikov, 2008, Near source observations and modeling of the Kuril Islands Tsunamis of 15 November 2006 and 13 January 2007, *Adv. Geosci.*, **14**: 105-116, doi:10.5194/adgeo-14-105-2008

Two major earthquakes near the Central Kuril Islands (M_w=8.3 on 15 November 2006 and M_w=8.1 on 13 January 2007) generated trans-oceanic tsunamis recorded over the entire Pacific Ocean. The strongest oscillations, exceeding several meters, occurred near the source region of the Kuril Islands. Tide gauge records for both tsunamis have been thoroughly examined and numerical models of the events have been constructed. The models of the 2006 and 2007 events include two important advancements in the simulation of seismically generated tsunamis: (a) the use of the finite failure source models by Ji (2006, 2007) which provide

more detailed information than conventional models on spatial displacements in the source areas and which avoid uncertainties in source extent; and (b) the use of the three-dimensional Laplace equation to reconstruct the initial tsunami sea surface elevation (avoiding the usual shallow-water approximation). The close agreement of our simulated results with the observed tsunami waveforms at the open-ocean DART stations support the validity of this approach. Observational and model findings reveal that energy fluxes of the tsunami waves from the source areas were mainly directed southeastward toward the Hawaiian Islands, with relatively little energy propagation into the Sea of Okhotsk. A marked feature of both tsunami was their high-frequency content, with typical wave periods ranging from 2–3 to 15–20 min. Despite certain similarities, the two tsunamis were essentially different and had opposite polarity: the leading wave of the November 2006 trans-oceanic tsunami was positive, while that for the January 2007 trans-oceanic tsunami was negative. Numerical modeling of both tsunamis indicates that, due to differences in their seismic source properties, the 2006 tsunami was more wide-spread but less focused than the 2007 tsunami.

Rabinovich, A. B., Vilibić, I. and S. Tinti, 2009, Meteorological tsunamis: Atmospherically induced destructive ocean waves in the tsunami frequency band, *Physics and Chemistry of the Earth, Parts A/B/C.* **34**(17-18): 891-893, doi:10.1016/j.pce.2009.10.006

no abstract; first paragraph

Vela Luka is a small town hidden in a bay on Korčula Island in the Adriatic Sea. In the early morning of 21 June 1978, the sea suddenly began to rise in the town, overtopping the piers and surging into the streets. The rumble of the incoming water awakened inhabitants who witnessed a series of destructive ocean waves, flooding much of the city and causing devastation and widespread damage. Tsunami-like waves with trough-to-crest heights of up to 6 m and periods of about 18 min appeared without any warning, resulting in the greatest natural disaster in the modern history of Vela Luka. Subsequent scientific investigations indicated that the waves were not related to a seismic event or submarine landslide but to atmospheric processes, identifying this as a meteorological tsunami event (Hodžić, 1979/1980; Orlić, 1980).

Ross, V. and D. Dion, 2007, Sea surface slope statistics derived from Sun glint radiance measurements and their apparent dependence on sensor elevation, *J. Geophys. Res.*, **112**, C09015, doi:10.1029/2007JC004137

Sea surface slope variances are obtained by inverting narrowband (444, 501, 677, and 864 nm) Sun glint radiance measurements using a detailed analytical specular sea surface bidirectional reflectance distribution function (BRDF) that includes mutual wave shadowing and hiding. The resulting data set spans a wide range of environmental conditions including wind speeds from 0.5 to 13.5 m s^{-1} and many different viewing and source geometries. Analysis against wind speed and atmospheric stability produces trends similar to those found in previous studies, as well as finer tendencies that were formerly difficult to detect. Furthermore, the detailed nature of the BRDF model used in the analysis permits an investigation

of the correlation of the statistics with viewing geometry, revealing a strong relationship between sensor elevation and measured slope variance, especially at grazing angles.

Stephenson, F. E. and A. B. Rabinovich, 2009, Tsunamis on the Pacific Coast of Canada Recorded in 1994–2007, *Pure and Applied Geophysics*, **166**(1-2): 177-210, doi:10.1007/s00024-008-0440-7

In the last 15 years there have been 16 tsunami events recorded at tide stations on the Pacific Coast of Canada. Eleven of these events were from distant sources covering almost all regions of the Pacific, as well as the December 26, 2004 Sumatra tsunami in the Indian Ocean. Three tsunamis were generated by local or regional earthquakes and two were meteorological tsunamis. The earliest four events, which occurred in the period 1994–1996, were recorded on analogue recorders; these tsunami records were recently re-examined, digitized and thoroughly analysed. The other 12 tsunami events were recorded using digital high-quality instruments, with 1-min sampling interval, installed on the coast of British Columbia (B.C.) in 1998. All 16 tsunami events were recorded at Tofino on the outer B.C. coast, and some of the tsunamis were recorded at eight or more stations. The tide station at Tofino has been in operation for 100 years and these recent observations add to the dataset of tsunami events compiled previously by S.O. Wigen (1983) for the period 1906–1980. For each of the tsunami records statistical analysis was carried out to determine essential tsunami characteristics for all events (arrival times, maximum amplitudes, frequencies and wave-train structure). The analysis of the records indicated that significant background noise at Langara, a key northern B.C. Tsunami Warning station located near the northern end of the Queen Charlotte Islands, creates serious problems in detecting tsunami waves. That station has now been moved to a new location with better tsunami response. The number of tsunami events observed in the past 15 years also justified re-establishing a tide gauge at Port Alberni, where large tsunami wave amplitudes were measured in March 1964. The two meteorological events are the first ever recorded on the B.C. coast. Also, there have been landslide generated tsunami events which, although not recorded on any coastal tide gauges, demonstrate, along with the recent investigation of a historical catastrophic event, the significant risk that landslide generated tsunami pose to coastal and inland regions of B.C.

Thomson, R. E., A. B. Rabinovich, and M. V. Krassovski, 2007, Double jeopardy: Concurrent arrival of the 2004 Sumatra tsunami and storm-generated waves on the Atlantic coast of the United States and Canada, *Geophys. Res. Lett.*, **34**, L15607, doi:10.1029/2007GL030685

A detailed analysis of over one hundred tide gauge records from the Atlantic coast of North America reveals that the arrival of the 26 December 2004 Sumatra tsunami on this coast coincided with the presence of tsunami-like waves being generated by a major storm tracking northward along the eastern seaboard of the United States. According to the tide gauge records, waves from the two events coalesced along the shores of Maine and Nova Scotia on 27 December where they

produced damaging waves with heights in excess of 1 m. Tsunami waves were identified in almost all outer tide gauges from Florida to Nova Scotia with maximum tsunami heights for the northern regions estimated to be 32–39 cm. In the south, maximum tsunami wave heights were in the range of 15 to 33 cm.

Thomson, R. E., A. B. Rabinovich, I. V. Fine, D. C. Sinnott, A. McCarthy, N. A. S. Sutherland, and L. K. Neil, 2009, Meteorological tsunamis on the coasts of British Columbia and Washington, *Physics and Chemistry of the Earth*, **34**(17-18): 938–955, doi:10.1016/j.pce.2009.10.003

Tsunami-like sea level oscillations recently recorded by tide gauges located at offshore, as well as sheltered, sites along the coasts of British Columbia (Canada) and Washington State (USA) are identified as meteorological tsunamis. The events resemble seismically generated tsunamis but have an atmospheric, rather than seismic, origin. The event of 9 December 2005 was sufficiently strong to trigger an automatic tsunami alarm, while other events generated oscillations in several ports that were potentially strong enough to cause damage to marine craft. Analysis of coincident 1-min sea level data and high-frequency atmospheric pressure data confirms that the events originated with atmospheric pressure jumps and trains of atmospheric gravity waves with amplitudes of 1.5–3 hPa. The pronounced events of 13 July 2007 and 26 February 2008 are examined in detail. Findings reveal that the first atmospheric pressure event had a propagation speed of 24.7 m/s and an azimuth of 352°; the second event had a speed of 30.6 m/s and an azimuth of 60°. These speeds and directions are in close agreement with high-altitude geostrophic winds (the jet stream) indicating that the atmospheric disturbances generating the tsunami-like sea level oscillations are likely wind-transported perturbations rather than freely propagating atmospheric gravity waves.

Vilibic, I., S. Monserrat, A. Rabinovich, and H. Mihanovic, 2008, Numerical Modelling of the Destructive Meteotsunami of 15 June, 2006 on the Coast of the Balearic Islands, *Pure and Applied Geophysics*, **165**(11-12): 2169–2195, doi:10.1007/s00024-008-0426-5

A destructive tsunami-like event (locally known as "rissaga" waves) occurring on 15 June, 2006 in Ciutadella Harbour (Menorca, Balearic Islands) is reproduced by a numerical model forced by a travelling atmospheric disturbance. The disturbance is reconstructed from microbarograph measurements, being the only available instrumental data at the time of the event. The model is verified based on two weaker 1997 events, which were recorded by a number of bottom pressure recorders operating at that time on the Menorca shelf, in Ciutadella Inlet and adjacent Platja Gran Inlet. Both 1997 events are numerically simulated and good agreement is achieved with observations in time, frequency (including eigenfrequencies of the affected inlets) and wave heights. Subsequently the same model is applied to simulate the 2006 event. The vigorous currents with speeds up to 400 cm/s are found to occur specifically at those areas of the harbour where the most severe damage and sinking of boats had been reported. Maximum simulated sea-level heights of 2.5 m were about one half of those reported by eyewitnesses. This difference is apparently caused by quality and spatial resolution of

bathymetry data. However, in general, the model is capable of reproducing the event fairly well and can probably be used for future assessment and mitigation activities on the coasts of the Balearic Islands.

15 Seawater

Feistel, R., D. G. Wright, K. Miyagawa, A. H. Harvey, J. Hruby, D. R. Jackett, T. J. McDougall, and W. Wagner, 2008, Mutually consistent thermodynamic potentials for fluid water, ice and seawater: A new standard for oceanography, *Ocean Sci.*, **4**: 275-291, doi:10.5194/os-4-275-2008

A new seawater standard for oceanographic and engineering applications has been developed that consists of three independent thermodynamic potential functions, derived from extensive distinct sets of very accurate experimental data. The results have been formulated as Releases of the International Association for the Properties of Water and Steam, IAPWS (1996, 2006, 2008) and are expected to be adopted internationally by other organizations in subsequent years. In order to successfully perform computations such as phase equilibria from combinations of these potential functions, mutual compatibility and consistency of these independent mathematical functions must be ensured. In this article, a brief review of their separate development and ranges of validity is given. We analyse background details on the conditions specified at their reference states, the triple point and the standard ocean state, to ensure the mutual consistency of the different formulations, and the necessity and possibility of numerically evaluating metastable states of liquid water. Computed from this formulation in quadruple precision (128-bit floating point numbers), tables of numerical reference values are provided as anchor points for the consistent incorporation of additional potential functions in the future, and as unambiguous benchmarks to be used in the determination of numerical uncertainty estimates of double-precision implementations on different platforms that may be customized for special purposes.

Millero, F. J., R. Feistel, D. G. Wright, and T.J. McDougall, 2008, The composition of standard seawater and the definition of the reference-composition salinity scale, *Deep-Sea Res II.*, **55**(1): 50-72, doi:10.1016/j.dsr.2007.10.001

Fundamental determinations of the physical properties of seawater have previously been made for Atlantic surface waters, referred to as "Standard Seawater". In this paper a Reference Composition consisting of the major components of Atlantic surface seawater is determined using these earlier analytical measurements. The stoichiometry of sea salt introduced here is thus based on the most accurate prior determination of the composition, adjusted to achieve charge balance and making use of the 2005 atomic weights. Reference Seawater is defined as any seawater that has the Reference Composition and a new Reference-Composition Salinity S_R is defined to provide the best available estimate of the Absolute Salinity of both Reference Seawater and the Standard Seawater that was used in the measurements of the physical properties. From a practical point of view, the value of S_R can be related to the Practical Salinity S by

S_R = (35.16504/35) g kg^{-1} x S. Reference Seawater that has been "normalized" to a Practical Salinity of 35 has a Reference-Composition Salinity of exactly S_R = 35.16504g kg^{-1}. The new independent salinity variable S_R is intended to be used as the concentration variable for future thermodynamic functions of seawater, as an SI-based extension of Practical Salinity, as a reference for natural seawater composition anomalies, as the currently best estimate for Absolute Salinity of IAPSO Standard Seawater, and as a theoretical model for the electrolyte mixture "seawater".

16 Tidal Analysis and Processes

Foreman, M. G. G., J. Y. Cherniawsky, and V. A. Ballantyne, 2009, Versatile harmonic tidal analysis: improvements and applications, *J. Atmospheric and Ocean Tech.* **26**(4):806–817, doi:10.1175/2008JTECHO615.1

New computer software that permits more versatility in the harmonic analysis of tidal time series is described and tested. Specific improvements to traditional methods include the analysis of randomly sampled and/or multiyear data; more accurate nodal correction, inference, and astronomical argument adjustments through direct incorporation in the least squares matrix; multiconstituent inferences from a single reference constituent; correlation matrices and error estimates that facilitate decisions on the selection of constituents for the analysis; and a single program that analyzes one- or two-dimensional time series. This new methodology is evaluated through comparisons with results from old techniques and then applied to two problems that could not have been accurately solved with older software. They are (i) the analysis of ocean station temperature time series spanning 25 yr, and (ii) the analysis of satellite altimetry from a ground track whose proximity to land has led to significant data dropout. This new software is free as part of the Institute of Ocean Sciences (IOS) Tidal Package and can be downloaded, along with sample input data and an explanatory readme file.

17 Atmosphere-Ocean in General

Greatbatch, R. J., X. Zhai, C. Eden, and D. Olbers, 2007, The possible role in the ocean heat budget of eddy-induced mixing due to air-sea interaction, *Geophys. Res. Lett.*, **34**, L07604, doi:10.1029/2007GL029533

The traditional point of view is that in the ocean, the meridional transport of heat is achieved by the wind-driven and meridional overturning circulations. Here we point out the fundamental role played by ocean mixing processes. We argue that mixing (i.e., water mass conversion) associated with eddies, especially in the surface mixed layer, can play an important role in closing the ocean heat budget. Our results argue that the lateral mixing applied at the surface of ocean/climate models should be playing an important role in the heat balance of these models, indicating the need for physically-based parameterizations to represent this mixing.

Jessup, A. T., W. E. Asher, M. Atmane, K. Phadnis, C. J. Zappa, and M. R. Loewen, 2009, Evidence for complete and partial surface renewal at an air-water interface, *Geophys. Res. Lett.*, **36**, L16601, doi:10.1029/2009GL038986

A wind-wave flume is used to determine the extent to which the thermal boundary layer (TBL) at a wind-forced air-water interface is completely renewed from below. We measure skin temperature, T_{skin}, radiometrically, temperature immediately below the TBL, $T_{subskin}$, using a temperature profiler, and net heat flux using the gradient flux technique. The T_{skin} probability density function, $p(T_{skin})$, and surface renewal time scale, τ, were measured using passive and active infrared imaging techniques, respectively. We find that the mean percentile rank of $T_{subskin}$ in $p(T_{skin})$ is 99.90, implying that complete surface renewal occurs. This result suggests an alternative to radiometric measurement of T_{skin} through the simple combination of an infrared camera and an *in situ* temperature sensor. Comparison of the temperature difference across the TBL to the expected cooling implies that a significant portion of events only partially renew the TBL. This result should impact efforts to improve air-sea transfer models.

18 Biophysical Processes in General

Bard, S. M., B. R. Ruddick, and C. T. Taggart, 2008, The flux of stuff: Developing an inexpensive and accurate method to track dispersion of environmental contaminants in aquatic ecosystems, *Mar. Environ. Res.*, **66**, 187-189, doi:10.1016/j.marenvres.2008.02.052

For decades, aquatic toxicologists and environmental scientists have been frustrated in accurately measuring, across a range of scales, the dispersion of contaminants, effluent plumes, pollution gradients, suspended particulates, sediments, biological propagules, natural and manmade tracers. Of particular concern for aquatic toxicologist is the necessity to establish contaminant exposure levels at a given field site from water-borne effluent of interest, whether it be pulp mill and other industrial effluents, municipal sewage, mine acid drainage, produced waters from offshore oil and gas exploration, etc. Conventional technologies include instrumented drifters, current meters, various dyes and chemical tracers, and a plethora of numerical models. These technologies suffer prohibitive expense, compromised time and space resolution, and the paucity of numerical-model validation. We present concepts, rationale and field-trial results of an inexpensive magnetically-attractive particle and magnetic particle–collector system (patent pending) for measuring dispersion. The system is based on specially designed magnetically-attractive non-toxic particles that incorporate user-designed specific gravity, size and shape (to mimic study propagules) and markings (for multiple release purposes) used to measure dispersion via the autonomous magnetic particle–collector array. The system has the rare ability to time-integrate particle dispersion at scales of hours to months and meters to thousands of kilometers^2 without using power or electronics. In addition to applications in aquatic toxicology mapping effluent plumes, sewer systems, etc., this technology can be used to examine erosion and sedimentation in watersheds, larval dispersion, alien species invasion, population/ species connectivity,

aquaculture settings, and each with the added advantage of dispersion model development and validation.

Benoît, H.P., T. Hurlbut, and J. Chassé, 2010, Assessing the factors influencing discard mortality of demersal fishes using a semi-quantitative indicator of survival potential, *Fish. Res.*, **106**: 436-447, doi:10.1016/j.fishres.2010.09.018

Understanding the factors affecting the likelihood that discarded fish will die can contribute to better management of resources by enhancing the potential for successful live release and by improving the estimation of otherwise unaccounted fishing mortality. Semi-quantitative measures of individual fish vitality or physical condition, obtained by at-sea observers aboard commercial fishing vessels, are often used as an indicator of survival potential for discarded fish. The present study and previous ones have shown that these measures relate well to eventual survival. However, observer subjectivity in fish vitality scoring can affect the precision and accuracy of inferences drawn from an analysis of the observations. Here we propose the use of a mixed-effects multinomial proportional-odds model, which is appropriate for modelling ordinal vitality data and is a useful approach for addressing observer scoring subjectivity. This model was used to analyse data collected for eleven fish taxa captured by four gear types. The effect of eight factors previously shown to affect discard survival was evaluated. The gear type used and amount of time that fish spent on deck prior to discarding most strongly and consistently affected the distribution of fish among vitality levels. Sea surface and air temperatures, and fish body size, were also important factors for a number of taxa, while other factors such as the depth fished, catch size and fishing activity duration were important only for certain taxa. A random effect in the model, used to account for observer subjectivity, was significant for most taxa and fisheries. Failure to account for this effect could affect both the precision and accuracy of inferences on the survival potential of discarded fish.

Hannah, C. G., 2007, Future directions in modelling physical-biological interactions, *Mar. Ecol. Prog. Ser.*, **347**: 301–306, doi:10.3354/meps06987

Reflection on 5 yr of deliberations of the International Council for the Exploration of the Sea (ICES) Working Group on Modelling Physical–Biological Interactions and the discussions at the workshop on 'Future Directions in Modelling Physical–Biological Interactions' has led to 3 broad themes concerning future work in the field. Firstly, model validation, the rigorous assessment of the level of confidence in the model predictions, is crucial for any model that will be used for practical applications. Secondly, determining the level of model complexity required to capture the essential features of the problem being addressed is an open problem. Finally, all the problems are multidisciplinary and there is a need for more integration of physics, chemistry and biology, on the one hand, and observationalists, experimentalists and modellers, on the other. The process of model validation provides a framework for connecting these themes.

Sameoto, J., T. Ross and A. Metaxas, 2010, The effect of flow on larval vertical distribution of the sea urchin, *Strongylocentrotus droebachiensis*, *J. Exp. Mar. Biology*, **383**:156-163, doi:10.1016/j.jembe.2009.11.014

Most meroplanktonic larvae have been considered to behave as passive particles in the water column, and their dispersal determined by advection. However, larvae may influence their horizontal transport by sinking or swimming between overlying water masses. The flow conditions under which larvae influence their vertical distribution through depth regulation are presently unclear. Using an annular flume, we examined the effect of increasing flow, repeated exposure to flow, and acceleration and deceleration on the vertical distribution of 4-arm stage echinoplutei of *Strongylocentrotus droebachiensis*. Specifically, we generated different levels of vertical velocity and shear strengths by manipulating horizontal velocity (u). We increased and decreased flow speed incrementally from no flow ($u = 0$ cm s^{-1}) to intermediate flow ($u = 0.48$ cm s^{-1}) to high flow ($u = 1.02$ cm s^{-1}) for each of 3 cycles within each of 2 independent trials. We used a high resolution digital camera to record, and image-analysis to quantify, larval distribution. In the absence of flow, larvae swam upwards and aggregated near the surface of the flume. With increasing flow, increasing numbers of larvae were observed in the mid to low water column indicating a negative influence on larval ability to aggregate near the surface. No differences were observed between distributions in acceleration and deceleration phases of the cycles; however, results suggest that increased exposure can decrease the ability of larvae to regulate their vertical position over time. Vertical shear can result in the re-orientation of swimming larvae and likely compromised larval ability for directed swimming in our study. The threshold shear level beyond which larvae cannot regulate their vertical position is > 2 s^{-1}, suggesting that echinoid larvae may be more vulnerable to shear than other weak swimmers, most likely because of their shape. However, echinoid larvae can likely influence their vertical distribution within many areas in the ocean, since shears > 2 s^{-1} are present only in highly turbulent regions such as fronts.

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