Freshwater-Marine Coupling in the Hudson Bay IRIS

Project Leader

Barber, David (University of Manitoba); Sydor, Kevin (Manitoba Hydro)

Network Investigators

Zou Zou Kuzyk (Institut national de la recherche scientifique - Eau, Terre et Environnement); Bruno Tremblay (McGill University); Simon Prinsenberg (University of Manitoba)

Collaborators and Research Associates

Sergei Kirillov (Arctic and Antarctic Research Institute); Helmuth Thomas (Dalhousie University); James Hamilton, Charles Hannah, Youyu Lu, Ingrid Peterson, Roger Pettipas (Fisheries and Oceans Canada - Bedford Institute of Oceanography); Sophie Johannessen, Robie W. Macdonald, Lisa Miller (Fisheries and Oceans Canada - Institute of Ocean Sciences); Yves Gratton (Institut national de la recherche scientifique - Eau, Terre et Environnement); Kevin Sydor (Manitoba Hydro); Jean-Francois Lemieux, Maria Pastor (McGill University); Sam Bentley (Memorial University of Newfoundland); Miguel Goni (Oregon State University); David Huard (Ouranos); Frédéric Dupont (Québec-Océan), Celine Gueguen (Trent University); Martin Vancoppenolle (Université catholique de Louvain); Anne de Vernal (Université du Québec à Montréal); Michel Gosselin (Université du Québec à Rimouski); Louis Fortier, Jean-Eric Tremblay (Université Laval); Jerome Sirven (Université Pierre et Marie Curie); Thomas Krumpen (University of Kiel); Igor Dmitrenko, Steven Ferguson, Ryan Galley, Mats Granskog, Klaus Hochheim, Greg McCullough, Jill Oakes, Tim N. Papakyriakou, Gary A. Stern, Emmelia Wiley (University of Manitoba); Fiamma Straneo (Woods Hole Oceanographic Institute (WHOI))

Postdoctoral Fellows

Katherine Leonard (Columbia University - Lamont-Doherty Earth Observatory); Alexander Slavin (McGill University)

PhD Students

Louis Renaud (McGill University); Peter Hülse (Memorial University of Newfoundland); Pamela Godin, John Iacozza (University of Manitoba)

MSc Students

Amelie Bouchat, Melissa Gervais, Yukie Hatta (McGill University); Geoff Gunn, Masters Student (University of Manitoba)

Technical Staff

Shannon Nudds (Fisheries and Oceans Canada - Bedford Institute of Oceanography); Simon Senneville (Université du Québec à Rimouski); Alex Hare, Brian Horton (University of Manitoba)

Abstract

Climate models predict warming in the Hudson Bay watershed that may alter the amount and timing of runoff and hence, of the load of suspended solids, dissolved organic matter and other major nutrients, and heat delivered to the Bay. In the Churchill and Nelson estuaries, such changes will be superimposed on earlier changes in the hydrological regime – diversion of Churchill River flows into the Nelson River and a shift of a third of total discharge from summer to winter. Our study of transfer pathways through river estuaries into Hudson Bay will improve our understanding of the effects of these changes. The overarching objective of this project is to describe the impact of freshwater quality and quantity on marine processes within Hudson Bay. In particular we are interested in understanding the principal processes which couple the freshwater and marine systems in Hudson Bay and to examine the cumulative impacts of climate change and hydroelectric development on Hudson Bay. Our key industry partner (Manitoba Hydro) will use this information to examine aspects of environmental impacts due to development of dams along the Nelson River, including the planned development of Conawapa Generating Station. More specifically our team will determine the fluxes, pathways and fate of suspended solids and dissolved organic matter transferred through the Churchill and Nelson estuaries during the open water season when mixing in the estuary is determined by wind-driven waves, tides and fluvial and marine currents, and under ice, when mixing is determined by tides and fluvial and marine currents alone. We will also investigate the relative significance of fluvial loading and littoral resuspension to concentrations of suspended solids in the estuaries and Hudson Bay and to study the effect of suspended solids and dissolved organic matter on radiative transfer in the estuary and nearby Hudson Bay. This team will also investigate historical effects of climate on Hudson Bay by interpretation of data stored in bottom sediments within our three supersites – the estuaries of the Nelson and Churchill Rivers, and of the Grande Rivière de la Baleine – and also in sediments deposited at the Bay-wide scale.

Key Messages

1. Ice cover strongly affects tidal amplitudes, velocities and phases in the Nelson River Estuary. In the mid-winter, tidal amplitude and range are significantly reduced due to under-ice friction in Hudson Bay. Tidal speed is amplified due to reduction of cross-section of the channel by formation of fast ice (Wang et al. 2012).
2. Suspended sediment concentration in the Nelson River Estuary is reduced when fast ice is present. The ice armors shallow nearshore shoals protecting them from erosion. This demonstrates the importance of ice effects on estuarine variability and the complexity of processes in a seasonally ice-covered estuary (Wang et al. 2012).
3. In contrast to Hudson Strait, colored dissolved organic matter (CDOM) in Hudson Bay is controlled by terrestrial inputs. CDOM absorption was reduced significantly within the Bay, likely due to photobleaching. However, there was no or negligible indication of absorption removal during initial estuarine mixing. Spectral slope parameters at shorter wavelengths were the best indicators for absorption removal by photobleaching. (Granskog 2012)
4. Sediment accumulation rates in the Great Whale River appear to be relatively steady over timescales of 50-100 year. Under present day conditions 23 % of the discharged sediment accumulates in a 25 km^2 area off the river mouth. The remaining 77 % are either deposited further offshore, possibly along the northeastern shore as a result of Hudson Bay's counterclockwise circulation, or dispersed into the Hudson Bay system. Differences between 137Cs and 210Pb sediment accumulation rates suggest an offshore shift in the locus of fine sediment deposition during the past ~150 year, which may be a result of ongoing climatic warming leading to decreasing sea-ice coverage and a more energetic marine environment and an increased offshore transport of terrestrial matter (Hülse and Bentley Sr. 2012).

5. Watershed and seasonal ice each supply roughly half of freshwater inventory, equivalent to ~3 m depth spread over the upper mixed layer, in Hudson Bay. The spatial distribution differs: Sea ice meltwater contribution grades from <2 m freshwater in northwest to >3 m in southeast; influence of fluvial water is greater near the southern and eastern shores, lowest in northern and central Hudson Bay (<0.25 m) and highest near the mouth of James Bay (>2 m) (Granskog et al. 2007).
6. A conceptual model for an Arctic sea driven by river runoff, atmospheric fluxes, sea ice melt/growth, and winds was developed and applied to Hudson and James Bays for the period 1979-2007. Model results are consistent with records from instruments within Hudson Bay. Simulations of the halocline, the baroclinic boundary current, spatial variability of freshwater content, and the fall maximum in freshwater export in Hudson Bay and James Bay clarified the important differences in the freshwater balance of the western and eastern sides of Hudson Bay (St-Laurent et al. 2012).
7. Exchange between the previously-described coastal fresh water conduit, which carries relatively nutrient-rich, river-derived fresh water anticlockwise around the littoral zone of the Bay (Granskog et al. 2009), and central Hudson Bay was described; model results suggest this process effectively increases the residence time of fluvial water in Hudson Bay to an average of 3 years. Isotopic data, which distinguish river-derived fresh water from sea-ice melt imply a somewhat longer (~5 year) flushing time for the interior portion of Hudson Bay. Distinguishing between runoff and sea-ice melt is especially important in Hudson Bay because both fresh water sources are large, which permits significant interaction that may be impacted by climate change and hydroelectric development (Macdonald and Kuzyk 2011).
8. Complementary studies of autumn (Hochheim and Barber 2010) and spring (Hochheim et al. 2011) inter-decadal variability and long-term trends in the formation and breakup/melt of the Hudson Bay ice pack were analyzed in relation to climate variability and trends. Together these papers demonstrate that the ice-free season is becoming longer in both spring and autumn, and that this growth is quantitatively predictable from climate data. An integration, synthesis and updating of these papers is currently in review for a special publication on Hudson Bay.
9. The role of light and nutrients as affected by fresh water stratification and sea-ice cover in regulating marine primary production in Hudson Bay was investigated using sedimentary dinoflagellate cysts and geochemical tracers as proxies (Heikkila et al. 2013). This work, presently in review, discusses the potential for certain cyst species to be used as tracers for past fresh water inputs, nitrate availability to surface waters, and sea-ice in the Hudson Bay system.
10. Foster et al. (2012) present the first database for mercury uptake and transfer exclusively within zooplankton food webs in northern marine waters. Evidence of food web linkages and mercury biomagnification in both THg and MMHg concentrations suggest that exposure to mercury at higher trophic levels including humans can be affected by processes at the bottom of Arctic marine food webs.

Objectives

1. Model the dynamic forcing of ocean and sea ice circulation throughout Hudson Bay with a particular emphasis on understanding the relative contributions of climate change versus hydro electric regulation on freshwater-marine processes in Hudson Bay.
2. Understand the role that freshwater plays in physical and biological processes in Hudson Bay.

3. Retrieve/redeploy all ArcticNet Long Term Observatory and Manitoba Hydro (MH) funded moorings.
4. Data analysis and publication of a Hayes - Nelson estuary sediment budget and sediment transport study (publication in collaboration with Manitoba Hydro).
5. Data analysis and publication leading to Hudson Bay carbon flux papers (see collaborator list).
6. Data analysis and publication related to climate effects on sea ice in Hudson Bay.
7. Model interaction of sea ice and tidal motions in Hudson Bay.

Introduction

Freshwater loading has a major influence on coastal arctic marine waters. Freshwater fluxes into Hudson Bay are dominated by the large-scale hydrological cycle of the Hudson Bay watershed. Recent evidence (Déry et al. 2005) has shown that freshwater input to Hudson Bay has decreased over the past decades due to climate variability and increased water use. There has also been a notable shift in the seasonality of Hudson Bay discharge related in part to storage of water in reservoirs and later release for the generation of hydroelectricity (Déry et al. 2011). The annual cycle of sea ice growth and melt over Hudson Bay also plays an important role in the freshwater budget of the Bay and the associated exchange of freshwater between the estuaries, coastal current, and sea ice features. These dynamics have both biological and biogeochemical impacts (see summary in Macdonald and Kuzyk 2011).

Imported heat and nutrients make estuaries highly productive regions and preferred habitats in Hudson Bay (Stewart and Lockhart 2005, Kuzyk et al. 2008). Beyond the estuaries, freshwater runoff affects primary productivity negatively by increasing vertical stability of the water column, and positively through nutrient additions. Suspended solids are associated with nutrient loading that supports primary production, but may also reduce light penetration needed for production (e.g., Herdendorf et al. 1977) and they carry most of the organic and heavy metal pollutant load transported in this system (e.g., Hare et al. 2008; Kuzyk et al. 2010).

Our team focuses on three ArcticNet Hudson Bay IRIS supersites. The first two, the estuaries of the Churchill and Nelson Rivers, are appropriate regions to focus much of our study of fluvial loading to Hudson Bay. The Nelson delivers 13% of total annual runoff into the Hudson-James Bay system, and fully one-third in winter (Déry et al. 2005) and with it an equal or greater proportion of terrigenous suspended solids and dissolved organic matter (DOM). The Nelson is a highly productive estuary (Baker 1989) and is summer home to the largest concentration of beluga in the world (Stewart and Lockhart 2005). Together the two western ArcticNet supersite estuaries are affected by hydro-electric development resulting in more than 75% reduction in the flow of the Churchill River and a 30% increase in the Nelson. The third supersite, the estuary of the Grande Rivière de la Baleine, is unaltered by hydro-electric development and presents a further contrast in draining a watershed confined to the Precambrian Shield, whereas the Nelson River drains predominantly Plains geography. Climate models predict warming in the Hudson Bay watershed that may alter the amount and timing of runoff and hence, of the loads of suspended solids, DOM and other major nutrients, and heat delivered to the Bay. These delivery mechanisms affect physical-biological, and freshwater marine coupling within the Bay.

We are in the process of addressing a number of interrelated objectives that are designed to gain insights into the processes which control freshwater-marine coupling in Hudson Bay. The following objectives highlight our ongoing program:

- To understand the components and drivers, both spatial and temporal, of the freshwater balance of Hudson Bay and to link these components to hydroelectric regulation and climate change.
- To determine sources, fluxes and sinks of suspended sediments and dissolved organic matter (DOM)

over the seasonal cycle in Hudson Bay and in particular for the three Hudson Bay IRIS supersites.

- To determine how freshwater fluxes affect the marine ecosystem, biogeochemical processes and contaminant transport (through collaboration with other teams in our IRIS).
- To determine how sea ice affects freshwater-marine coupling and associated marine ecosystem function particularly in terms of the dynamics freshwater plumes under sea ice.
- To understand the significant role played by the boundary current in the freshwater budget of the system, and its sensitivity to wind-forcing.
- to model salient processes and to use these models to illuminate particular processes required in the development of the Hudson Bay IRIS.
- Through these studies to determine the relative roles of climate change versus hydroelectric development on freshwater-marine coupling in Hudson Bay by linking contemporary climate process studies to paleo-oceanographic analysis.

Activities

A Cold Estuaries Workshop was held in Winnipeg on 28-29 May 2012 with 48 participants from ArcticNet, University of Manitoba, University of Quebec at Rimouski, Trent University, University Laval, Memorial University Manitoba Hydro and associated consulting firms, Province of Manitoba, Government of Nunasiavut, and the Federal Department of Fisheries and Oceans. The overarching objectives of the workshop were to understand the relative contributions of climate change versus hydroelectric regulation to freshwater-marine coupling in Hudson Bay. The meeting summarized existing knowledge of freshwater-marine coupling in Hudson Bay, identified key gaps in our knowledge of these processes, and began the design of a suite of collaborative, multidisciplinary, large-scale field and observatory programs that would meet ArcticNet objectives and support MB hydro's monitoring interests beyond the end of ArcticNet. Workshop results and the upcoming field programs will form the central core of the ArcticNet IRIS-3 document which will focus around the natural science of freshwater-marine coupling in Hudson Bay. This document will evolve through our next major field push with completion in 2016/17.

As the CCGS Amundsen was in drydock for the summer, a reduced field sampling program was conducted aboard the CCGS Pierre Radisson. From 26 August to 3 September 2012, scientists from the Centre for Earth Observations Science (CEOS) at the University of Manitoba led a collaborative investigation of carbon, nutrient, mercury and sediment fluxes in the Nelson and Hayes estuaries (Supersite 705, Figure 1), in southwest Hudson Bay, as a contribution to BaySys2012. The primary goal of the expedition was to collect synchronous observations of several parameters associated with freshwater/marine and atmosphere/ocean fluxes in the estuarine mixing zone. The ship's barge and Zodiac craft were used simultaneously to collect samples along 40-50 km transects running seaward from fresh water in both the Nelson and Hayes Rivers to marine water in the outer estuary. At each station, we recorded CTD profiles (conductivity, temperature, turbidity, chlorophyll and CDOM fluorescence, and oxygen sensors) and atmosphere/water CO^2 partial pressures (Papakyriakou/Miller), and collected water samples for subsequent determination of salinity, delta-18O, DOC, DIC, alkalinity, major nutrients, chlorophyll, CDOM absorption and fluorescence, and suspended solids (McCullough/Gueguen/Barber).

These data supplement a similar data set collected during the BaySys2010 expedition on board the CCGS Amundsen, at which time weather conditions prevented the sampling team from reaching their objective of fully fresh water end-members to the same transects. In addition, on this expedition, samples were collected in order to investigate the decay rate of CDOM in order to improve our understanding of its distribution as a tracer of river water in Hudson Bay (Granskog).

Several subsidiary goals were accomplished, including sampling suspended particulates in the rivers for Hg and MeHg determination (Hare/Wang), collecting of

Figure 1. Top: ArcticNet Long Term Observatories and stations for the Hudson Bay supersites. The Churchill mooring (707) was retrieved and redeployed by ArcticNet. Mooring stations in the Riviere de la Grande Baleine (702) are no longer active due to budget constraints on mooring equipment and ship costs. Bottom: 2012 CTD and water quality stations in Nelson-Hayes estuary. Station 705a, a long-term mooring installed by Manitoba Hydro could not be retrieved.

dredged samples in the estuary for identification of benthic fauna (Jansen) and a helicopter survey of the Nelson estuary tidal flats, during which shallow sediment cores were obtained at 3 sites for determination of bulk density, particle size distribution (McCullough), carbon concentration and characterization (Kuzyk) and pore water CDOM fluorescence spectra (Gueguen). The determinations of Hg and MeHg in the particulate fraction of the Nelson River load complements determinations of total Hg and MeHg concentrations determined in 2006 (Hare, at the time a PhD student with Gary Stern). We attempted and failed to retrieve a Manitoba Hydro-funded mooring which had been re-deployed in the outer Nelson estuary in 2011 (first deployed in 2007).

Results

St-Laurent et al. (2012) completed and validated a conceptual model of the Hudson Bay driven by winds, rivers, atmospheric fluxes, and sea ice. The model reproduces the seasonal migration of the halocline, the baroclinic boundary current, the spatial variability of freshwater content, and the fall maximum in freshwater export that have been observed using moored instruments (Figure 2). The simulations show that the freshwater inputs and sinks are balanced in very different ways in different regions of Hudson Bay (the ice growth dominated western area versus the ice melt dominated eastern area).

It is anticipated that the collaborative effort between BIOS and CEOS using the Nucleus for European Modelling of the Ocean (NEMO) model will provide opportunities to better understand the year round role of wind forcing in Hudson Bay. In addition, a similar effort covering the IRIS 4 region (Wu et al. 2012) provides opportunity for comparison of methodological strengths and weaknesses and study of coupling between Hudson Bay and broader regional oceanography.

Past studies have mapped the distribution of CDOM in Hudson Bay (Granskog et al. 2007) and have used CDOM as a tracer for river water discharge from the Nelson Estuary. While terrestrial (river-derived) inputs are important in Hudson Bay, the system receives seasonally a substantial freshwater input from melting sea ice (Granskog et al. 2007, 2011). Granskog (2012) have since compared the removal of CDOM absorption derived from simple salinity–CDOM relationship to that derived using both salinity and delta-18O as tracers. The use of delta-18O provides a means to separate the contributions from river water (and to distinguish between rivers) and sea-ice melt and resolve their contribution to changes in salinity.

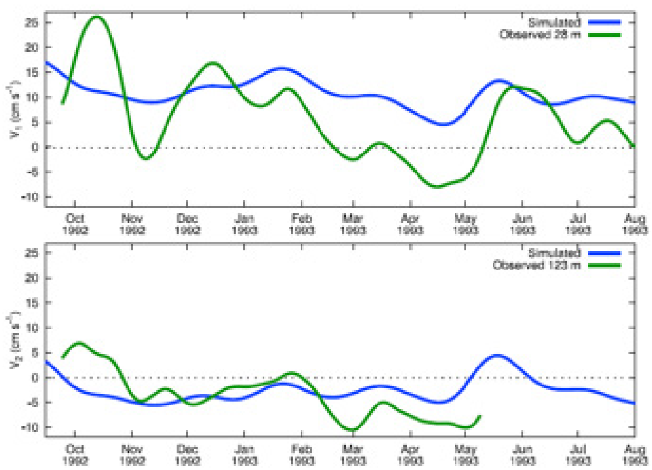

Figure 2a. Comparison between observed and simulated velocities at a northeastern Hudson Bay station. V1 (V2) is the velocity in the upper (lower) model layer. Data from the lower current-meter are not available after May 1993. Note the episodes of flow reversal in V2.

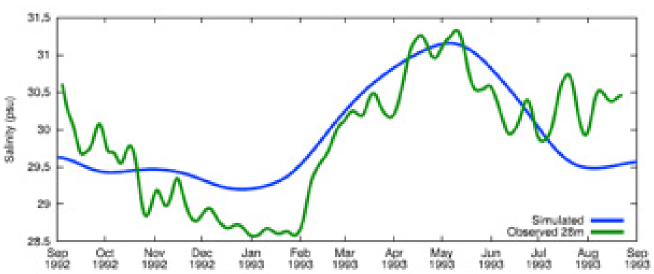

Figure 2b. As above, but comparing observed salinity and the pseudo-salinity (St-Laurent et al. 2012).

Granskog (2012) also studied removal of CDOM absorption in order to understand why it is high in a system where one would expect the opposite due to high circulation rates nearshore, high turbidity, long ice-cover and low productivity. Photobleaching and remineralization of CDOM are discussed as the primary processes by which removal of CDOM absorption takes place.

Box and gravity core samples collected during 2007 and 2009 cruises were analysed to study river discharge conditions of the Great Whale River. Radiochemistry (210Pb and 137Cs), granulometry and physical sedimentary structures provided insights into sedimentary processes and patterns of the freshwater/marine interface in the Great Whale River Estuary. Sediment accumulation over the past 50-100 years has been relatively stable, however, differences between 137Cs- and 210Pb-derived sediment accumulation rates indicate an offshore shift in the locus of fine sediment deposition during the past ~150 year. The authors hypothesize that this may be a result of ongoing climatic warming leading to decreasing sea-ice coverage and a more energetic marine environment similar to that observed during ice free conditions by Wang et al. (2012). Results from St. Laurent et al. (2012) indicate that changes in wind could also play a role in freshwater circulation in the region.

Currently, 23 % (40,000 t/yr) of the discharged sediment accumulates in a 25 km2 area off the Great Whale River. The remaining 77 % (136,000 t/yr) are either deposited further offshore, possibly along the northeastern shore as a result of Hudson Bay's counterclockwise circulation, or dispersed into the Hudson Bay system. Decadal variability in grain diameter suggests that environmental processes such as changes in river discharge, and estuary processes such as windier, more energetic conditions control sediment transport and deposition. Future collection of longer cores will help elucidate the role temperature, wind and sea ice variation plays in the offshore transport of terrestrial sediment (Hülse and Bentley Sr. 2012).

Widely distributed box-core sediments, which have been dated and geochemically characterized in previous studies (cf., Kuzyk et al. 2008, Kuzyk et al. 2009), were characterized for dinoflagellate cyst composition to evaluate the potential to apply select cyst species as tracers of past fresh water inputs, nitrate availability and sea ice (Heikkila et al. 2013). Spatial distribution and production of dinoflagellate cysts are primarily regulated by vertical stratification and nitrate availability, as interpreted from sedimentary geochemical proxies.

Finally, in the past year, a database of individual zooplankton taxa collected over a period of eight years (2003−2010) from across Hudson Bay (including Hudson Strait and Foxe Basin) was investigated to determine mercury uptake and transfer. The range in isotopic signatures of delta-15N indicated 4 trophic levels. Food web linkages and mercury biomagnification was evident both with total mercury and monomethylmercury concentrations increasing from prey to predator, and with trophic magnification factors (Foster et al. 2012).

Discussion

The conceptual model by St. Laurent et al. (2012) offers a new ability to study the effects of climate change in Hudson Bay. Changes in wind pattern or intensity (Wan et al. 2010) would have a direct impact on the velocity of the boundary current, and in turn, on the fresh water export from the basin. More cyclonic (anticyclonic) winds would favor a larger export (storage) of FW and a saltier (fresher) basin. As noted in past annual reports, changes in wind pattern and intensity also have a significant effect on sea ice extent in the bay (Hochheim and Barber 2010; Hochheim et al. 2011). Variations in sea ice concentration across Hudson Bay are significantly related to surface temperature and surface zonal winds from spring and the preceding fall. The use of the NEMO model at CEOS will provide an opportunity to incorporate Ouranos climate scenario output and drive projections of both marine and terrestrial freshwater and sea ice circulation in Hudson Bay.

The combination of studies in unaltered (Great Whale River) and altered (Nelson/Hayes and Churchill) freshwater estuaries is contributing to our understanding of the components and drivers, both spatial and temporal, of the freshwater balance of Hudson Bay and allowing us to link these components to hydroelectric regulation and climate change. Combined, the observational (mooring) study by Wang et al. (2012) and soft core study by Hulse and Bentley (2012) have created snapshots of both the sedimentation processes, and their variability in responses to change in river flow, and sediment resuspension and transport processes under tidal and other marine current influences. In both estuaries, a significant fine-grained fraction of the sediment load is carried in a plume well beyond the river mouth, increasing the importance of CDOM studies in order to track the circulation and fate of river waters (Granskog 2012). Wang et al. (2012) also find that local erosion and re-deposition play a dominant role in the Nelson River estuary, underscoring the importance of fast ice in armoring the tidal flats and preventing erosion. Combined, these studies provide a strong basis for comparative examination of the contribution of hydroelectric regulation and climate change in changing the energetics of sedimentation in Hudson Bay.

Recent and ongoing work with geochemical and micropaleontological proxies (dinoflagellate cysts) in Hudson Bay sediments are important in filling in gaps in our knowledge of the modern organic carbon cycle in the Bay and how it is affected by freshwater inputs. These studies also lay the groundwork for forecasting and tracking future changes in the organic carbon cycle and for retrospective analyses. Specific, regional species-environment relationships were identified by Heikkila et al. (2013), which will allow several main cyst species to be used as proxies in these analyses.

The studies of CDOM reported in Granskog et al. (2007) and CDOM and $\delta^{18}O$ in Granskog (2012) have substantially improved our ability to determine sources, fluxes and sinks of river water and thus its associated suspended sediments and dissolved organic matter (DOM) over the seasonal cycle in Hudson Bay and to trace water parcels from different sources as they circulate the Bay. However, much of this work is concentrated in nearshore regions adjacent to river estuaries, with relatively sparse measurement in offshore sites and sub-surface portions of the water column. This was identified as a key gap in our knowledge during the May, 2012 Cold Estuaries workshop.

Analysis of a zooplankton database covering samples taken from 2003-2010 by Foster et al. (2012) is an initial effort to determine how freshwater fluxes ultimately affect contaminant accumulation in the food web of this system. The results follow on studies of contaminant distribution in abiotic media (marine sediments) and inferences about their biogeochemical controls in the Hudson Bay system (Kuzyk et al. 2010; Hare et al. 2010). The latest results suggest that exposure to mercury at higher trophic levels including humans can be affected by processes at the bottom of Arctic marine food webs. The authors have partially filled a gap in our knowledge of mercury concentrations in zooplankton, which constitute the base of the pelagic food web, and they recommend that further study of the linkages between trophic levels, and targeted study of feeding ecology, among other work will contribute to the understanding of how biomagnification may change in response to changes to freshwater fluxes.

Conclusion

The freshwater marine coupling project has made substantial progress towards having a complimentary suite of observational (Hochheim and Barber 2010, Hochheim et al. 2011, Hülse and Bentley Sr. 2012, Wang et al. 2012) and modeling studies (St-Laurent et al. 2012). However, a better understanding of sea ice dynamics and its control on the ocean-ice-atmosphere interface, as well as the underlying ocean system is needed. The impact of declining sea ice cover (i.e. delayed freeze-up in fall, and earlier spring melt (Hochheim and Barber 2010; Hochheim et al. 2011)) will impact oceanography, vertical mixing, and biogeochemical processes in Hudson Bay (Granskog 2012, St-Laurent et al. 2012). The interaction between tides and fast ice in Hudson Bay is also of interest. Furthermore, winter ice formation is also of interest as some stratification in the ocean is lost (Wang et al. 2012), although there are numerous practical limitations in our ability to observe winter ice.

In the past year, CEOS has joined DFO-EC Lin (Prinsenberg) to implement the NEMO numeric ice-ocean model. It is now being run on the Westgrid supercomputer at the University of Manitoba. This effort will continue by validating model simulation for specific years with available DFO and ArcticNet observations, and by upgrading the present ice-ocean model for shallow and narrow strait ice and ocean processes that occur within the Canadian Arctic Archipelago. Ouranos climate scenario output will be incorporated and used to drive the NEMO model for the purposes of IRIS projections. It is anticipated that this component of the project, namely incorporation of Ouranos output, testing and implementation, will begin in January 2013. Also in January 2013, CEOS will be meeting EC weather branch and the Canadian Ice Service officials to discuss how field monitoring and model efforts can be coordinated to improve their weather and ice forecasts for the Canadian Arctic.

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