BaySys – Contributions of climate change and hydroelectric regulation to the variability and change of freshwater-marine coupling in the Hudson Bay System

An NSERC CRD collaboration between Manitoba Hydro and the Universities of Manitoba, Laval, Québec à Rimouski, Calgary, Northern British Columbia, and Trent.

Synopsis

The past century has seen significant hydroelectric development on rivers flowing into Hudson Bay, with more than 21,000 MW of annual production on the Nelson and La Grande river systems. Freshwater entering Hudson Bay is susceptible to modification, both in terms of water quality and quantity, through exchange processes in the watershed, and through climate forcing of the hydrological cycle both in space and time. A unique aspect of this system is the role that freshwater plays on both sea ice thermodynamic and dynamic processes within Hudson Bay. This freshwater-marine coupling affects all aspects of the Hudson Bay physical, biological and biogeochemical systems through the control which sea ice has on the exchange of light, heat and momentum in the marine system.

Here we propose an NSERC Collaborative Research and Development (CRD) project to examine the influence of freshwater on Hudson Bay marine and coastal systems. Specifically, we will provide a scientific basis to separate climate change effects from those of regulation of freshwater on physical, biological and biogeochemical conditions in Hudson Bay. The project will address this objective from a “systems” perspective, with sub-objectives to examine the climate, marine, and freshwater systems, and to study the cycling of carbon and contaminants.

This multidisciplinary ‘system’ approach will include retrospective analysis, fieldwork, and modeling efforts. Bay-wide field studies will be carried out on board the CCGS Amundsen, and will focus on collecting data over large spatial scales during the spring melt season. These efforts will complement existing data from the summer and fall periods, collected during past field programs. Winter field studies will also be conducted in the Nelson and Churchill estuaries to obtain a complete picture of conditions before key biologic and geochemical processes begin in the spring. Opportunistic sampling of other rivers and estuaries will be combined with remote sensing to extend observations to the basin scale. Combined, these field efforts will provide the first comprehensive physical, biological and biogeochemical status of Hudson Bay. Watershed models and coupled physical-biogeochemical models of the marine environment will be informed by the field observations, and used to project conditions for the 2030s and 2050s. The models will be forced with scenarios of climate change and regulation, allowing for the separation of those two impacts on the Hudson Bay system.

The results of this project will strongly influence science, industry, and policy in Canada. For the scientific community, the project will vastly expand knowledge of climate impacts on the Arctic system, in a region where there are substantial gaps and limitations in existing knowledge. For Manitoba Hydro the project fills a regulatory need to understand its influence on Hudson Bay, and to collect baseline data prior to building additional generating capacity on the Nelson River. For other industries, such as shipping and tourism, an improved understanding of the future of Hudson Bay will help with strategic decision-making. The project will also benefit Canada’s knowledge economy by training 25 highly qualified personnel who will be working at the intersection of academia and industry.
1. Background

As the largest continental shelf sea in the world, Hudson Bay receives an annual freshwater loading of about 760 km$^3$ from more than 42 rivers within a drainage basin of over $3 \times 10^6$ km$^2$ in area [Déry et al., 2011]. An even larger seasonal freshwater flux, estimated at 1200 km$^3$ or more [Prinsenberg, 1988; Granskog et al., 2011], is withdrawn from or added to the water column due to the formation or decay of sea ice in the Bay. The timing, duration, volume and location of freshwater loading to Hudson Bay thus have a major influence on the properties and processes of the marine waters and the dynamics of sea ice, which in turn strongly influence primary productivity, carbon and contaminant cycling in the Bay. Distinguishing between runoff and sea-ice melt is especially important in Hudson Bay because each contribute considerable annual fluxes of freshwater to Hudson Bay [Granskog et al., 2007, 2009, 2011], and yet they may be affected differently by climate change and regulation [Macdonald and Kuzyk, 2011; Yi et al., 2012].

Although overall freshwater input to Hudson Bay has decreased over the past decades [Déry et al., 2005, 2011], discharge from the wettest, southeastern portion of the Nelson watershed has increased over the last century (Figure 1 A) [McCullough et al., 2012] and is expected to increase in the next century [Clair et al., 1998]. Recent flooding in the summers of 2010, 2013, and 2014 in Prairie Canada emphasize this. Similarly, fresh water supply is expected to increase in eastern Hudson Bay as precipitation in northern Quebec is predicted to increase in the 21st century [Sottile et al., 2010]. There has also been a notable shift towards higher winter discharge into Hudson Bay [Déry et al., 2011]. Meanwhile, decadal variability and long-term trends in the formation, breakup, and melt of the Hudson Bay ice pack demonstrate that the ice-free season is becoming longer in both spring and autumn as a result of climate change [Hochheim and Barber, 2014].

In addition to climate-induced changes, discharge from several of the large rivers (i.e., Nelson, Churchill, La Grande) emptying into Hudson Bay has been regulated mainly for hydroelectric power generation but also to provide water for agricultural irrigation and for flood control. This has implications for the Hudson Bay marine environment. When compared to the natural, unregulated rivers, regulated rivers in Manitoba (Nelson River), Quebec (La Grande Rivière) and elsewhere exhibit a
“flattened” hydrograph (Figure 1B) with a suppressed seasonal cycle and shifted timing of streamflow input to Hudson Bay [Déry et al., 2011].

Many of the key physical, biological, and biogeochemical processes occurring in Hudson Bay, including sea ice growth and decay, are strongly linked to freshwater input and its exchange among estuaries, coastal currents, and central Hudson Bay. In mid-winter, tidal amplitude and range are significantly reduced by Bay-wide ice, while in the Nelson estuary, tidal speed is amplified by the presence of fast ice which forms most efficiently when freshwater inputs are high [Wang et al., 2012b]. Further, ice provides shielding to near-shore shoals protecting them from erosion. The dynamics of freshwater-marine coupling and sea ice generation and decay also have biological and biogeochemical consequences. The heat and nutrients from freshwater inputs make estuaries highly productive regions relative to other parts of Hudson Bay [Stewart and Lockhart, 2005; Kuzyk et al., 2008]. A strong relationship between freshwater input and air-sea CO₂ exchange has been identified [Else et al., 2008a, 2013], suggesting that changes in the timing, quantity, and quality of freshwater inputs to the Bay may significantly affect its ability to absorb atmospheric CO₂. Beyond the estuaries, freshwater runoff affects primary production (PP) positively through nutrient additions and by enhancing entrainment of nutrients into surface waters affected by the coastal current [Kuzyk et al., 2010] and negatively by increasing vertical stability of the water column in the interior of the Bay. Freshwater runoff is also a major source of contaminants such as mercury to the marine ecosystem [Hare et al., 2008]. This variability in the role of freshwater, including river inputs and sea ice melt, demonstrates the potential complexity of responses to climate variability and change as well as regulation [Else, 2007; MacDonald and Kuzyk, 2011; Wang et al., 2012b].

Past field efforts in the region have provided a basis for understanding basic ice-atmosphere processes, nutrient and contaminant cycling, and the spatial air-sea carbon exchange. These efforts have primarily been conducted during the late summer to fall transition. Notable exceptions are the 2009 UM and MB Hydro study, a winter field program focusing on characterization of ocean–sea-ice–atmosphere coupling and sedimentary processes in the Nelson River estuary, and a multi-year Groupe interuniversitaire de recherches océanographiques du Québec (GIROQ) program that studied hydrodynamic control of primary and secondary productivity of estuaries. The GIROQ program, held from spring to summer 1988-1990, was based in La Grande Rivière and provided a fundamental understanding of plume dynamics, and ice algae and PP in sub-ice environments. A limited amount of work in this region continues in a collaborative project led by the Arctic Eider Society. The proposed field programs, detailed below, will be by far the largest effort to date to simultaneously capture physical, biological, and biogeochemical processes of freshwater marine coupling in Hudson Bay during the winter to summer transition. These field programs, coupled with historical analysis, re-evaluation of previously collected data, and modeling activities will provide an interdisciplinary foundation for innovative research contrasting impacts of freshwater regulation and climate change on Hudson Bay.
2. Detailed Proposal

2.1. Overarching goal, hypotheses and approaches

To address the overarching goal of providing a scientific basis to separate climate change and regulation impacts on the Hudson Bay system, we propose a four-year (2015-2018) comprehensive study that will integrate field-based experimentation with coupled climatic-hydrological-oceanographic-biogeochemical modeling. The study will be carried out by researchers from six academic institutions in close cooperation with Manitoba Hydro and its subcontractors. Research teams are organized to investigate the following five inter-connected subsystems (Figure 2) with continuous consultation, integration and feedback from Manitoba Hydro and other project participants.

Team 1) Marine and Climate System – D. Barber
Team 2) Freshwater and Littoral System – T. Stadnyk
Team 3) Marine Ecosystem – J.E. Tremblay
Team 4) Carbon Cycling – T. Papakyriakou
Team 5) Contaminants – F. Wang

Our central hypothesis is that factors that can be primarily attributed to climate change, such as a long-term change in temperature, atmospheric circulation, sea ice, and supply of freshwater will have a different impact on Hudson Bay than factors that can be primarily attributed to regulation, such as seasonal shifts in the hydrograph.

Teams 1 and 2 will use existing data, modeling and analysis, not previously used, to attribute causality for observed and projected climate change to the marine and freshwater physical systems. The research conducted by Teams 3-5 will collect and analyze data and apply innovative techniques that have been developed in order to better understand the fundamental processes of the respective biological, carbon and contaminant systems. The objectives of this study can only be achieved using a ‘systems’ approach, drawing expertise from and integrating across all science teams. This approach not only calls for thorough investigation of each major component of the natural system and their integration, but also the design and implementation of a coordinated field program and a fully integrated modeling program run in both ‘upstream’ and downstream’ modes.

Figure 2 - Schematic view showing the conceptual relationship of the BaySys sub-systems.
All teams will be supported by graduate and post-graduate level highly qualified personnel (HQP). Their involvement in all aspects of the project will be mutually beneficial. They will be instrumental in project implementation and will graduate with knowledge that is directly relevant to our Manitoba Hydro industry partner. In addition, the interaction between HQP and industry will provide a basis for each of them to develop strong professional networks among the partner organizations early in their career.

We propose a highly-coordinated field program (Figure 3) integrating a winter estuarine field program, a spring/summer Bay-wide campaign, mooring-based automated observatories, and automated and in situ river sampling. Our study of the Lower Nelson River Basin (LNRB) will extend from the Notigi Control Structure in the northwest, and the outlet of Lake Winnipe at Jenpeg generating station in the south downstream to Hudson Bay. This is the Manitoba Hydro-regulated portion of the Nelson River, and thus will be of particular interest to this project for the separation of climate change from regulation effects. Detailed methodologies are described in section 3.2 (Science Teams); below, we provide an overview of the coordinated field program.

- **River sampling (Summer 2015 to 2018):** Sampling of river and lake water and sediment will be carried out in the LNRB by Teams 3, 4 and 5 in collaboration with the ongoing Coordinated Aquatic Monitoring Program (CAMP), which is a partnership program between Manitoba Hydro and the Province of Manitoba. Established in 2008, CAMP is a long-term aquatic monitoring program to study and monitor the health of rivers and lakes affected by Manitoba Hydro’s generating system (www.campmb.com). Much of the data from the CAMP program (hydrometrics, water quality, benthic invertebrates, fish community, mercury levels in fish, phytoplankton, and sediment quality) are directly relevant to freshwater-marine coupling (Teams 1 and 2), riverine flux estimate of nutrients (Team 3) and mercury (Team 5). Additional measurements (e.g., methylmercury (Team 5) and organic carbon (Teams 3, 4 and 5) and sediment coring (Teams 4 and 5) will be carried out in conjunction with the CAMP program.

- **Mooring-based automated observatories (Fall 2015 to 2018):** In the fall of 2015, four moorings will be installed in the Nelson River mouth and estuary and near the mouth of the Churchill River, using the CCGS Pierre Radisson or another ship of opportunity. Oceanographic and biological properties will be recorded continuously by the moorings for the full duration of the project, which will be supplemented by data from one existing deep-water mooring. The data will build on data from multiple moorings collected in the Nelson Estuary by Manitoba Hydro beginning in 2004, and during a single previous winter expedition (Manitoba Hydro-UM collaboration, 2009) in the Nelson

![Figure 3 - Proposed field programs of BaySys]
River mouth. The proposed mooring network will improve characterization of important but rarely measured winter loading from the watershed. This is relevant because one separable contribution of regulation to freshwater-marine interactions in Hudson Bay may be the winter loading of freshwater, sediments and nutrients to the estuary.

- **Winter estuaries campaign (February/March 2016):** This field program will be approximately six weeks in length and will directly support work by Teams 1, 3, 4, and 5. It will be the most comprehensive effort thus far to simultaneously characterize physical, biological and biogeochemical conditions in Hudson Bay sub-Arctic estuaries during peak winter sea ice cover. The campaign will be operated out of a shore-based camp along the Nelson River Estuary using the logistics of a base in Gillam, MB. Smaller-scale concurrent sampling will be carried out in the Churchill River Estuary, with logistics out of the Churchill Northern Studies Centre near the town of Churchill. The campaign will involve extensive helicopter time to deploy automated equipment and to carry out sampling activities across multiple transects on both fast and mobile ice in the estuaries at regular time intervals. Samples will also be collected at upstream stations. Field sampling will be supported by collection and analysis of remotely sensed optical, the ESA Sentinel-1 SAR and RADARSAT imagery.

- **Spring/summer Bay-wide campaign (June/July 2016):** This six-week campaign will directly support Teams 1, 3, 4 and 5. It will be the first Bay-wide survey of Hudson Bay during the peak ice melt period, which is the season of highest primary productivity in the Bay and thus critical to understanding freshwater-marine coupling. Cross-Bay surveys and a series of near- to off-shore transects around the periphery of the Bay will be carried out on board the Canadian Research Icebreaker CCGS *Amundsen* with in-kind support from ArcticNet. The cruise plan will follow spring breakup and first open water, which proceeds from northwestern to southeastern Hudson Bay. At selected stations, we will make detailed observations of physical, chemical and biological properties across the atmosphere, snow, sea ice, ocean, and sediment column. Instruments on board will record certain atmospheric and oceanographic variables continuously. The *Amundsen*’s helicopter and work boats will also allow us to sample a higher resolution network (instrumental profiles and water samples) in the estuaries of the Churchill and Nelson Rivers, thus providing contrast to the winter estuary campaign. In addition, Teams will sample as many accessible rivers as possible around the perimeter of the Bay (e.g., the Baker Lake System, Hayes, Winisk, La Grande Baleine, Inuksuac, Kogaluc, and Povungnituk Rivers).

A fully integrated modeling program will incorporate historical, modeling, reanalysis, and satellite remote sensing data as a means of up-scaling process studies in space and time. Of particular interest will be future freshwater, sediment, nutrients and contaminant fluxes to Hudson Bay, and the circulation of ice, freshwater and sediment in the Hudson Bay in response to changes in dynamic and thermodynamic forcing. A coupled atmosphere/sea-ice/ocean model will be used in direct support of the over-arching goal to distinguish climate change from regulation. Team 1 will analyze differences between observed and modeled timing of ice cover formation and decay (statistical and numerical models) both regionally and Bay-wide in terms of seasonal and annual freshwater loading from the watershed. Then, by apportioning variability and trends in seasonal and inter-annual runoff volumes between climate forcing and regulation (Team 2), we will test for distinct and/or interlinked forcing by each as they affect ecosystem functioning on Hudson Bay (Teams 3-5).
2.2. Science Teams

The objectives, hypotheses and methodologies for each science team are summarized below.

Team 1: Marine and Climate System
Leader: D. Barber (U. Manitoba); Manitoba Hydro Co-Lead: S. Toews


The objective of Team 1 is to understand and differentiate between how changes in climate variability and regulation will affect (or have affected) processes related to mass and energy exchange between the freshwater, marine, sea ice and atmosphere systems. The focus of Team 1 will be processes determining timing, location and volume of freshwater supply to Hudson Bay. Over 1.4 m of freshwater is supplied annually by melting sea ice, and another 0.9 m by runoff from the Bay’s watershed [Granskog et al., 2011; Prinsenberg, 1988]. Most of this is supplied to the southern half of the Bay, where most of the ice melts and where over two-thirds of all terrestrial runoff to the Bay debouches [Granskog et al., 2011]. Strong vertical stratification imparted by this annual replenishment of freshwater dominates biogeochemical cycling in Hudson Bay, causing the chronic nutrient limitation that has been invoked to explain low biological productivity compared to other estuarine systems [e.g. Anderson and Roff, 1980; Ingram et al., 1996; Ferland, 2011; Sibert et al., 2011]. Seasonal timing and volumes of both sea-ice melt and runoff will be affected by changing climate in the 21st Century, and timing and location of runoff is additionally affected by diversion and seasonal storage for hydroelectric purposes.

Sea ice processes respond to atmospheric, oceanic, and freshwater inputs to the system (Figure 4). A series of recent publications have reported quantitative relationships between timing of sea ice formation and decay, and seasonal temperature and wind patterns driven by hemisphere-scale atmospheric circulation [Hochheim and Barber, 2010, 2014; Hochheim et al., 2011]. These relationships are represented in a model of the 2041-2070 Hudson Bay sea ice-ocean system [Joly et al., 2011]. At the same time, sea ice may be affected by regulation [Anctil and Couture, 1994] which will tend to increase winter freshwater discharge into the Bay, compared to unregulated discharge, even in a changed climate scenario [LeBlonde et al., 1996; Déry et al., 2011]. There is complex interaction between the formation of under-ice plumes and the development of the Bay-wide brackish surface layer created by mixing of seawater with freshwater from river runoff and ice-melt. Ice prevents deep mixing caused by wave action, so that the fresher surface waters spread more widely in winter [Ingram and Larouche, 1987]. This widespread freshwater plume promotes thicker ice growth but without the brine...
formation associated with freezing of seawater [Macdonald et al., 1995] thereby limiting thermohaline vertical circulation. However, in coastal upwelling zones where ice-deficit polynyas also form, brine released from growing ice may find pathways to sink passed the halocline into Hudson Bay deep waters. These processes are not well quantified in the Hudson Bay system.

Formally, we restate our overarching objective as three highly interrelated hypotheses:

*H1.1:* The spatial and temporal pattern of Bay-wide sea ice growth and decay is a dominant factor forcing freshwater-marine coupling processes in Hudson Bay.

*H1.2:* The seasonality and magnitude of river runoff is a dominant factor controlling freshwater-marine coupling processes in Hudson Bay.

*H1.3:* Climate variability and change directly affect the vertical mixing and horizontal distribution of fresh and marine waters in Hudson Bay.

In the section below, we describe an observational data collection program that returns data pertinent to all three hypotheses. Ultimately, these data will support descriptive, statistical investigation of the three hypotheses. But more importantly, it will support calibration and validation of process-driven atmosphere–sea-ice–ocean models to run experiments designed to distinguish between climate change and regulation. Integration of continental-scale freshwater modeling from Team 2 will permit comparison between regulated and unregulated rivers on marine processes in Hudson Bay.

**Methodology**

We will study processes involved in freshwater-marine coupling by ship-based surveys at two scales: i) The icebreaker *CCGS Amundsen* will be used to sample in pack ice and open water along cross-Bay and shore-perpendicular transects throughout the entire Bay (Figure 3). ii) Partway through the six-week mission, the *CCGS Amundsen* and its work boats (Zodiac, air-ice boats and barge) will be used to conduct higher resolution sampling in the Churchill and Nelson River estuarine regions. In the winter surveys just prior to these ship-borne surveys, we will use snowmobiles and helicopters to survey landfast and mobile pack ice, and the sub-ice brackish water plume in the estuary of the Nelson River (and snowmobiles to survey the Churchill River estuary). Both winter and spring surveys will be supported by oceanographic and ice dynamics data collected using moorings installed during the previous fall at both sites.

Freshwater circulation and mixing will be measured by vertical profile sampling using conductivity, temperature, depth (CTD) casts and water sampling (using Niskin bottles on the *CCGS Amundsen’s* rosette or equivalent bottles deployed manually from small boats or through holes in the ice) for four tracers: salinity, H$_2$O oxygen stable isotope ratio ($\delta^{18}$O) and deuterium, and absorption and fluorescence by chromophoric dissolved organic matter (CDOM) (hereinafter $A_{CDOM}$ and $F_{CDOM}$). Salinity and $\delta^{18}$O have previously been used to distinguish freshwater sources at the Bay-wide scale [Granskog et al. 2012]. $A_{CDOM}$ and $F_{CDOM}$ are conservative freshwater tracers at the estuarine scale [Gueguen et al., 2011] and CDOM has the advantages over the more conservative $\delta^{18}$O that we can record continuous water column profiles using fluorescence sensors, and we can map $A_{CDOM}$ surface concentrations Bay-
wide through satellite remote sensing. Salinity, \( A_{\text{CDOM}} \) and \( F_{\text{CDOM}} \) will be measured in the field (Guildline Autosal and Horiba Aqualog). Samples for \( \delta^{18}\text{O} \) and deuterium composition will be returned to the Centre for Earth Observation Science (UofM) labs for analysis. Samples will also be analyzed for total suspended solids (GF/F filtration in the field) on estuarine and shore-perpendicular surveys. Discrete water samples will be supplemented by continuous instrument profiles (salinity, temperature, \( F_{\text{CDOM}} \), beam attenuation and/or turbidity). Optical properties will be sampled for radiative transfer information and satellite validation (Satlantic HyperSAS and free-falling HyperOCR profiler).

Observational data from field surveys described below will be collected and analyzed by all HQP on this team. These data will be combined with historical and remote sensing data to demonstrate relationships between climate–sea-ice–runoff and stratification-inhibited upwelling-nutrient limitation, and to infer processes that underlie these relationships.

**Task 1.1 Winter estuarine survey (MSc1, MSc2, MSc3, MSc4, PhD1, PDF1).** The goal of the Team 1 winter survey will be to (i) characterize the ice cover in the two estuaries, in general, and of the pack ice bordering the Nelson Estuary polynya, in particular, and (ii) to study sub-ice freshwater-marine mixing and circulation processes at the mouths of large (Nelson) and small (Churchill) sub-Arctic rivers. In the Nelson Estuary, we will conduct replicate surveys of the sub-ice river plume along parallel transects following the plume, during both spring and neap tidal, by helicopter (mobile pack ice) and skidoos (landfast ice). Routine measurements at selected stations will include a suite of ice observations (e.g., thickness, freeboard, snow cover, salinity, biomass), and water column profile observations of freshwater tracers described above, plus parameters of interest to Teams 3, 4 and 5. We will deploy moorings in landfast ice north of the river mouth (upstream of the river plume), in the river mouth, and east of the river (in the prevailing path of the plume). These landfast ice-tethered moorings will be instrumented to record velocity profiles, salinity, temperature, turbidity and CDOM below the ice.

**Task 1.2 Spring/summer survey (MSc1, MSc2, MSc3, MSc4, PhD1, PDF1).** The general objective of Team 1 in participating in the Bay-wide and estuarine spring surveys is to study processes governing (i) the mixing of freshwater with seawater and (ii) the horizontal distribution of freshwater throughout Hudson Bay and Hudson Strait, and in greater detail in coastal waters near river estuaries surrounding the Bay. Our goals include distinguishing between sea ice melt and river runoff sources of freshwater, and to map their distribution in 3D. Several members of the team have participated in previous surveys of the Bay (ArcticNet missions in 2005, 2007 and 2010). These earlier surveys were conducted in late July to September, when the marine system was characterized by a fully developed, deep surface mixed layer—generally >70 m. This proposed study would be the first survey to investigate these processes on a Bay-wide scale when the surface mixed layer is being renewed, and when it is expected to be relatively shallow and fresh, and predominantly of ice melt origin. The ship-borne surveys in and outside of river estuaries will provide the opportunity for detailed investigations of conditions during or soon after the spring freshet (for unregulated rivers) and immediately after the departure of most sea ice from the area.

The transects (Figure 3) are designed to repeatedly cross the coastal path of cyclonic freshwater circulation around the Bay [Granskog, 2009]. In addition, rivers around the periphery of the Bay will be sampled by helicopter (Zodiac and or barge) for concentrations of freshwater tracers in runoff sources
The focused estuarine sampling will take place throughout a grid of the order ~50x50 km near the mouth of the Churchill River and ~70x150 km in and east of the Nelson River estuary. Similar, though smaller area, transects will be conducted along key rivers along the Quebec coast (e.g., James Bay mouth and La Grande Rivière). A longitudinal transect and several cross-river transects will be surveyed in each river up to freshwater (including the Hayes River, which shares the Nelson Estuary). Routine data collection at stations will consist of profiling and sampling for freshwater tracers (as described above), plus sampling for parameters of interest to Teams 3, 4 and 5. For freshwater endpoints, prior to and during the course of these estuarine surveys, water samples will be collected as frequently as practicable at the nearest suitable upstream stations on the Churchill and Nelson Rivers. The Churchill, Nelson and Hayes Rivers are all hydrometrically monitored within 100 km of Hudson Bay, allowing for estimate of tracer fluxes.

**Task 1.3 Moorings (MSc3, MSc4, PhD1, PDF1).** The primary purpose of the Nelson Estuary moorings is (i) to complement and extend ice- and ship-based data collected during field campaigns and (ii) to assist in comparing fluvial-marine mixing and sediment transport processes in open water and sub-ice conditions. On a larger scale, the Churchill and Nelson moorings will describe flow, turbulence and freshwater tracers in the coastal current in southwestern Hudson Bay, and the Nelson River mooring directly in the mixing zone for the largest single source of terrestrial freshwater west of James Bay. These data will help to validate estuarine mixing and coastal current dynamics in the ocean model.

We will deploy only bottom-mounted instruments through the winter of 2015/16, to minimize risk of loss by ice. The moorings will be redeployed with surface buoys and carry instruments in the upper water column over the 2016 open water season. In subsequent years, they will be recovered and redeployed only once annually, using the over-wintering, bottom-mounted configurations. In winter configuration, sensors will be placed on or near the bottom mount to record salinity, temperature, CDOM, turbidity, ice thickness using ice profiling sonars (IPS), and velocity profiles and ice velocity using acoustic Doppler current profilers (ADCP). A laser particle size analyzer (LISST) will be mounted in the inner estuary mooring to record size distributions and concentrations of sediment mobilized in the river mouth. The summer configuration of the mooring offshore from the Churchill River and outer Nelson Estuary mooring will include additional sensors at mid-water column and near surface to record salinity, temperature, CDOM and turbidity. The open water configuration of the two inner Nelson Estuary moorings will include salinity and temperature records at 1 or 2 m intervals to the surface using conductivity/temperature chains with 3-4 CTD sensors.

**Task 1.4 Remote sensing (PhD1, PDF1).** We will conduct a Bay-wide survey of the timing (weekly time scale) of sea ice formation and decay (5 km spatial resolution) by analysis of remotely-sensed data following Hochheim and Barber [2014]. Optical satellite data will be used to map seasonal and inter-annual patterns of the Nelson-Hayes freshwater plumes using empirically-derived local relationships between CDOM and salinity. The distribution of terrigenous dissolved organic matter and continental runoff in the surface waters of the Bay will be assessed using a new optical proxy, CDOM UV spectral slope \( S_{275-295} \), developed by Fichot, et al. [2013, 2014b]. The remote sensing algorithm for \( S_{275-295} \) will be tuned using in situ data collected during the 2016 field campaigns. Seasonal, inter-annual and long-term variability (1998-2016) in satellite-derived \( S_{275-295} \) will be studied in parallel with climate-driven
and anthropogenic changes in river discharge and physical drivers (sea ice, wind, SST). This will be validated against sample river water collected by helicopter for freshwater tracer concentrations in Bay-wide runoff sources in collaboration with Teams 3-5.

**Task 1.5 Coupled atmosphere/sea ice/ocean model (PhD1, PDF1).** In support of Team 1 hypotheses, sea ice and oceanographic models will be used to further study the effects of freshwater loading and ice cover on the circulation of Hudson Bay. The Nucleus for European Modeling of the Ocean (NEMO) model [Vancoppenolle et al., 2009a, 2009b] will be used. The implementation of the NEMO ice-ocean model at the University of Manitoba (U. Manitoba) is based on a configuration used and provided by the Bedford Institute of Oceanography (BIO) in order to obtain projections of sea ice state and dynamical variables in the Beaufort Sea, Hudson Bay, and Baffin Bay regions. It will provide a framework and tool with which to simulate projected changes in marine state and dynamic variables, while also enabling an integration of observations and numerical analyses.

The NEMO model includes the ocean general circulation model, Ocean PArallelise (OPA) coupled with version 2.0 of the sea ice model Louvain-la-Neuve Ice Model (LIM), with plans to upgrade to the more recent Los Alamos Sea ice model, CICE. In our study, the model will be run with ¼-degree grid spacing (for a horizontal resolution of ~ 10km–15 km within Hudson Bay) and will include up to 50 unequally-spaced vertical levels to the maximum depth of Hudson Bay. Published techniques to improve resolution of vertical mixing and horizontal diffusion in shallow, shelf environments (e.g. Shapiro et al. 2012; Luneva and Holt, 2013) will be implemented as is appropriate or necessary; a 15-minute time step will be used. Projections will be computed relative to the 1979–2009 climatology from NEMO hindcast simulations, following Chapman and Walsh [2007] using version 2 of the Common Ocean Reference Experiment (COREv2) forcing for ocean-ice reference experiments with 1.875° atmospheric resolution. The model will then be forced with CMIP-5 climate scenarios and freshwater forcing provided by Team 2 to predict future sea ice and oceanographic conditions in Hudson Bay. Variables modeled will be selected based on the integrated science plan, and will include, at a minimum, projections of ice concentration, thickness and drift velocity, as well as salinity, temperature, and ocean current profiles throughout the Bay.

Specifically, the NEMO model will be used to estimate relative contributions of hydroelectric regulation and climate change to changes in ocean, sea ice and biological processes in Hudson Bay. Numerical experiments will be conducted in two phases. In Phase I, we will force simulations with historical climate data, and available hydrometric data from 1979–2009. In Phase II, we will use climate and runoff output provided by Task 2.1 to force simulations of 2030s and 2050s ocean and sea ice processes. The same simulated climate and runoff forcing will inform the coupled NPZD (Team 3) ecosystem-NEMO model to assess changes in biogeochemical processes. Changes in freshwater-marine coupling due to regulation and climate change impacts will be studied by between-model comparison of parameters and derived entities including temperature and salinity profiles at strategic locations throughout the Bay, sea ice concentration and thickness, and circulation and mixed-layer depth, amongst others.

Phase I: To assess initial regulation impacts, we will use numerical experiments to study freshwater-marine coupling in Hudson Bay following regulation associated with the Notigi control structure, Jenpeg
generating station in the Nelson River, and the Rivière La Grande complex using available discharge data and COREv2 atmospheric forcing from 1979–2009. The river module will be incorporated following Brickman and Drozdowski [2012], who applied the NEMO model to shelf seas in Maritime Canada by adapting interior boundary conditions to accommodate monthly river transport time series. During this Phase, we will validate the NEMO model for Hudson Bay using in situ data collected in the field components of this project, as well as with similar data collected on previous surveys of Hudson Bay in 2005, 2007 and 2010. Field work proposed in this project will be conducted in winter and early post-break-up, times for which we have insufficient ice and under-ice data to adequately validate models. We will also use satellite-derived data, including sea ice concentration and drift measurements, to validate NEMO output of sea ice processes.

Phase II: To assess and distinguish impacts of climate- and regulation-induced change on Hudson Bay, we will run numerical experiments using historical (1979–2009) and projected (2030s and 2050s) precipitation and temperature forcings, in each case with both regulated and unregulated scenarios (a total of 6 scenarios). We will use bias-corrected CMIP-5 (output of Task 2.1) for climate forcing and regulated and simulated unregulated runoff scenarios (output of Tasks 2.3 and 2.4). During this phase, we will also use Team 2 runoff outputs to conduct freshwater tracer experiments examining freshwater circulation and coupling throughout Hudson Bay.

**Significance and Innovation**

The pairing of a winter survey followed by a spring/summer mission, as proposed here, has never before been conducted in Hudson Bay. This team offers unprecedented potential for study of processes that will be affected by climate change and increased winter river flow of regulated rivers. While runoff supplies nutrients to the photic zone, freshwater in general limits nutrient recycling from deep water by inducing strong vertical stratification. The impacts of climate change and regulation on these two processes are expected to be significant, but they have never been quantitatively distinguished at the scale of such a large estuarine system as Hudson Bay. Partnership of the BaySys team with Manitoba Hydro and ArcticNet allows us to have a much more extensive marine sampling program than would be possible otherwise. Past surveys funded by Manitoba Hydro, ArcticNet, Fisheries and Ocean Canada and NSERC provide guidance in the strategic placement of moorings, locations of bay-wide and estuary sampling transects and provide ocean and freshwater state variables at locations and times other than those proposed here. Models, using these state variables, allow us to predict future conditions and to conduct model experiments of the relative contributions of regulation and climate change to this system. This complementarity of people, techniques and platforms, is highly innovative, bringing together University, Government and Industry scientists into a highly-coordinated measurement and modeling study of freshwater-marine coupling in Hudson Bay.
Team 2: Freshwater Systems

Lead: T. Stadnyk (U. Manitoba); Manitoba Hydro Co-Lead: K. Koenig.

Members: G. Ali (U. Manitoba), M. Braun (Ouranos), S. Clark (U. Manitoba), S. Déry (University of Northern British Columbia (UNBC)), B. Girling (Manitoba Hydro) and R. Roy (Hydro Québec)

The objective of Team 2 is to investigate the role of freshwater timing and magnitude on contemporary and future projections of freshwater-marine coupling in Hudson Bay as a means of understanding the relative contributions of regulation and climate change to the system (Figure 5). Results from this team will be central to the ability of other teams to evaluate the impacts of climate change and hydroelectric regulation on the physical, biological and biogeochemical processes in Hudson Bay. The outcomes have the potential to benefit regulators with operation and optimization strategies, future infrastructure development, and implementation of adaptation measures for current development.

Multi-model studies are required to perform robust projections of future runoff that enable quantification of the uncertainty associated with these projections [Chen et al., 2011a, 2011b; Bohrn, 2012; Cohen et al., 2013]. While hydrologic modeling under changing conditions is not new [Peel and Blöschl, 2011], it is seldom done at the continental-scale and rarely involves distinguishing of natural climate from river regulation [Adam et al., 2007].

Projection of net changes in runoff under climate and regulation are expected to be highly uncertain due to the typical nonlinear characteristic behaviour of hydrologic systems in general [Blöschl and Zehe, 2005; Koutsoyiannis, 2010], and the LNRB in particular. The proposed partnership between scientists and industry will involve detailed, physically-based, multi-model streamflow projections at continental (50-100km) and regional-scales (~10km) derived from multiple climate projections under naturalized and regulated conditions. Five hydrologic models (HYPE, WATFLOOD, VIC, HEC-HMS and HMETS) will be used to project streamflow under two future time horizons (2030s and 2050s). Simulations will be performed in both “naturalized” (i.e., free-flowing) and “regulated” (i.e., series of reservoirs simulated by hydroelectric operators) regimes, with relative differences between projected and historical conditions enabling separation of climate-only from climate-and-regulatory changes.

Figure 5 - Hudson Bay continental-scale drainage basin with underlain 100 km grid showing the Nelson (orange), lower Nelson (green) and La Grande Rivière sub-basin delineations, with the Notigi control structure and Jenpeg generating station highlighted in (red) on the lower Nelson. Hydrometric gauges currently in operation from Water Survey of Canada shown (black); Quebec hydrometric network not shown.
Team 2 will address one central objective:

**H2.1: Freshwater export into Hudson Bay is expected to increase under climate change, with regulation having the potential to influence the variability and timing of annual peak flows.**

**Methodology**

To address the objective, the following four tasks will be conducted:

**Task 2.1 Continental-scale runoff projection (PDF1).** The objective here is to quantify freshwater export into Hudson Bay under diverse projected future climate scenarios. We propose to build off the existing Arctic-HYPE modeling initiatives [Isberg, 2014] to establish a hydrologic model for the Hudson Bay watershed. The HYPE hydrological simulation system (HYSS) [Lindström et al., 2010] was selected because it is open source, dynamic, semi-distributed and process-based with snow modules essential for arctic watersheds. Specifically, the following steps will be taken to develop the freshwater projections:

1) Climate model output from the CMIP-5 suite of global climate models (GCMs) [Taylor et al., 2012] will be bias-corrected and used to obtain future precipitation (P) and temperature (T) for the 2030s and 2050s time horizons using 1979-2009 as a baseline climate period. Principal components analysis (PCA) will be used to derive like-groupings of future climate (P, T) to reduce the number of scenarios required for hydrologic modeling. We will select a range of future climate groupings covering the spectrum of plausible future climates.

2) A continental-scale model of the Hudson Bay watershed will be built using the HYPE model, building off existing landcover and DEM data retrieved for the Arctic-HYPE initiative [Isberg, 2014]. The model will be forced with climate projections from 1) to produce freshwater exports under climate change for the watershed at a coarse spatial resolution (50-100 km, daily time steps) to provide average annual hydrographs for the 2030s and 2050s relative to historical conditions. The model will be calibrated (in unregulated tributaries) using previously derived and gap-filled hydrometric records [Déry et al., 2011]. Downscaling climate data will not be an issue given the coarse resolution of the continental-scale hydrologic model; will used to derive delta-change factors to perturb historical climate data [Prudhomme et al., 2002].

Freshwater exports from this sub-project will not incorporate the effects of regulation, but will assess the impacts of future climate on changes on freshwater export into Hudson Bay for the 2030s and 2050s.

**Task 2.2 Uncertainty assessment (MSc1).** The objective here is to quantify modeling and parameter uncertainty for future flow projections, and to provide higher-resolution hydrologic outputs for the LNRB. We propose to perform systematic model testing to partition sources of model uncertainty under scenario-driven changing climate conditions. A three-tiered uncertainty assessment is proposed:

1) The Bayesian total error analysis (BATEA) framework will be used to allocate proportions of model error between model structure, input data, calibration data, and calibration methodology. BATEA distinguishes error sources within a Bayesian framework [Kavetski et al., 2006a, b], and will allow better communication and management of prediction error.
2) The Generalized Likelihood Uncertainty Estimation (GLUE) framework will be applied to address equifinality issues with model parameterization. GLUE assumes that it is not possible to find a single “best” parameter set but rather aims to identify a population of possible (behavioural) parameter sets leading to acceptable (process-based) simulations [Beven and Binley, 1992]. GLUE will allow us to produce confidence intervals for flow projections.

3) The Dynamic Identifiability Analysis (DYNIA) framework will assess the importance of a model parameter (and the processes it represents) through time. DYNIA functions recursively over multiple time windows to identify periods of high information content for specific model parameters [Wagener et al., 2003]. Application DYNIA will result in identification of parameters that are highly sensitive to change, allowing us to make inferences about hydrological processes that are more (or less) sensitive to climate shifts.

Computationally, such uncertainty assessments are not feasible for the entire Hudson Bay domain, so specific focus will be on the LNRB under the assumption that identified modeling uncertainty can be extrapolated to Hudson Bay freshwater projections. Four hydrologic models of the LNRB will be set up either as lumped systems (HMETS [Brissette, 2013]) or using finer spatial resolution (~10-km, hourly or daily time steps) to derive hydrologic response under projected climates from Task 2.1, including two previously established models of the LNRB (WAFLOOD [Kouwen, 2013] and HEC-HMS [U.S. Army Corps of Engineers, 2014]), and one additional model (VIC [Liang et al., 1994]). The LNRB models will be nudged at regulated inflow points (i.e., Notigi and Jenpeg; Figure 5) using model output from Task 2.1 for corresponding climate scenarios. The four hydrologic models have contrasting model structures and parameter complexities, to which the three-tiered uncertainty framework will be applied. The comprehensive uncertainty assessment proposed is motivated by the fact that future climate-driven and regulation-driven changes are inherently uncertain and pose significant problems for both the scientific and water infrastructure management communities.

Task 2.3 Regulated system modeling (PhD1, MSc2, MSc3). The objective here is to incorporate regulation effects into projected freshwater exports for two major rivers in the Hudson Bay drainage system: the LNRB and La Grande Rivière. These rivers are influenced by hydropower developments by Manitoba Hydro and Hydro Québec, respectively, with future development being a possibility. Hydropower regulation has the potential to influence both the timing and magnitude of freshwater export into Hudson Bay, which will be examined as follows:

1) Lower Nelson system: projected future monthly streamflow will be provided at key nodes within the Manitoba Hydro system (as specified by them) for the 2030s and 2050s time horizons under the various climate scenarios from Task 2.1 (~10 streamflow projections total). Manitoba Hydro will, using in-kind contributions, provide output from their system model (SPLASH) in the form of average monthly streamflow export into Hudson Bay from the lower Nelson River under assumed inflow conditions (i.e., climate scenario), and assumed export market conditions and future development scenarios.

2) La Grande system: similar to the lower Nelson system, projected future streamflow under the various climate scenarios (Task 2.1) and two time horizons (2030, 2050) will be provided to Hydro Québec. Hydro Quebec will provide data from their system to project streamflow export.
into Hudson Bay under various assumed conditions from the La Grande system for each inflow condition.

Comparison to historical observed [Dery et al., 2005; 2011] and climate-only projections (Task 2.1) will afford shifts in both the magnitude and timing of average annual (monthly) freshwater export from each respective system to be quantified for both time horizons. Possible impacts on the freshwater export into Hudson Bay can be evaluated via comparison with climate-only projections, and will provide model forcing for other teams in the project.

**Task 2.4 Projected freshwater sensitivity to climate and regulation (PDF2).** The objective here is to quantify the relative impacts of climate change from those caused by regulation on the timing and magnitude of freshwater export into Hudson Bay. To achieve this, a more detailed sensitivity analysis and comparison of historical, climate-induced, and climate and regulated changes to freshwater exports will be conducted. The following methodology will be used:

1. Analysis of projected average annual freshwater export under climate-induced change relative to historical (observed) records for all major rivers entering Hudson Bay;
2. Analysis of freshwater exports from the lower Nelson River based on comparison of historical (observed), climate-induced projected (Tasks 2.1 and 2.2), and projected possible regulation under future climates (Task 2.3).
3. Analysis of freshwater exports from the La Grande Rivière from historical (observed), climate-induced projected (Task 2.1), and projected regulation under future climates (Task 2.3).

This sub-project will quantify the anticipated change in freshwater export induced by climate, and assess the potential impact that regulated systems may have on the timing and magnitude of freshwater export into Hudson Bay, providing a scientific basis to separate the effects of climate change from regulation.

**Significance and Innovation**

The activities proposed by Team 2 push the boundaries of previous studies by focusing on a large, pan-Arctic system experiencing changes in climate [Bring and Destourni, 2014; Barber et al., 2012], and specifically the LNRB with its complex hydraulic and ice-affected regime, regulatory aspects, and direct linkage to Hudson Bay [Wang et al., 2012b]. To understand the sensitivity of, and potential changes in these processes, an understanding of possible changes in freshwater export (magnitude), timing, and variability are crucial. Results produced by Team 2 will serve as input forcing to all other teams associated with this project. The benefit of this research to Manitoba Hydro is to better understand the cumulative effects of operating Manitoba Hydro’s hydroelectric system on the water regime and associated aquatic environment of the Nelson Watershed and Hudson Bay. This study will also explore the resiliency of Manitoba Hydro’s system to climate change by improving the understanding of system operation flexibility to manage projected future streamflow conditions under existing licenses. In addition, it will enhance the understanding of hydrological model uncertainty, including an investigation of how data spatial resolution impact climate change scenario assessment and inflow forecasting tools.
Team 3: Marine Ecosystems

Lead: J.-E. Tremblay (Laval); Manitoba Hydro Co-Lead: G. Swanson, J. Hunt

Members: C.J. Mundy (U. Manitoba), P. Archambault (Université de Québec à Rimouski (UQAR)), S. Bélanger (UQAR), L. Fortier (Laval), C. Lovejoy (Laval), and F. Maps (Laval)

The objective of Team 3 is to assess how different drivers collectively affect biological productivity and the diversity and interaction of water column organisms (microbes, algae and consumers) and the benthos, with an aim to identify the fate of nutrients entering Hudson Bay through marine gateways and regulated versus unregulated rivers. In Hudson Bay, river runoff, sea ice dynamics and ocean physics [Ingram et al., 1996] influence the growth conditions of marine organisms (Figure 6). The relative importance of the different factors and their interactions vary in space (locally, regionally) and time (seasonally, inter-annually) [Legendre et al., 1996; Kuzyk et al., 2010]. Under climate warming, increased river flow, reduced ice formation and decreased winter convection is expected to reinforce vertical stratification, decrease upward nutrient supply and lower overall biological productivity at the bay-wide scale [Joly et al., 2011]. Horizontal nutrient deliveries by rivers will probably make a greater contribution to coastal productivity in such a setting, unless storms became sufficiently frequent or powerful to erode the vertical stratification. These changes are also likely to shift the seasonal peak of primary production (PP) forward, thereby affecting the coupling between primary producers and consumers as well as the vertical export of organic matter to the benthos. In the near-shore zone, the timing of biological production will be impacted by the quantity and quality of runoff.

Retrospective remote sensing recently pointed to a small, but non-significant increasing trend in Bay-wide PP from 1998 to 2010 [Bélanger et al., 2013]. However, the inter-annual variability is relatively large and the time series is presently too short to examine whether this variability is part of decadal, hemispheric climate patterns (e.g., North Atlantic or Arctic Oscillation). In addition, the accuracy of present satellite-based algorithms of PP remains to be verified for Hudson Bay. For instance, the presence of high concentrations of CDOM in near-shore areas causes a methodological interference for the chlorophyll-a estimation from remote sensing. In relatively clear offshore waters, sparse field data show that phytoplankton typically aggregates in sub-surface chlorophyll maxima that are not visible from space [Ferland et al., 2010]. Remote sensing algorithms...
therefore need to be adapted and validated for the Bay to augment their accuracy and power for trend analysis.

While it is clear that climate change and regulation could impact the estuarine and marine ecosystems of Hudson Bay in several ways, basic understanding of how the biota 1) responds to atmospheric forcing of the upper ocean and sea ice, 2) are affected by the timing and volume of regulated or unregulated river flow, and 3) affects freshwater-marine coupling by processing inorganic and organic nutrients in different sectors of the Bay, is rudimentary. This knowledge gap is largely due to the paucity of synoptic riverine and Bay-wide data during the winter-summer transition period, when the majority of annual biogeochemical fluxes likely take place. Most of the existing, fragmentary knowledge of ecological processes in the Bay has been obtained during late summer and fall [Estrada et al., 2012; Lapoussière et al., 2013], whereas modeling efforts based on these data have focused on the central area of the Bay [Sibert et al., 2011]. Resolving seasonality and focusing on the critical spring-summer transition are necessary steps toward evaluating the ecological consequences of climate change and flow regulation on the Bay.

The following three hypotheses will be investigated with respect to inshore-offshore gradients:

**H3.1:** *Through their impacts on light transmission and mixed-layer thickness, sea ice/snow dynamics, winter convection and/or river runoff determine the timing of biological production.*

**H3.2:** *River runoff and physical oceanic processes are both important drivers of nutrient loading, which controls productivity of the lower food web.*

**H3.3:** *Processing of the inorganic and organic nutrients transported by rivers modulates their impact on Hudson Bay.*

**Methodology**

In order to test these hypotheses, a three-pronged approach will be used combining in situ (shore-based winter operations from Churchill and Bay-wide sampling from CCGS *Amundsen* in 2016, moorings for project duration, historical data on nutrients and basic biological parameters), remote-sensing (from 1998 to end of project) and coupled numerical modeling. Discrete data aim to define the current state of biological diversity and productivity in the Bay and, where possible, to provide reference points by which to assess future and prior change (with respect to less comprehensive historical data). These data will also be used to refine algorithms for the remote sensing of PP as well as the parameterization and initialization of the numerical model. Remote sensing images and modeling will then be used to fill spatial and temporal gaps in discrete sampling and to identify drivers of variability and change across the Bay.

**Task 3.1 Assess the timing of PP (MSc1).** During years of mooring deployment, information on the timing of PP in the water column will be obtained from irradiance and chlorophyll fluorescence sensors mounted on the moorings. Retrospective (1998 onward) and current satellite imagery will be used to characterize the spatial distribution and seasonal evolution of phytoplankton biomass and PP in open waters. Mooring data and remote sensing images will be compared with the physical data provided by Teams 1 and 2 to assess the impact of fluctuations/changes in the hydrograph, sea-ice, meteorology, and ocean properties on the timing of PP. For the main sampling season (2016), this analysis will be
complemented and validated by direct estimates of PP in sea ice and the water column during winter (Churchill Estuary area) and summer (Bay-wide). Plausible impacts of long-term changes in the timing of different lower food-web processes under different physical forcing scenarios (provided by Teams 1 and 2) will be assessed with a numerical biogeochemical model.

**Task 3.2 Estimate the magnitude of PP (MSc2 and PhD5).** During 2016, winter baseline concentrations of inorganic and organic nutrients in sea ice and the coastal and marine waters of the Bay will be measured on samples taken by helicopter and from the ice camp. The CCGS *Amundsen* expedition will provide summer nutrient distributions in the Bay and the net productivity of offshore waters will be estimated by difference from the winter data. Direct estimates of PP and nutrient uptake will be obtained by incubating bottom-ice cores and water-column samples obtained during winter (Churchill area) and summer (Bay-wide). During summer, additional incubations will be performed with benthic algae at neritic stations. Concurrent samples will be taken to relate productivity to the biodiversity and abundance/biomass of pelagic microbes, pelagic zooplankton, fish and benthic organisms under a host of environmental conditions near different rivers and in offshore waters. In order to resolve longer-term variability and change, the satellite images produced under task 3.1 will be combined to estimate PP at daily, seasonal and annual time scales in relation to the monthly continental freshwater fluxes and sea ice concentration and extent provided by Teams 1 and 2.

Historical and current nutrient and discharge data for the Nelson and Churchill rivers (upstream and downstream of the Churchill River Diversion) and the Hayes River will be provided by Manitoba Hydro’s CAMP program. Data from other rivers across the Bay from helicopter surveys during the Bay-wide expedition of the CCGS *Amundsen* will be obtained to compare nutrient flows and ratios across watersheds and between regulated and unregulated rivers. River nutrient transports will be estimated by combining concentration data, discharge-concentration relationships (where possible) and volume discharge data provided by Team 2. Nutrient transports from rivers will be used to assess their relative contribution to overall productivity (i.e., assuming that all surface nutrients are converted to biomass during summer). A nutrient budget will be calculated by combining these riverine fluxes with nutrient transports across the northern oceanic gateways leading in and out of the Bay. This budget will provide validation for the biogeochemical model for 2016, which will then be used to project productivity into the future based on the sea ice and runoff scenarios provided by Teams 1 and 2.

**Task 3.3 Evaluate nutrient processing along freshwater-marine gradients (PhD2).** The chemical form under which nutrients spread and how far they reach into the Bay depends on several processes, including biomass synthesis and bacterial transformations along flow. Local changes in the composition of nutrients as well as in the stable isotopic signature of inorganic nitrogen pools along several freshwater-marine gradients will be assessed. These measurements will be related to discharge and chemical tracers of freshwater (Teams 2 and 1; see [Granskog et al. 2011]) and contrasted between regulated and unregulated rivers and watersheds. For selected rivers (minimally the Nelson, Hayes and Churchill), incubations will be performed in ship-board microcosms to investigate the degree of nutrient limitation as well as major cycling pathways of nitrogen (e.g., assimilation into biomass, ammonification, denitrification), which is considered as the limiting element for biological productivity in the Bay. Molecular techniques will be employed to assess death versus persistence of freshwater microbes entering the marine ecosystem with respects to gradients in salinity and nutrient availability.
**Task 3.4 Biogeochemical modeling (PhD1).** All observational data acquired during this project will contribute to the refinement of a biogeochemical model of the Bay, schematically represented in Figure 7. This model was originally developed and validated mainly based on late-summer data [Sibert et al., 2011]. This model currently includes the dynamics of both the sympagic (organisms associated to the sea ice) and the pelagic (plankton within the water column) systems and their interaction. Primary producers (micro-algae) are split in a large and a small fraction, as are zooplankton consumers. The currency of this mass-balanced model is nitrogen that primary producers can use in two forms from distinct nitrate and ammonium pools. Dynamic links of all these components to particulate and dissolved organic nitrogen pools complete the ecosystem model.

The essential processes represented in this nutrient, phytoplankton, zooplankton, detritus (NPZD) model are implemented by using numerical methods that are generally accepted in the marine ecosystem modeling community, including (1) Michaelis–Menten kinetics of nutrient uptake, (2) temperature/light-dependent growth for phytoplankton and temperature-dependent biological processes (e.g., respiration, ingestion, etc.), (3) Holling (Type II or III) functional response of grazers to primary producers, (4) photoacclimation of phytoplankton growth, (5) sinking of phytoplankton and detritus and (6) remineralization of these detritus and dissolved organic matter. “Simple” NPZD-type models have proven able to capture significant pelagic ecosystem properties and dynamics in the Arctic Ocean and its ancillary seas [Ji et al., 2013; Lavoie et al., 2009; LeFouest et al., 2005, 2011; Martin et al., 2013; Sibert et al., 2011].

The NPZD model is based on partial differential equations and as such can be coupled to any Eulerian regional circulation model. It is currently coupled to a regional circulation model of the Hudson Bay / Foxe Basin / Hudson Strait system of 10 km of horizontal resolution [Saucier et al., 2004; Sibert et al., 2011] and to a regional model of the Gulf of St Lawrence of about 5 km of horizontal resolution based on the NEMO model [Brickman and Drozdzowski, 2012]. NEMO is the same modeling platform that will be employed by Team 1 to model the circulation in Hudson Bay at a finer horizontal resolution than the current 10 km in order to improve the physics of the coastal circulation and its response to the
freshwater dynamics. The ecosystem model will be coupled with NEMO outputs during the second half of the project in order to provide a better insight on the biogeochemistry occurring in the coastal area of Hudson Bay and close to its most important estuaries. Finally, recent developments in our ability to infer the 3D distribution of the pelagic phytoplankton biomass from surface satellite observations [Ardyna et al., 2013] will promote the close collaboration between our remote sensing and biophysical modeling experts and greatly expand our ability to challenge the performance of the 3D-coupled NPZD model. After this final step, the oceanic and hydrological forcing scenarios produced by Teams 1 and 2 will be used with this coupled 3D ecosystem model to predict plausible changes in the timing and magnitude of primary and secondary production associated to the sea ice and within the water column of Hudson Bay, in response to climate change and freshwater inputs.

Detailed methodologies for processing and analysis of observational and remotely sensed data follow:

**Remote sensing estimations of PP (PhD4):** Open water PP will be assessed using the model of Bélanger et al., [2013]. The accuracy of this model depends on the dependent variables derived from satellite observations and a series of parameters or constants. Dependent variables include solar irradiance penetrating the ocean (E_d), chlorophyll-a concentration (Chl-a) and diffuse attenuation of downwelling irradiance (K_d). Those variables are estimated from satellite-based measurements of sea-leaving radiance (R_a) using semi-analytical algorithms such as Garver-Siegel-Maritorena (GSM) [Maritorena et al., 2002] and quasi-analytical algorithm (QAA), [Le et al., 2002, 2005]. During 2016, in-water measurements of Chl-a and spectral E_d and upwelling radiance will be performed to tune the algorithms for use in Hudson Bay. Novel approaches [e.g., Huot et al., 2013; Ardyna et al., 2013] will be used to reduce the uncertainty of parameters and constants, including photosynthetic parameters of phytoplankton (derived from photosynthesis-irradiance curves), specific absorption coefficients by phytoplankton, and the vertical distribution of Chl-a. The regionally-tuned algorithms will be used to provide PP estimates at an 8-day resolution from 1998 onward, using merged ocean color data products (SeaWiFS, MODIS, MERIS, VIIRS, OLCI). Strategies will be employed to fill sampling gaps due to sea ice, cloud cover or signal contamination by CDOM and re-suspension in nearshore areas [Babin et al., in prep; IOCCG report, in prep]. Spatial patterns, as well as the temporal trends and variability in the timing, intensity and duration of the phytoplankton spring-summer bloom [Zhai et al., 2012] will be related to the riverine, oceanic and atmospheric drivers provided by Teams 1 and 2 and used to validate the biogeochemical model.

**Nutrients (PhD5):** During winter, nutrient samples will be obtained from melted ice cores and surface waters through leads or holes in the ice. During the CCGS Amundsen expedition, water-column samples will be obtained with a CTD-Rosette equipped with sensors to measure in vivo fluorescence, turbidity, transmissivity, dissolved oxygen, nitrate, photosynthetically active radiation, temperature and salinity. Sampling for nutrients will be performed in the sub-surface chlorophyll maximum and at standard depths (5, 10, 20, 30, 40, 50, 60, 70, 80, 100, 125, 150, 175, 200, 250 meters, and near bottom). Samples will be collected in acid-cleaned polyethylene tubes after thorough rinsing and filtration through a GF/F filter. Concentrations of nitrate + nitrite, nitrite, phosphate and silicate will be determined on fresh samples using standard colorimetric methods [Grasshoff et al., 1999] adapted for the AutoAnalyzer 3 (Bran + Luebbe) and ammonium will be determined manually with the fluorometric method [Holmes et al., 1999]. Urea samples will be analyzed using the method of Mulveena and Savidge [1992] and Goeyens et al. [1998]. Samples for total dissolved nitrogen (TDN) will be analyzed
by high-temperature catalytic combustion. DON will be calculated by difference between TDN and inorganic N. The bulk composition of DOM will be characterized using 3D fluorescence spectroscopy (excitation-emission matrices, EEMs). EEMs will be decomposed using parallel factor analysis (PARAFAC), [Stedmon and Bro, 2008], which can be used to identify terrestrial, marine, and anthropogenic components of DOM as well as their freshness and lability [Guéguen et al., 2011].

**Point estimates of PP and nitrogen cycling (PhD5):** Local estimates of total, net, and regenerated PP in sea ice and the water column will be acquired using *in situ* and *in vitro* techniques. During winter, a time-series of net PP in sea ice will be estimated at an “autonomous” site, where the flux of oxygen \( (F_{O_2}) \) at the base of the sea ice will be assessed using the gradient transport hypothesis \( F_{O_2}=K_Z[\Delta O_2/\Delta Z] \); where \( K_Z \) is the vertical eddy diffusivity and \( [\Delta O_2/\Delta Z] \) is the vertical under-ice gradient in dissolved oxygen concentration – see similar approaches by Cota *et al.* [1987] and Glud *et al.* [2014]. A high vertical resolution down-looking ADCP will be used to estimate \( K_Z \) and a vertical array of optodes to estimate \( [\Delta O_2/\Delta Z] \). During the warming period, this system will be combined with a fine vertical scale flow-through measuring \( pCO_2 \) and \( O_2 \) gradients, with an added capacity to measure nutrients [Ehn *et al.*, 2014]. Point estimates of total, net and regenerated PP at various sites will be obtained *in vitro* with stable isotopic labeling methods. Daily rates of PP and nitrogen assimilation will be assessed simultaneously using trace additions of \( ^{13}C \)-labelled sodium bicarbonate and \( ^{15}N \)-labelled substrates (\( NH_4^+, NO_3- \) or urea) following the methods described in Tremblay *et al.* [2006]. Uptake rates of will be corrected for isotopic dilution following the approach of Raimbault and Garcia [2008]. For the freshwater-marine gradient work, surface samples will be supplemented with additions of filtered river water or inorganic nitrogen adjusted for the salinity of the sample. Responses of PP and nutrient assimilation will be assessed relative to unamended controls. Rates of key nitrogen cycling steps, including nitrification, ammonification, nitrogen fixation and sediment denitrification will be assessed *in vitro* using \( ^{15}N \)-labeling techniques [Christman *et al.*, 2011; Mohr *et al.*, 2010; Rysgaard *et al.* 2004].

**Microbial diversity and gene surveys (PhD3):** The biodiversity and distribution of pelagic microbes will be assessed with molecular techniques following the approach of Comeau *et al.* [2011, 2013]. Water samples will be collected and filtered sequentially through 3.0 and 0.2 micron filters. Filters will be preserved in commercial buffer (RNAlater), which stops degradation of RNA and DNA, and stored at -80°C until extraction. In Laval’s laboratory, DNA and RNA will be recovered using commercial kits (e.g., Qiagen All-Prep) and RNA will be immediately converted to cDNA. The DNA and cDNA samples will be prepared for high-throughput amplicon sequencing using the Illumina MySEQ platform at the IBIS/Université Laval Plateforme d’Analyses Génomiques and analyzed using a combination of Mother and Qiime [Comeau *et al.*, 2011; Mohit *et al.*, 2014]. Taxa will be classified based on NCBI taxonomy and our curated Arctic Reference database. All raw reads will be publicly available once deposited in the NCBI Sequence Read Archive (SRA). The Bacteria, Archaea and Eukarya from different river systems and offshore waters will be compared. Our high throughput sequencing will provide the sensitivity needed to identify source populations of microbes and infer decay (loss) curves [Garneau *et al.*, 2006; Monier *et al.*, submitted]. Transcriptomics and quantitative polymerase chain reaction (qPCR) targeting key genes will be employed to identify active nutrient cycling pathways and their response to experimental perturbations along freshwater-marine gradients. For example, genes involved in key steps of the nitrogen cycle will be identified from metagenomes or metatranscriptomes using phylogenetic techniques [Alonso-Saéz *et al.*, 2012] and quantified using qPCR, providing an
estimate of the number of transcripts and a measure of the effects of perturbations in the different experimental microcosms [Pedneault et al., 2014].

**Benthic ecology (MSc2):** The composition and distribution of the epibenthic megafaunal and infaunal communities will be assessed through direct sampling from the CCGS *Amundsen*. Multivariate analyses will be employed to compare the spatial organisation of communities with abiotic factors to identify the environmental parameters driving diversity patterns. Statistical community distribution models will then be used to create distribution maps, filling the gaps in discrete sampling with probabilistic estimates of the presence/absence of distinct communities.

An Agassiz trawl will be used to sample for epifauna (organisms living on the surface of the sediment), and a box core for sampling infauna (organisms living within the sediment) and sediment. Samples will be washed with seawater in a sieve (1 mm mesh) and organisms will be counted and identified to the lowest taxonomical level possible. The USNEL box core will be deployed to quantitatively sample infaunal diversity and abundance (macrobenthos, >500 micron). A subsample of about 0.125 m² area and 12-15 cm depth will be collected and passed through a 0.5 mm mesh sieve to separate sediment from infauna. Organisms will be preserved for further taxonomical identification in the laboratory. The volume of sediments sieved from each box core will be measured and organisms will numbered, weighed and identified to the lowest taxonomical level possible under a dissecting microscope. Species names will be verified using the World Register of Marine Species (http://www.marinespecies.org/index.php) and the Integrated Taxonomic Information System (www.ITIS.gov).

Sediments will be homogenised by hand through a plastic bag and stirred before sub-sampling approximately 1 gram of wet sediments. Sediments will be then mixed with 5 to 10 ml of dispersant (sodium hexametaphosphate) and 40ml of water in a plastic container and shaken for 24 hours to break aggregation of sediment and separate particles. Samples will then be split as many times as necessary to obtain an obscuration rate between 8 – 12% within the sample chamber of the LS13 320 Beckman-coulter. Each sample will be run several times (minimum three) until the coefficient of variation of the mean grain size is less than one. If organic matter is suspected to affect grain size distribution it will be removed with hydrogen peroxide and processed for a second granulometry analysis. All the statistical analyses will be performed with GRADISTAT on raw data obtained from the LS13 320 Beckman-coulter.

In order to define distinct communities from the co-distributions of individual species, Bray–Curtis dissimilarity measures will be used to build a community dissimilarity matrix. This matrix will be subjected to a hierarchical cluster analysis using Ward's minimum variance agglomeration method to detect compact, spherical clusters [Ward, 1963]. A number of well-defined clusters corresponding to dissimilarity between communities of less than 20% will be selected. Non-metric multidimensional scaling (nMDS) ordination, based on the Euclidean distance on Hellinger standardized biomass data will be carried out to visualise the position of the clusters on the ordination diagram (Legendre and Gallagher, 2001). The relationship between epibenthic and infaunal community composition and the environmental variables will be evaluated by redundancy analysis (RDA), [Legendre and Legendre, 1998]. Generalized linear models (GLM), [McCullagh and Nelder, 1989] will be used to link the presence of a given community (response variable) with local environmental conditions (predictor
variables used in the RDA). To make projections at the Bay-wide scale, only the significant variables retained for each community will be included in a second set of GLMs. The values obtained will represent the probability of presence (or habitat suitability) for each community, which will be mapped using ArcMap™.

**Pelagic zooplankton and ichthyoplankton (PhD2):** The abundance and diversity of zooplankton and fish will be assessed using a combination of direct sampling, imaging and acoustics during the CCGS *Amundsen* expedition. High-resolution images of zooplankton will be obtained with the LOKI system, an *in situ* imaging system that resolves planktonic particles larger than 200 µm. Machine learning algorithms will be employed to identify and enumerate organisms. LOKI profiles will be validated and complemented by vertical net tows of a 5-Net Vertical Sampler (5NVS), a structure carrying four 1-m² aperture nets (three with 200-µm mesh and one 500-µm), and one 50-µm mesh net with 0.1-m diameter aperture. Acoustic surveys of fish biomass will be performed underway with the Simrad SX90 fisheries sonar on board the CCGS *Amundsen*, which can also assist in the detection of marine mammals. The ichthyoplankton assemblage will also be sampled directly with a Double Square Net sampler (DSN) consisting of a rectangular metal frame with two 6-m long nets (750-µm and 500-µm mesh) and a 1-m² mouth aperture, towed in a double-oblique cast at a speed of 1 m s⁻¹. The animals captured during the different net tows will be preserved for subsequent identification, enumeration and sizing in the Laval laboratory.

**Significance and innovation**

This work will provide the first comprehensive information on winter nutrients and physical conditions in selected rivers and near-shore environments of Hudson Bay, a vast subarctic inland sea of prime ecological importance for resident, migrating and resident animals. This knowledge is crucial to understand and assess the pre-conditioning of biological productivity during spring and early summer. There is a gap in data for biological processes during this crucial time of the year, when a large portion of biogeochemical fluxes occurs. The new data will complement data for the late summer and fall periods, allowing improved tuning of remote-sensing algorithms of PP and biogeochemical models of the Bay. These tools will then be used to assess previous conditions (retrospective processing of remote sensing data back to 1998 at least) and project future responses (modeling) to changes and variability in the physical environment with respect to each of regulation and climate change. Surveys of the Bay will define the current state of the ecosystem with respect to the diversity and abundance of pelagic and benthic organisms that comprise the lower food web supporting the production of renewable resources. This will serve as a reference point for limited comparisons with historical data and comprehensive comparisons with future surveys.
Team 4: Carbon Cycling

Lead: T. Papakyriakou (U. Manitoba); Manitoba Hydro Co-Lead: R. Gill, W. Hamlin

Members: Z.Z. Kuzyk (U. Manitoba), B. Else (U. Calgary), C. Guéguen (Trent U.), L. Miller (DFO), S. Rysgaard (U. Manitoba)

The objective of Team 4 is to differentiate the relative importance of climate-related impacts and industrial impacts on the Bay’s carbon source/sink status (Figure 8). Continental shelf seas act as an interface between terrestrial, oceanic, and atmospheric carbon stores in the global carbon cycle. Despite only covering ~7% of the global ocean surface, shelf seas account for about 14-30% of oceanic primary productivity, 80% of organic matter sedimentation, 75-90% of the sink of suspended load carried by rivers, and 50% of the calcium carbonate deposits [Gattuso, et al., 1998]. They also account for 30% of the atmospheric CO$_2$ absorbed by global oceans based on recent pCO$_2$ (partial pressure of CO$_2$) climatologies [Chen and Borges, 2009]. As the largest continental shelf sea in the world, Hudson Bay must play an important role in global carbon cycles, but a shortage of observations from the winter, spring, and early-summer seasons, and from the major estuaries (e.g., Nelson River estuary), has limited our understanding of the system [Else et al., 2008a; Kuzyk et al., 2008].

The question of changing river runoff is particularly important in Hudson Bay, which receives a disproportionately large percentage of the total riverine input of dissolved organic carbon (DOC) to the Arctic Ocean [Mundy et al., 2010]. Since microbial and photochemical mineralization of organic carbon in the upper mixed layer is typically efficient in ocean margins [Fichot et al., 2014; Guéguen et al., 2011], the input of terrestrial carbon to Hudson Bay is thought to reduce the efficiency of atmospheric CO$_2$ absorption over a vast area [Else et al., 2008b]. This effect may become even more intense in the future if changes to the permafrost and peatland ecosystems in the Hudson Bay watershed results in increased [Keller et al., 2014] or altered [e.g., Woods et al., 2011] carbon transfers to the marine environment. A better understanding of carbon cycling in Hudson Bay that is derived from expanded, multi-season observations and integrated gas flux-biogeochemical measurements therefore has great significance to the scientific community, who currently lack a firm understanding of Hudson Bay’s current and future role as a source or sink for atmospheric CO$_2$. Such an understanding is also important.
to hydroelectric utilities like Manitoba Hydro, who are interested in how their activities may be impacting downstream areas. The insight that can be gained from integrated studies that consider both physical and biogeochemical processes influencing carbon cycling is also urgently needed as a basis for developing carbon-climate models [e.g., McGuire et al., 2010].

To address the research objective, Team 4 research will be directed by two hypotheses:

**H4.1:** Seasonal variations in river discharge, along with variations in PP and sea ice melt/formation have a strong impact on Hudson Bay’s overall CO₂ source/sink status.

**H4.2:** Long-term changes in river runoff driven by regulation and climate change modify Hudson Bay’s role as a source or sink for atmospheric CO₂.

**Methodology:**

Team 4 will be responsible for the measurement of carbon system variables within the Bay and its major estuaries. Discrete water samples for dissolved inorganic carbon (DIC) and total alkalinity (TA) analyses will be collected in the field and measured using an infrared DIC analyzer (Apollo SciTech) and by potentiometric titration (TA) [Miller et al., 2011]. Dissolved CO₂ in seawater (expressed as pCO₂) will be measured using gas equilibrators coupled to infrared gas analyzers; on board the CCGS Amundsen these measurements will be made continuously [Else et al., 2012], while off-ship (e.g., barge, ice camp and river) pCO₂ measurements will be made using portable analyzers at discrete locations [Demarty et al., 2009]. In addition, pCO₂ can be confidently calculated from the measured DIC and TA data. Air-sea CO₂ exchange will be estimated along the ship-track using both bulk and eddy covariance techniques [Else et al., 2011] making use of tower-based measurements from the icebreaker’s foredeck.

Dissolved organic carbon (DOC) will be measured on discrete samples by high-temperature catalytic combustion at the U. Manitoba Centre for Earth Observation Science (CEOS) labs in Winnipeg. Suspended particulate organic carbon (POC) samples will be obtained at specific depths using submersible pumps loaded with combusted GF/F filters. The samples will be analyzed at CEOS for OC and nitrogen content and stable carbon isotope composition (δ¹³C). Select POC samples will be characterized using δ¹³C, Δ¹⁴C, and biomarkers of terrestrial organic matter sources such as lignin phenols, in order to characterize the contemporary terrestrial POC inputs to the Bay (e.g., contribution of old permafrost-derived carbon).

We will also assess the role of the two main DOM removal processes (i.e., photodegradation and microbial alteration). Photoproduction of DIC from CDOM and FDOM will be investigated using absorption and excitation emission spectroscopy [Guéguen et al., 2011; 2012; 2014] and DIC measurements [Miller et al., 2011]. In addition to absorbance and fluorescence properties, chemical biomarkers such as dissolved lignin and δ¹³C-DOC will be evaluated to establish the DOM sources. Photomineralization will be carried out on 0.20-μm filtered estuarine waters using a Suntest XLS+ solar simulator. The spectral irradiance of the solar simulator in the UV region (295-400 nm) will be adjusted so that it closely matches that of measured midday solar spectral irradiance on a clear summer
day. Photomineralization rates of DOC will be estimated using the coastal Arctic Ocean quantum yield model developed by Bélanger et al. [2006]. Microbial degradation of DOM will be conducted using river microbial inocula added to estuarine and Bay waters [Fellman et al., 2010]. Microbial degradation of DOM will be conducted using river microbial inculcate added to estuarine waters [Fellman et al., 2010].

**Task 4.1 Fall Cruise (Mooring Deployment) (PhD1, PhD2, PhD3, PhD4, PDF).** During the 2015 fall mooring deployment cruise in the Nelson estuary, carbon system variables will be measured across the marine to freshwater gradient by Coast Guard Ship and barge. The primary goal will be to collect samples (pCO₂ and other carbon system parameters) between marine and freshwater end-members, and as many between points along a horizontal salinity gradient as possible. This sampling plan will allow us to investigate the effects of freshwater/marine mixing on carbon system parameters. Although the sampling duration will be limited, this survey will be an important part of establishing the seasonal carbon cycle in the Nelson estuary (hypothesis H4.1).

**Task 4.2 Winter Camp (PhD1, PhD2, PhD3, PhD4, PDF).** During the 2016 winter camp, carbon system variables will be measured on water samples collected under the ice from floes accessed by snowmobile and helicopter. Again, the primary goal will be to collect surface variables spanning the salinity gradient seawater of the Nelson River’s terminus. Vertical profiles through the ice and into the water column may be collected if possible. In addition to water samples, carbon system variables will be measured on melted sea ice core samples [Miller et al., 2011]. A similar, albeit scaled-down, sampling program will be conducted at the terminus of the Churchill River, and seawater into its estuary. Sampling will be coordinated with other project teams. These observations will ultimately allow an understanding of the impact of sea ice formation and melt on surface carbon chemistry in estuarine systems characterized by high (Nelson River) and low (Churchill River) winter season discharge.

**Task 4.3 Bay-Wide Survey (PhD1, PhD2, PhD3, PhD4, PDF).** The 2016 Bay-wide spring/summer survey by the CCGS Amundsen will allow us to broadly sample variables regionally across shelf, basin and estuarine environments of the Bay (Figure 3). We will make use of our underway systems, ship’s rosette and sediment coring equipment for surface, water column and benthos sampling along the ship track. The Amundsen’s small boats and helicopter will provide access to the terminus of the Bay’s major rivers and estuaries.

**Task 4.4 Remote Sensing (PhD2).** The spatial and temporal coverage of seawater pCO₂ and air-sea exchange derived from in situ measurements will be extrapolated across the Bay in space and time using satellite-based remote sensing from numerous platforms (MODIS, AVHRR, MERIS, QuickSCAT) so that regional trends may be assessed relative to observed variation in atmospheric, hydrologic and oceanic drivers. The methodologies are well suited for the integration of air-sea CO₂ exchange totals from regions typically showing extreme spatio-temporal variability in surface fluxes [Else et al., 2008b]. An independent satellite-based assessment of total DOC photomineralization across the Bay will be undertaken [Bélanger et al., 2006; 2008; Fichot et al., 2014], providing the opportunity to assess the regional and Bay-wide influence of photochemical processing of organic matter on pCO₂. The remote sensing algorithms will be tuned using in situ data collected during the 2016 field campaigns.
Task 4.5 Biogeochemical Modeling (PDF). Sea-ice and oceanographic modeling will be used in support of our objective to distinguish effects of climate variability from hydroelectric regime forcing on the Bay’s carbon system parameters, and net CO$_2$ exchange budgets. In close collaboration with Teams 1, 2, and 3, relationships developed in support of H4.1 will be used to augment and optimize a biogeochemical module [Sibert et al., 2011; Lavoie et al., in prep] for the Bay and which will be incorporated into NEMO so that $p$CO$_2$ (and main carbon system parameters), and CO$_2$ exchange budgets can be forecasted for various climate and river flow scenarios (Team 1) in support of H4.2. Details are outlined by Teams 1 and 3.

Significance and Innovation:

Broadly speaking, Team 4 expects to produce two key results from these efforts. First, we will provide a first-ever annual budget of air-sea CO$_2$ exchange in Hudson Bay. Current inventories of air-sea gas exchange on continental shelf seas (e.g., Borges [2005]; Cai et al. [2006]) lack estimates for Hudson Bay and in some cases do not even acknowledge the omission. Since these inventories are referenced in key science and policy reports like the IPCC assessments (see for example, Solomon et al., [2007]), putting Hudson Bay “on the map” will be a significant contribution to both scientists and policy-makers. Second, we will provide a quantitative assessment of how climate change and regulation will modify the air-sea CO$_2$ exchange budget in the future. This has significance for the scientific community, and will help Manitoba Hydro assess their “carbon footprint”.

The main challenge in delivering these results lies in reconciling the large spatial and temporal scales that we are proposing to study with geographically and time-limited field programs. To address that challenge, Team 4 will employ innovative techniques and sampling strategies. First, a focus on identifying key processes that influence $p$CO$_2$ (and hence air-sea gas exchange) will allow for upscaling using remote sensing and biogeochemical modeling. Past experience has shown that the summer and fall seasons in Hudson Bay are amenable to such an approach [Else et al., 2008b], but similar approaches have not yet been tried for the more complicated winter and spring seasons. To our knowledge, such an undertaking has never been attempted for a continental shelf sea as large and complex as Hudson Bay. Second, the use of proxies and biomarkers on sediment cores to assess changes in carbon composition and burial rates provides an innovative avenue to expand the temporal domain of our study. When combined with historical data on river discharge from Manitoba Hydro, these techniques will allow an investigation of the past impacts of climate change and hydroelectric development on carbon cycles in the Bay. By better understanding carbon cycles within the context of physical and ecosystem processes, this team will achieve reliable assessments of current and future air-sea CO$_2$ exchange budgets in Hudson Bay.
Team 5: Contaminants

Lead: F. Wang (U. Manitoba); Manitoba Hydro Co-Lead: A. Zacharias, S. Wakelin

Members: D. Lobb (U. Manitoba), P. Owens (UNBC), E. Petticrew (UNBC), R. Macdonald (U. Manitoba), G. Stern (U. Manitoba)

The objective of Team 5 is to examine how contaminant transport and transformation in the Hudson Bay ecosystem responds to regulation and a changing climate. While many chemical contaminants can be studied, we will focus on mercury because it is one of the primary contaminants of concern associated with regulation due to enhanced mercury methylation in flooded reservoirs and wetlands [St. Louis et al., 1994]. Furthermore, since the fate and effects of mercury are very sensitive to climatic, hydrological and ecological changes [Wang and Zhang, 2013], mercury can also serve as a “tracer” contaminant to reveal processes governing many other contaminants in the northern environment [Wang et al., 2010].

River impoundment due to regulation creates a seasonally flooded water level fluctuation zone, which is a known hotspot for the production of methylmercury (Process A in Figure 9) [St. Louis et al., 1994]. Similar production of methylmercury can also occur in estuarine sediments (Process B in Figure 9) [Compeau and Bartha, 1985]. In both cases, the enhanced production of methylmercury is attributed to anaerobic mercury methylators such as sulphate-reducing bacteria [Compeau and Bartha, 1985] or iron-reducing bacteria [Fleming et al., 2006] whose activity is enhanced by the influx of organic carbon in the oxic-anoxic transition zone. In studying methylmercury distribution in seawater from the Beaufort Sea, we have recently reported the formation of methylmercury in sub-surface seawater (Process C in Figure 9) [Wang et al., 2012a], though the identity of the methylator remains unknown. Similar sub-surface production of methylmercury has also been reported in other oceans [e.g., Sunderland et al., 2009; Cossa et al., 2009].

To date, management of mercury contamination has primarily focused on source reduction. However, recent research suggests that the effectiveness of controlling “external” mercury sources is being increasingly modified by changes in “internal” biogeochemical processes in the aquatic ecosystem that

Figure 9 - Schematic view of freshwater-marine coupling showing the production of methylmercury in hydroelectric reservoirs (A), estuarine sediment (B), and sub-surface seawater (C). Hg\(^0\): elemental mercury; Hg(II): oxidized Hg; MeHg: methylmercury; OC: organic carbon.
affect the methylation of inorganic mercury (i.e., processes A, B and C in Figure 9) [Wang et al., 2010]. Such changes can be induced by large engineering operations such as regulation, but can also be due to natural flooding, or other climate-induced effects that affect the flux of organic matter or the redox conditions [Stern et al., 2012; Wang and Zhang, 2013].

Suspended sediments are the major source of particulate organic matter, and their origins are expected to affect their nature and role in the transport and methylation of mercury in Hudson Bay. The overall magnitude and the distribution of sources and sinks of suspended sediment and associated organic carbon and mercury along the lower Nelson River, within its estuary and along the coast of the Bay are expected to change in response to changes in water flows, water levels and ice cover. For instance, increases in the water quantity in the lower Nelson River watershed, particularly increases in peak flow, has historically increased the mobilization and transport of suspended sediments and associated organic carbon and mercury [Kuzyk et al., 2010; Wang et al., 2012a].

Lower trophic level organisms such as zooplankton provide a critical linkage for water-to-food web transfer of mercury and subsequent biomagnification. Co-funded by a Manitoba Hydro Postgraduate Research Program, we have recently developed mass balance models for total mercury in the Hudson Bay system for both contemporary and preindustrial times [Hare et al., 2008]. We discovered an unusually large total mercury flux associated with the cycling of suspended sediments in the Bay due to the postglacial isostatic rebound of the seafloor [Hare et al., 2008]. We have also provided the first thorough study on how mercury and methylmercury are being accumulated in Hudson Bay zooplankton [Foster et al., 2012]. A major gap remaining is the mass budget of methylmercury in the coastal and marine system.

To achieve the objective, Team 5 will address the following three hypotheses:

**H5.1:** Organic matter is a primary control over mercury methylation in the water column and in sediments.

**H5.2:** The suspended sediments in Hudson Bay have multiple sources, including: erosion and runoff from land surfaces within the watershed, erosion of the banks and beds of the rivers and estuaries of the Bay, erosion of the Bay’s coastline, resuspension of sediments within the Bay, as well as organic material produced within the Bay, which affect their role in the transport and methylation of mercury in Hudson Bay and will respond differently to climate change.

**H5.3:** Flooding and changing climate are playing an increasingly important role in mercury accumulation at the base of the Hudson Bay marine and coastal food webs.

**Methodology**

**Task 5.1 Relationship between mercury methylation and organic matter remineralization (PhD1).** Although it is well known that mercury methylation requires the availability of organic matter, it has only recently been recognized that the nature of the organic matter (e.g., recent vs. aged material) is also
a critical control [Sunderland et al., 2009; Wang et al., 2012a]. Based on this finding, we will carry out research in three different systems:

1) The Nelson estuary as part of the Winter Estuaries Campaign in February/March 2016: The focus will be on estuary sediment as a source of methylmercury (Process B in Figure 9). In collaboration with Teams 1, 3 and 4, water samples (dissolved and particulate) will be collected along the axial distance (river to estuary) at different water depths. Sediment and porewater samples will be collected from sediment cores collected at the axial distance. These cores will be collected in collaboration with Team 4. Snow and sea ice samples will also be collected to test the recent postulation that in situ mercury methylmercury might also occur in sea ice [Beattie et al., 2014].

2) The sub-surface seawater as part of the Bay-wide Campaign in June/July 2016. The focus will be on the sub-surface production of methylmercury (Process C in Figure 9) and relationships with organic matter supplied by various sources. In collaboration with Teams 1, 3 and 4, water samples (dissolved and particulate) will be collected at stations from different depths at a high vertical resolution (every 10-20 m), with an especially high resolution around the depth of nutrient maxima.

3) The regulated lakes (Southern Indian Lake and Wuskwatim Lake). The focus will be on lake sediment as a source of methylmercury (Process A in Figure 9). The field research will be carried out in collaboration with the CAMP program (2015-2018) and with Teams 3 and 4. Water samples (dissolved and particulate) will be collected in different seasons from various water depths. Sediment and porewater samples will be collected from sediment cores collected at a shallow site and a deep site.

The sampling for mercury and methylmercury samples will follow strictly clean-hands-dirty-hands protocol [Wang et al., 2012a]. The analysis of mercury and methylmercury will be done either at the Portable Laboratory for Mercury Speciation (PILMS) on board the CCGS Amundsen (Bay-wide Campaign), or at the Ultra-Clean Trace Elements Laboratory (UCTEL) at CEOS, U. Manitoba (other field programs), following our well-established procedures [Wang et al., 2012a]. Dissolved and particulate organic carbon (Team 4), δ13C of particulate matter (Team 4), nutrients (phosphate, nitrate, silicate; Team 3) and δ18O (Team 1) will be measured in collaboration with other teams. Sediment cores will be further analyzed by a suite of fingerprinting techniques (see Task 5.2).

Data will be analyzed for the relationship between mercury methylation and the rate of organic matter remineralization in a way similar to the study in the North Pacific Ocean [Sunderland et al., 2009] and Beaufort Sea [Wang et al., 2012a]. Such relationship will provide the scientific basis for differentiating the sources of organic matter and methylmercury in Hudson Bay and its watershed.

**Task 5.2 Suspended Sediment and Organic Matter Fingerprinting (MSc1, MSc2, PhD2).** Working closely with Team 4, we will assess the sources of organic matter and suspended sediment within the LNRB, its estuary, and Hudson Bay using traditional (surveys and budgets) and fingerprinting techniques. Fingerprinting is based on the principle that materials entering the water have a property signature that reflects their origin. A variety of physical and chemical properties have been used in the development and application of fingerprinting techniques. These properties include geochemistry, radiochemistry, stable isotopes and reflectance [Koiter et al., 2013b; Martinez-Carreras et al., 2010]. The sources are discriminated using multi-parameter statistics. Such techniques have been shown to be
very powerful in identifying source areas for sediments in watersheds worldwide [Gibbs, 2008; Koiter et al., 2013a]. Identification of sediment source areas within the study region, and quantification of their relative contributions to the organic matter associated with suspended sediments, in addition to knowledge of how the amount and form of organic matter affect mercury methylation, will provide information on the hydrogeomorphic processes responsible for the production and transport of sediment and associated organic matter and, therefore, how regulation of rivers and climate change may affect methylmercury levels.

In collaboration with Teams 3, and 4, it is proposed to collect suspended sediment samples and sediment cores from the Bay and the Nelson River estuary (and possibly the Churchill River estuary) as part of the coordinated field programs, and from the two reservoirs in coordination with the CAMP program. In addition, soil and subsoil materials will be collected from banks of the river and estuary, the shoreline of the Bay, and from potential inland source areas; in total, 2-5 samples will be collected by depth at 5 representative locations in each of these potential source areas.

Lignin phenols as employed previously in studies of Hudson Bay organic matter sources [Kuzyk et al., 2008] and Compound Specific Stable Isotope (CSSI) analysis [Gibbs 2008] will be the primary means of fingerprinting the sources of the suspended sediments. The CSSI technique is new to Hudson Bay studies but has been successfully used to differentiate between terrestrial and marine sources of organic carbon in harbour sediments, with additional information obtained regarding the microorganisms and indicators of ecosystem health [Harji et al., 2010]. This technique discriminates plant sources of organics, microbial sources, and organics bound on soil particles that are transferred as sediment through the catchment, to the receiving water body. This method is an effective tracing technique because the isotopic composition of the individual organic carbon does not change significantly with time [Boyd et al., 2006], and thus any potential degradation of the organics is not a factor in the analysis. Lipids (e.g., fatty acids) are separated and analyzed, and the stable isotopic composition from mid-chain to very long chain lipids (C16 to C40) is analyzed. This class of lipids is particularly well preserved in soil through aggregation and non-preferential degradation by microbes, and due to moderate to poor solubility, is usually found in the upper horizons of soil, which are most prone to erosion. Plant sources (e.g., coniferous trees, mosses, lichens) contribute unique isotopic signatures to the soil; signatures are unique due to plant type, growing conditions, altitude, among others. Soils from differing sources are analyzed for the isotopic signatures and compared to sediment samples found in the aquatic system. The lignin and CSSI analysis will be complemented by the use of inorganic (e.g., As, Ti, Hg) and radionuclide ($^{137}$Cs, $^{210}$Pb, $^{239,240}$Pu) tracers, and spectral reflectance. FAs from soils, sediment and plant material will be extracted with dichloromethane and methanol using Soxhlet extractors.

Characterization of the fatty acids will be done by gas chromatography (GC) (Agilent-6890) at the University of Northern British Columbia. Stable isotopes of these FAs as well as bulk $^{13}$C and $^{15}$N will be determined by GC – isotope ratio mass spectrometry (IRMS) at the G.G. Hatch Stable Isotope lab at University of Ottawa. Lignin phenols will be analyzed by GC-MS at CEOS. Radionuclides will be measured using alpha and gamma spectrometers in the Environmental Radiochemistry Laboratory at the U. Manitoba. The reflectance of soil and sediment will be characterized by CEOS’s ASD FieldSpec-3 diffuse reflectance radiometers over a range of 350-2500 nm. Prior to analyses, samples are dried and
characterized for particle size distribution using laser diffraction and image analysis in the Landscape Dynamics Laboratory at the U. Manitoba. Statistical analysis (e.g., un-mixing models or principle component analysis) is used to apportion the sources, thereby identifying the degree of contribution of each source to the sediment [Gibbs 2008, Harji et al., 2010].

**Task 5.3 Mass balance modeling of methylmercury in Hudson Bay (PDF).** Mass balance modeling of methylmercury in Hudson Bay will follow a similar method we recently used to build the mass budget for total mercury in the Bay [Hare et al., 2008]. Major sources and sinks considered will include the atmosphere, rivers, coastal erosion, oceanic circulation, sedimentation and biotic uptake. Atmospheric deposition of methylmercury is expected to be of minimal importance; nevertheless, it will be evaluated primarily based on snow and snowmelt. In addition to the detailed methylmercury data on the Nelson River obtained as part of the Estuaries Campaign (Task 5.1), the lower section of other major rivers (e.g., the Baker Lake System, Churchill, Hayes, Winisk, La Grande Baleine, Inuksuac, Kogaluc, and Povungnituk Rivers) will also be sampled during the Bay-wide Campaign via helicopter and boat in collaboration with Teams 3 and 4. Coastal erosional flux of methylmercury will be evaluated based on permafrost cores taken from the coastal area; some of the cores have already been collected and archived. Oceanic and sedimentation fluxes will be evaluated based on data obtained during the Bay-wide Campaign.

**Significance and Innovation**

This will be the first study where methylmercury production in regulated rivers is put in the context of other methylmercury sources in estuaries and the ocean. By relating methylmercury production to organic carbon remineralization rate, and by identifying the sources of the different forms of organic matter affecting this process, this study provides new and powerful tools to apportion the relative contribution of regulation and climate change in methylmercury production in the Hudson Bay coastal and marine system. The study will also result in the first-ever mass balance model for methylmercury in Hudson Bay, which will provide the basis for sensitivity analysis on how methylmercury in the biotic system responds to future changes, and for development of models under hydrological and climatic scenarios. This will also be the first study to use fingerprinting in an attempt to distinguish sediment from terrestrial and marine sources in Hudson Bay in relation to specific geomorphic processes along the coast and within the lower Nelson River and its watershed. The understanding gained will enable better prediction of the potential impacts of changes in hydrology resulting from climate change and hydroelectric development on sediments and associated carbon and contaminant levels within Hudson Bay.
2.3 Integration among research teams

The combined research efforts of the five science teams in this proposal represent an unprecedented and innovative effort to provide a scientific basis to separate climate change effects from those of regulation of freshwater on physical, biological and biogeochemical conditions in Hudson Bay. However, these teams cannot complete their work in isolation from each other. Each team will be collecting data and/or providing model outputs that are crucial to the success of other teams. Teams will rely heavily on the proposed field programs, and will create an integrated science plan in advance in order to ensure complete and efficient use of limited (and expensive) field resources. Following the field programs, teams will fully integrate to provide project updates in order to correctly sequence and coordinate their analysis and modeling. Combined, the steps below will ensure coordinated sequencing of data analysis efforts for all teams. Additional details are provided in the following project management section. The project schedule will be reviewed and updated as required in consultation with the SSC.

Specific examples of the interplay between teams are described below:

**Team 1:** The Marine/Climate team will provide state variables for multilayer ocean, sea ice and atmosphere variables. These will provide the framework for examination of freshwater-marine coupling. Sea ice dynamic and thermodynamic processes will provide the central variable controlling exchanges across the OSA in both regulated and climate change scenarios. The modeling, retrospective and remote sensing analysis of sea ice and freshwater circulation and timing will be coupled to other physical and biogeochemical processes in Hudson Bay of interest to Teams 3-5. NEMO model outputs will be dependent on the climate model ensembles prepared by Team 2 (Task 2.1). This is necessary to ensure consistent use of climate projections associated with regional model outputs across the various teams.

**Team 2:** The Freshwater systems team (with the help of Ouranos) will provide climate projections by fall 2015, with associated first-generation runoff projections from the continental-scale Hudson Bay model by summer 2016. All other teams in the project are dependent to some degree on the outputs from Team 2, particularly the continental-scale freshwater projections (Task 2.1.2). Given the reliance of other teams on both climate and freshwater projections, Team 2 will focus on modeling in Years 1 and 2, and on uncertainty and sensitivity analyses in Years 3 and 4. Revision-controlled dissemination of runoff scenarios will be a priority for Team 2 and updates will be regularly communicated to team leads.

**Team 3:** In order to expand the capability of the current version of the 3D NPZD ecosystem model and meet the needs of Team 4 in particular, three biogeochemical modules (oxygen, CO₂ and alkalinity) will be adapted for the Hudson Bay system, in collaboration with Lavoie. These models were initially developed for a biogeochemical model of the Gulf of St. Lawrence [Lavoie et al., in prep]. The ecosystem model will benefit greatly from the new data that will be provided by Teams 1, 2 and 4. Their data outputs will be crucial to adequately represent the initial conditions of the system (during winter) prior to the biologically-active season at the base of sea-ice and in the water column. The diverse and process-oriented data that will be collected will also provide a unique opportunity to validate the complex model outputs not only against standing stock data (Chlorophyll-a biomass, zooplankton biomass, etc.), but also against rates of key physiological processes (nutrient uptake, growth, ingestion, relative loss through consumption, sedimentation, and denitrification etc.).
Developments in our ability to infer the 3D distribution of pelagic phytoplankton biomass from surface satellite observations [Ardyna et al., 2013] will promote the close collaboration between our remote sensing (Bélanger) and biophysical modeling (Maps) experts and greatly expand our ability to test the performance of the 3D-coupled bio-physical ecosystem model. After this essential step, the oceanic and hydrological forcing scenarios produced by Teams 1 and 2 will be used with the model to predict plausible changes magnitude of primary and secondary production associated to the sea ice and within the water column of Hudson Bay, in response to climate change and freshwater inputs. The biological components of the model will feed directly into the biogeochemical modules that deliver the gas flux modeling by Team 4.

**Team 4.** In collaboration with Teams 3 and 5, sediment box cores will be obtained from depositional basins near the Nelson River estuary, dated using radioisotopes, and characterized using δ¹³C and biomarkers to evaluate evidence for recent (last ~150 years) change in OC composition and/or burial rates, which may be related to changes in river runoff driven by regulation and climate change during this period. Additional data sets will be made available through collaboration with other sub-projects, including CDOM/FDOM, δ¹⁸O, water and sea ice temperature/salinity (Team 1), river discharge measurements (Team 2), PP and nutrients (Team 3), and sediment fingerprinting (Team 5).

**Team 5.** Biotic uptake will be evaluated based on recently published data of methylmercury in Hudson Bay zooplankton [Foster et al., 2012], as well as new data on methylmercury in phytoplankton, zooplankton and fish collected in collaboration with Team 3. This will allow us to develop the first mass balance model for methylmercury which will allow us to identify the relative importance of regulation in the western and eastern parts of the Bay, natural flooding events and other climate-induced changes in methylmercury accumulation by zooplankton and fish. While our focus is on methylmercury, we propose to analyze all the samples for total mercury as well, which will allow us to revisit and update the total mercury mass balance model by Hare et al. [2008]. Sediment fingerprinting data will be used by Teams 3 and 4 in their effort for nutrients and carbon source and flux estimate.

A number of steps will be taken to ensure the data integration described above occurs and that scheduled activities move forward as planned. First, a Science Steering Committee (SSC) comprised of team leads from Manitoba Hydro and the universities, and co-chaired by David Barber and Kevin Sydor will meet at least once every 4 months. This committee will discuss progress towards key milestones, and provide resolutions for any issues relating to project risks and implementation. Second, each team will provide status reports on a quarterly basis. These will document work completed, review scheduled activities, describe progress of HQP, and report on budget and risks. If needed, teams can propose changes to their work plans using these reports. Finally, each team will prepare reports upon the completion of key phases of their research. The “Phase 1” report will review data-collection and data processing activities and results from preliminary analysis by each team. “Phase 2” reports will describe the integration of datasets among teams and results of modeling efforts. All of these will lead into publications, conference presentations and theses as well as the final synthesis reports. It will also be crucial to involve MSc. and PhD, Postdoctoral Fellows (PDFs), research associates, technicians and team members from universities and Manitoba Hydro. Research associates and technicians will play a key role in planning and overseeing the safe implementation of the proposed field programs, and in ensuring that subsequent analysis follows lab procedures for safety and consistency (where applicable).