1.4 Hydro-ecological responses of Arctic tundra lakes to climate change and landscape perturbation (Tundra Lakes)

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ABSTRACT

The Arctic Climate Impact Assessment (2005) concluded that the annual mean warming for the areas north of 60°N to be 3.7°C for the period 2070-2089. Hence, the Arctic is expected to display a warming that is more than twice the global average, show decreases in snow cover and ice extent, display further retreat/degradation of permafrost, and have increased inter-annual variability in extreme precipitation events. Such significant changes/shifts in climatic regimes are expected to have far-reaching cascading impacts on the hydrology and ecology of Arctic freshwater ecosystems, which are highly sensitive to climate variability and change (CVC). Large-scale permafrost degradation (i.e., increased depth of seasonal active layer and/or landscape slumping) is predicted to increase with the effects of climate warming, along with enhanced addition of geochemical loadings (e.g., carbon, nitrogen, phosphorus) to the freshwater environment. In addition, changes in the timing and duration of lake-ice characteristics in conjunction with altered geochemical loadings are projected to dramatically affect affecting freshwater ecosystem productivity levels, energy mobilization pathways and community structure. The goals of this research are to: 1) conduct three integrated landscape-lake process and modeling studies that will improve our regional understanding of the sensitivities/responses of upland tundra lakes to CVC; 2) to develop and validate an integrated landscape-geochemical, lake-ice, hydro-ecological model (MyLake) that is applicable to cold regions/Arctic lake systems; and, 3) to develop and test new and innovative automated water quality/hydrometric monitoring systems for application in the Arctic. The project is producing legacy data and products of direct benefit to the development of adaptation options for the conservation, protection and management of arctic freshwater ecosystems to present and future climate variability and change.

KEY MESSAGES

- The Arctic is expected to display a warming that is more than twice the global average, show decreases in snowcover and sea-ice extent, display further retreat of permafrost, glaciers and ice-caps, and have increased inter-annual variability in weather conditions.
- Projected higher surface air temperatures and altered climate regimes are expected to have pronounced effects on the freshwater cryosphere (snow, permafrost and freshwater ice), which in turn will have cascading effects on the hydrology, chemistry and ecology of Arctic lake ecosystems.
- This project has conducted three integrated landscape-lake process and modeling studies that have improved our regional understanding of the sensitivities/responses of upland tundra lakes to climate variability and change.
- The project has further developed and validated an integrated landscape-geochemical, lake-ice, hydro-ecological model (MyLake) that is applicable to cold regions/Arctic lake systems.
- The project is testing the application of new monitoring technologies (i.e., automated instrumented buoy and mooring system) and experimental mesocosms approaches to assess the effects of changing cryospheric conditions (landscape and aquatic) on geochemistry and ecological structure and function.
- Using lake shoreline permafrost slumping as an indicator of landscape climate change effects, we have found significant differences in lake chemistry, aquatic plant productivity, invertebrate food webs and fish communities between slumped and undisturbed lake catchments in the western Arctic.
- Enhanced understanding has been achieved in terms of understanding the variability and complexities of food web structures (including the presence/absence of fish) in a network of intensively studies upland lakes.
- This project has produced legacy data and products of direct benefit to the development of adaptation options for the conservation, protection and management of arctic freshwater ecosystems to present and future climate variability and change.
OBJECTIVES

Overall

• To develop a hydro-ecological modelling framework for small Arctic lakes that can be used to assess the vulnerability of arctic lake ecosystems to disturbance, such as future climate change, landscape changes or water withdrawal.

Specific

• To characterize and model the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality.
• To assess and model current and projected lake ice and related limnological conditions in Arctic lakes.
• To assess and model changes in food-web structure and productivity of tundra lake systems to present and future climate regimes.
• To develop a unique legacy database of freshwater biodiversity and related environmental information on Arctic tundra lakes.
• To develop and test innovative monitoring technologies and experimental approaches to attain an improved mechanistic understanding of the responses of tundra lakes to climate variability and change.

INTRODUCTION

The Arctic has been identified as the region in the Northern Hemisphere that is most susceptible to the effects of climate variability and change (CVC), and is expected to display a warming that is more than twice the global average (3.7°C for the period 2070-2089), a decrease in diurnal temperature range, a decrease in daily variability of surface air temperature in winter and an increase in daily variability in summers, show decreases in snowcover and sea-ice extent, display further retreat of permafrost, glaciers and ice-caps, and have increased interannual variability in weather conditions (IPCC 2001, 2007a,b, ACIA 2005). Such significant changes/shifts in climatic regimes are expected to have far-reaching cascading impacts on the hydrology and ecology of northern/Arctic freshwater ecosystems (Wrona et al. 2005, 2006). Freshwater systems are particularly sensitive to CVC because numerous hydro-ecological processes respond to even small changes in the climate regime. Furthermore, hydrological and ecological processes may change either gradually or in an abrupt manner when environmental/ecosystem thresholds are exceeded. A warming climate is expected to directly impact the magnitude and timing of freshwater fluxes to and from lakes and affect a range of physical, chemical and biological processes in the lakes. It is difficult to project the effects changing climate and environmental factors will have on Arctic lakes, partly related to a poor understanding of their interrelationships, and partly related to a paucity of long-term monitoring sites and integrated hydro-ecological research programs in the Arctic.

The lake-rich tundra landscape east of the Mackenzie River Delta, NT, contains aquatic ecosystems that are projected to be impacted by CVC and other environmental stressors (e.g., resource development) in the next few decades. Large-scale permafrost degradation (i.e., increased depth of seasonal active layer and/or landscape slumping) is predicted to increase with the effects of climate warming, along with enhanced addition of geochemical loadings (e.g., carbon, nitrogen, phosphorus) to the freshwater environment. In addition, changes in the timing and duration of lake-ice characteristics in conjunction with altered geochemical loadings are projected to dramatically affect under-ice and open-water oxygen regimes, 1º and 2º production relationships, and carbon flux.

In light of the need for better understanding of the hydrology and ecology of Arctic tundra lakes, a set
of integrated, multidisciplinary hydrological, climato-
logical, and ecological field studies were established
under the ArcticNet project “Hydro-ecological Re-
 sponses of Arctic Tundra Lakes to Climate Change
and Landscape Perturbation”. The overall objective
of this study is to develop a hydro-ecological model
for small tundra lakes that can be used to assess the
vulnerability of Arctic lake ecosystems to disturbance,
such as climate variability/change and those related
to development of Canada’s northern region. The re-
search priorities of the project are to: (i) characterise
and model the hydrological and geochemical linkages
between the contributing landscape and the lake water
quantity and quality; (ii) model current and projected
lake ice and related limnological conditions in upland
Arctic lakes; (iii) develop an improved process-based
understanding and modelling capability of the hydro-
ecological responses (changes in water quantity/quali-
ty, food web structure/function, and carbon dynamics)
of tundra lake systems to present and future climate
regimes; and (iv) develop a unique legacy database of
freshwater biodiversity and related environmental in-
formation on Arctic tundra lakes; (v) develop and test
new automated buoy-based water quality/hydrometric
monitoring system and innovative experimental ap-
proaches (mesocosms).

ACTIVITIES

Timeframe and study area: Fieldwork involved repeat-
ed sampling over 2008-present of a suite of more than
60 tundra upland lakes (ranging from undisturbed to
disturbed by permafrost thaw/slumping) located be-
tween Inuvik and Tuktoyuktuk in the Mackenzie Up-
land Region east of the Mackenzie Delta, NT (Figure
1). The most intensive and extensive field investiga-
tions took place on a subset of these lakes. A fully-au-
tomated prototype ice buoy and mooring system was
installed into Noell Lake for continuous year-round
monitoring (in real-time) of weather conditions, lake
ice cover (initiation, growth over winter, breakup in
spring), light penetration into the lake (through ice in
winter), and lake water quality (chemistry, tempera-
ture, oxygen levels).

The inception and development of a lake modelling and
monitoring network (Prowse et al. 2009) was used for a
third year of in depth field-based studies over the 2011
spring period. The network covers a latitudinal gradi-
ent from temperate southern regions to the far north-
ern Arctic. Field-based measurements were completed
at the following sites which fall within ArcticNet IRIS
Regions: Noell Lake, Inuvik, NT (IRIS 1 - Western and
Central Arctic), Resolute Lake, Resolute, Cornwall-
lis Island, NU; Color Lake, Axel Heiberg Island, NU;
Lake Hazen, Ellesmere Island, NU, and Lower Dumb-
bell Lake, Alert, Ellesmere Island, NT (IRIS 2 - Eastern
Arctic) and Ramsay Lake, Churchill, Manitoba (IRIS
3 - Hudson Bay). An additional site included in the net-
work is Knob Lake, Schefferville, PQ (IRIS 4 Eastern
Subarctic).
Research: Field work, historical data analyses and modelling simulations were carried out as part of the following research activities:

1. Characterization and modelling the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality (Peters, Wrona, Prowse, Thompson, Kokejl, Hille, di Cenzo):

- Creation of a geo-referenced database for hydrological and geochemical information of the 66 small tundra study lakes for geospatial analyses.

- Long-term temperature and precipitation records were established for the study region (data mining of historical instrumental records; infilling of missing data).

- This long term historical climate record was then used to examine secondary climatic factors controlling the lake water balance (i.e., spring freshet initiation, open water duration, evaporation, annual snowpack index, and annual rainfall index).

- The role of these above mentioned secondary climatic factors on the water balance of the two primary study lakes was investigated using hydrological and climatic data collected from the lakes during the 2008, 2009 and 2010 study years (i.e., lake water level, temperature, ice thickness, ice-on, ice-off, evaporation, catchment snow water equivalence, and rainfall), with additional data provided by Environment Canada for 2005, 2006, and 2007.

- Interpretation of pre-freshet, open-water, and pre-freeze-up water quantity (e.g., snow, rainfall, water level, evaporation) and water quality (e.g., geochemical and isotopic signatures of water sources, water temperature) information at a pair of representative lake basins (undisturbed vs. disturbed by permafrost thaw/slumping).

- Interpretation of water sample analytical results from 24 paired lakes (undisturbed vs. disturbed by permafrost thaw/slumping) over a climatic (latitudinal) gradient from the tree-line near Inuvik to Richards Island (parallel to the proposed gas pipeline) for key geochemical (pH, Cond, colour, DOC/DIC and suite of ions) and isotopic (18O, 2H, 13C DIC) parameters.

- Interpretation of (synoptic latitudinal survey) of water sample analytical results from >60 lakes (undisturbed and disturbed) for key geochemical (pH, Cond, colour, DOC/DIC and suite of ions) and isotopic (18O, 2H, 13C DIC) parameters.

- Assessment of hydro-geochemical models to determine the most appropriate for investigating the effects of changing climate on arctic tundra lakes.

2. Modelling current and projected lake ice and related limnological conditions in Arctic lakes (Prowse, de Rham, Dibike, Shrestha, Harder, Brooks, von de Wall, Wrona):

- Undertook field validation of modelled lake ice composition at 11 study lakes (along a latitudinal temperature and precipitation gradient) in late winter when the ice thickness was at its maximum.

- Continued expanded lake modelling and monitoring network (including lake sites in Sweden, Norway, Finland, and Russia) – to enhance our broader understanding and modelling capability.

- Completed a regional-scale return period assessment of river ice breakup/flooding and open water levels – to investigate the control of climate as a driver for spring freshet and ice breakup, and trends in the timing of breakup. Ice jam flooding can be an important mechanism through which some northern lakes have water and nutrients replenished. The northern extent of the regional analysis includes WSC sites located within ArcticNet Regions: IRIS 1 (Western and Central Arctic), IRIS 3 (Hudson Bay) and IRIS 4 (Eastern Subarctic).

- Completed comprehensive assessment of the influence of temperature indices (e.g. 0°C isotherm) and large-scale ocean and atmospheric circulation.
patterns (e.g. SOI, PNA, NAO) on the timing and magnitude of river ice breakup.

- Further developed, calibrated and validated a GIS-based maximum ice thickness model for both lakes and rivers using ECMWF ERA-40 and CRU 10’ gridded climate data, and observed freshwater ice thickness data compiled from multiple sources, encompassing Alaska, Canada, Sweden, Finland, and Russia. This represents an increase in the quantity and spatial extent of calibration and validation sites across the NH to further improve the model, and running the improved model using other climate and freshwater datasets, as indicated as next steps in last year’s progress report.

- A prototype ice-buoy and instrumented mooring system (developed in collaboration AXSY Technologies) installed into Noell Lake was visited several times in 2011 for servicing and troubleshooting (many lessons were learned) – a major satellite telemetry transmission problem (due to a migration to a 4G system for the region) was overcome, and no data was lost while data transmission was down.

- This monitoring system continues to provide year-round measurements (in real-time) of weather conditions, lake ice cover (initiation, growth over winter, breakup in spring), light penetration into the lake (through ice in winter), and lake water quality (chemistry, temperature, oxygen levels, dissolved organic carbon, chlorophyll-a). It is planned to leave the buoy/mooring system in Noell Lake for several more years.

3. Assessing and modelling changes in food-web structure and productivity of tundra lake systems to present and future climate regimes (Wrona, McCauley, Moquin, di Cenzo, Reist, Gantner):

- Pre-freeze-up (Fall 2011) sampling for water quality (2 intensively studied small tundra lakes; Noell Lake) to further examine the food-webs and productivity relationships in replicate upland lake systems along a latitudinal gradient NE of Inuvik.

- In March 2012, we plan to conduct lake ice surveys on 11 small tundra lakes, and Noell Lake (for ice thickness, ice physical properties, and ice geochemistry) – and through the holes in the ice we plan to collect: under-ice water quality information (pH, Cond, colour, DOC/DIC and suite of ions) and isotopic (18O, 2H, 13C DIC) parameters; pelagic and benthic samples where possible. This will provide crucial information the role that lake ice plays on water quality and food webs.

- Water chemistry analyses were (Fall 2011)/will be (March 2012) completed at Environment Canada National Laboratories for Environmental Testing and included: major ion concentrations; dissolved inorganic and organic carbon concentrations; total and dissolved phosphorus and phosphate concentrations; total dissolved nitrogen, nitrate/nitrite, and ammonia concentrations; and pH, conductivity, hardness, and alkalinity measurements.

- Replicate depth profiles of photosynthetically active radiation (PAR), temperature, dissolved oxygen, specific conductivity and oxidation-reduction potential (ORP) were/will be completed at each study lake.

- Subsamples/tissue samples of all fish species collected in previous years underwent trophic analysis, species identification (performed to genus or species level), and contaminants. Stable isotope analysis for δ13C, δ15N, and δ34S were used to characterize the trophic signatures of each abundant species and the trophic relationships within the lake food webs.

- Our findings on fish community structure and trophic relationships were overlaid with available bathymetric, elevation, distance upstream from the nearest lake hosting fish, lake order, slumped vs. unslumped shoreline characteristics and water chemistry information to elucidate factors affecting whether a lake does host fish.

- Completed supplemental mesocosm experiments (Moquin MSc thesis) quantifying food web/carbon dynamics relationships that were set-up at one of the experimental lake locations NE of Inuvik.
vik to further examine the effects of thermokarst slumping on food web structure and function.

- Field reconnaissance with an incoming MSc student (Paquette-Struger) for upcoming research on how in-lake primary and secondary productivity are influenced by bottom-up control, and how the abiotic factors controlling bottom-up control (e.g. ice-cover magnitude, extent, and duration; energy availability; nutrient concentrations; DOC; DIC; water temperature) are likely to respond to climate change.

- The prototype ice-buoy and instrumented mooring system installed into Noell Lake (described above) is providing crucial information on the major factors affecting food-web structure and function.

4. Developing a Unique Legacy Database of Freshwater Biodiversity and Related Environmental Information on Arctic Tundra Lakes:

- All the data collected and analysed under the activities summarized above are being archived and will contribute to a unique legacy database and will provide excellent baseline information of the current state of arctic tundra lakes.

RESULTS

1. Characterization and modelling the hydrological and geochemical linkages between the contributing landscape and the tundra lake water quantity and quality

Climate Factors Driving the Hydrological and Geochemical Responses of Tundra Upland lakes to Landscape Perturbation:

This research component focuses on two shallow tundra lakes located in the Mackenzie Upland Region northeast of Inuvik, one affected by shoreline retrogressive thaw slumping (Lake 5B) and one not affected (Lake 5A) which acts as a control lake (Figure 1). All the fieldwork and laboratory analyses for this research is now complete, and the data are being analysed and interpreted as part of an MSc project (E. Hille). It is notable that in 2011 Hille was awarded, and took time away from this research to accept, an NSERC Northern Research Internship with the Northern Partner Institutions being the Aurora Research Institute, Inuvik, and the Water Resource Division, Aboriginal Affairs and Northern Development Canada, Yellowknife. Some of the work under the Internship (e.g. developing a soils and permafrost database for the NT) will contribute to this research component. Hille is now back at University of Victoria working towards completion of the MSc project, and completion of the thesis is expected in summer 2012.

Some preliminary results include:

- Long-term temperature and precipitation records (1958-2010) were assembled for the study area which involved data mining of historical instrumental records, and infilling of missing data through regression techniques.

- Since 1958, the mean annual air temperature in the Inuvik region has been increasing by about 0.07°C per year. No significant positive or negative trends were observed in rainfall and snowfall amounts.

- As expected, warming air temperatures are associated with earlier spring freshet initiation, and greater evaporative losses during the open water season.

- In summer, rainfall is the predominant process through which water is delivered to the lakes – once water level falls below a threshold level, channelized lake inflow and outflow ceases. This suggests that if the relative importance of rainfall in this region increases with warmer temperatures (due to an intensification of the hydrologic cycle), that the lake water balance and summer time water levels would likely be impacted.
• Supra-permafrost groundwater flow does contribute some water to the lakes during the summer period.

• The Priestley-Taylor model for evaporation was used to validate a simpler model for evaporation (Hargreaves). The Hargreaves model was then used to determine evaporative fluxes from the study lakes for 2005-2009 (using in-situ micrometeorological measurements). Results from this exercise indicate that warmer air temperatures in this region will result in greater evaporative losses from the lakes.

• Shoreline Retrogressive Thermokarst Slumping (SRTS) exerts a control on snow accumulation in the catchment. Snow survey data collected from Lake 5B for the years 2005-2009 was used to evaluate the role of SRTS in controlling the snow distribution within the lake catchment. Deep snowpacks with high snow water equivalents (SWEs) were found along the headwalls of the slump, and shallower snowpacks with low SWEs were found in the centre of the slump. SRTS can act to create large snow drifts within affected lake catchments and may act to increase the total catchment SWE prior to spring melt.

• The concentrations of certain major ions (Mg\(^{2+}\), Na\(^+\), SO\(_4\)^{2-}, Ca\(^{2+}\)) in the lake unaffected by SRTS (Lake 5A), and its inflows and outflows, were highest prior to the onset of the spring freshet. During the spring freshet, ionic concentrations decreased, due to dilution effects of the snowmelt water. After the snowpack was ablated, ionic concentrations begin to increase again, due to an increase in subsurface flow contributions.

• The concentrations of certain major ions (Mg\(^{2+}\), Na\(^+\), SO\(_4\)^{2-}, Ca\(^{2+}\)) within the lake affected by SRTS (Lake 5B), and its inflows and outflows, were greater than that of the control lake (Lake 5A), but exhibited the same seasonal patterns. In addition, slump runoff appears to be a large source of SO\(_4\)^{2-} to the lake, especially during the summer months when the slump material is thawing. These results indicate that the observed effects of SRTS on shallow tundra lakes is undoubtedly linked to landscape-level flow off the slump in mid- to late-summer.

**Mesocosm Experiment - Impacts of Shoreline Retrogressive Thermokarst Slumping on Water Quality:**

An *in-situ* mesocosm experiment designed to further our understanding of the underlying mechanisms of the geochemical changes observed in Shoreline Retrogressive Thermokarst Slumping (SRTS) disturbed lakes was conducted in 2010. Twelve mesocosms were installed in a lake (Lake 5A) which is currently unaffected by shoreline slumping (Figure 2). To simulate the effect of SRTS on the lake, permafrost slumped material from an adjacent lake was added to the mesocosms. Using a randomized block design, 3 mesocosms were left untreated as controls, and the remaining 9 (3 replicates of each) were treated with depths of 1.5 cm, 3 cm, and 9 cm of sediment. After treatment, the mesocosms were sampled for water and sediment chemistry weekly/bi-weekly from mid-June to early September.

The water chemistry and physical parameters measured for this experiment were categorized into four function-
Table 1. Summary table of probability values of physical/water quality and chemical variables tested with a three-parameter mixed-effects model, which included: a) treatment level, b) time in weeks, c) an interaction term of treatment and time. Significant p values (p<0.05) are shaded. The final column refers to the trend of the response to increasing treatment. Other than standard chemical abbreviations, the following abbreviations are used: total phosphorus (TP), dissolved phosphorus (DP), orthophosphate (OP), total nitrogen (TN), total dissolved nitrogen (TDN), conductivity (Cond.), alkalinity (Alk.), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), turbidity (Turb.), and light attenuation coefficient (k). From Moquin 2011.

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Increasing sediment treatment effects were associated with increases in all phosphorus parameters including total phosphorus (TP), dissolved phosphorus (DP) and orthophosphate (OP). Potassium (K) and ammonia (NH₃) also increased with sediment treatment; however, no significant trends were found for total nitrogen (TN) or total dissolved nitrogen (TDN). Although for TN, low treatment was significantly different than the control. TP, DP and NH₃ were the only nutrients that changed significantly over time; they did so in a downward trend.

Nutrients:

Increasing sediment treatment effects were associated with increases in all phosphorus parameters including total phosphorus (TP), dissolved phosphorus (DP) and orthophosphate (OP). Potassium (K) and ammonia (NH₃) also increased with sediment treatment; however, no significant trends were found for total nitrogen (TN) or total dissolved nitrogen (TDN). Although for TN, low treatment was significantly different than the control. TP, DP and NH₃ were the only nutrients that changed significantly over time; they did so in a downward trend.
Cations/Anions:

All cations and anions measured increased with increasing sediment treatment as indicated by increasing conductivity, a general indicator of ion concentrations. Over time, calcium (Ca), magnesium (Mg) and sodium (Na) increased while chloride (Cl) and silicon dioxide (SiO₂) decreased. Sulfate (SO₄) did not change significantly over time. Sodium was the only variable which had a significant treatment by time interaction. The high treatment level increased over time while the concentration of other treatments did not vary significantly with time. This was expected as the sediments from this area are from ancient marine deposits (Mesquita 2008, Burn and Kokelj 2009). However, compared to the slumped lakes in Thompson’s (2009) study, the ionic concentrations in the mesocosms were low. Ion concentrations trended upwards over the course of the season. Temporal trends towards concentrations found in natural systems in nutrients and cations/anions suggest that ion exchange with new slump material may be a multi-year process. As such, the potential of this experiment to address long-term questions regarding the potency of permafrost-related sediments to affect geochemical change is limited.

Physical/Water Quality Parameters:

Treatment effects were associated with significant increases in colour, turbidity, and light attenuation coefficient. No sediment treatment effects were found for DOC. None of these physical parameters changed significantly over time.

2. Modelling current and projected lake ice and related limnological conditions in Arctic lakes

Modelling Current and Projected Lake Ice:

Field validation of lake ice models – the inception and development of a lake modelling and monitoring network (reported as Prowse et al. 2009) was used during for a third year of in-depth field-based lake ice measurements over the 2011 spring period (Figure 3). This included site visits to 13 lakes along a latitudinal temperature-precipitation gradient from temperate southern regions to the far northern Arctic, along with international locations in Sweden and Alaska. Water quality (temperature and dissolved oxygen) profiles were also gathered at each site. Data collected are being used for further development/validation of lake ice and ecology models (including MyLake) for high latitude applications.
Development of a GIS-Based Ice Thickness Model for the Northern Hemisphere:

The cryosphere integrates climate variations over a wide temporal and spatial scale through its direct connection to the surface energy budget, the water cycle, and surface gas exchanges (Lemke et al. 2007). As one of the eight cryospheric components, freshwater ice reflects temporal variations in climate (Fitzharris 1995). Such variations can have a wide range of impacts on freshwater ecosystems, and are significant to a number of socio-economic systems, particularly on-ice transport. Assessing the broad-scale implications of changes to freshwater ice requires a comprehensive understanding of its areal coverage and volume, not yet conducted for the Northern Hemisphere (NH), where it is a major cryospheric feature. To address this, a degree-day ice-growth model has been embedded in a GIS analytical procedure to quantify the large-scale spatial and temporal characteristics of freshwater ice. This model, introduced in last year’s progress report, has been further developed by increasing the quantity and spatial extent of calibration and validation sites across the NH to further improve the model, and running the improved model using other climate (ERA-40; CRU) and freshwater datasets (observed freshwater ice thickness database compiled from multiple sources, encompassing Alaska, Canada, Sweden, Finland, and Russia), to quantify freshwater ice in the NH using a GIS-based approach.

To calibrate the model, half of the maximum observed ice thickness measurements were compared to modelled peak-ice thickness values using the Nash-Sutcliffe efficiency E (NSE), and a regression coefficient (R²). Defining the appropriate ice growth coefficients for input into the model was approached in three ways, separately for rivers and lakes: (i) using a single ice growth coefficient across the NH; (ii) using an optimal coefficient defined for each observation site – does not define coefficients outside these sites; and (iii) defining optimal coefficients by hydro-climatic region (still in progress).

Figure 4. Preliminary calibration results for the model using a single ice growth coefficient across the Northern Hemisphere (left), and when using an optimal coefficient defined for each observation site (right).
Results to date suggest that the model performs adequately when using a single coefficient across the Northern Hemisphere, but the results improve considerably when optimal coefficients are defined on a site by site basis (Figure 4). Results also improve when explored on a smaller regional scale specific to source data.

Next steps include identifying and selecting an optimal number of hydro-climatic regions using both quantitative and qualitative approaches, calibrating the model using coefficients defined by hydro-climatic region, and validating the model using half of the maximum observed ice thickness measurements not used for model calibration.

Spatial and Temporal Analysis of River Ice Break-up:

The spring break-up of river ice is a critical period for river environments in cold regions. Since river ice is as a dominant control of annual, peak water levels on cold-region rivers (e.g., de Rham et al. 2008), break-up is responsible not only for ecological and morphological effects, but also has significant socio-economic implications (e.g., Prowse et al. 2007). In some instances, ice-jam flooding is the primary mechanism through which small arctic lakes have their water and nutrients replenished.

In 2011, a comprehensive assessment of the influence of temperature indices and large-scale ocean and atmosphere circulation patterns on river ice break-up timing was undertaken, based on an analysis of novel, event-based hydrometric variables representative of river ice break-up. Results of a trend analysis from 1969-2006 reveal that initiation and peak break-up water levels ($H_{ib}$, $H_{im}$) have declined significantly (Figure 5), while the timing of break-up initiation ($T_{ib}$), maximum break-up water level ($T_{im}$), and, last $B$ date” ($B$, a timing indicator used to specify when flow is no longer affected by ice) have been occurring significantly earlier in western and central Canada (Figure 6). In contrast, the break-up drive ($\Delta t_1$, time between $T_{ib}$ and $T_{im}$) and the break-up wash ($\Delta t_2$, time between $T_{im}$ and $B$) show considerable variability, whereas for the most part, an increase in break-up duration ($\Delta t_3$) is evident. Table 2 presents a

![Figure 5. Results of the Mann-Kendall test ($\alpha=0.1$) of a) $H_{ib}$ and b) $HM$ for the 1969-2006 period. Regulated rivers are indicated with black dots. From von de Wall 2011.](image-url)
The spatial and temporal variability of break-up timing were assessed separately with the spring 0°C isotherm and dominant ocean/atmosphere oscillations. Results show that TB, TM and B are significantly and positively correlated to the spring 0°C isotherm (Figure 7), while correlations between these break-up timing indicators and major ocean/atmosphere oscillations (Table 3) are predominantly significant for the Pacific North American Pattern (negative) and the El Niño Southern Oscillation (positive) over most of western Canada. In contrast, correlations between the Arctic and North Atlantic Oscillations with break-up timing are mostly non-significant over western Canada, while some significant positive correlations are found in eastern Canada. The results from this work provide a first order assessment of changes in break-up water levels over the period analyzed and shows that the temporal changes of event-based break-up timing variables are largely consistent with changes in the spring 0°C isotherm and large-scale climatic controls.

This research was part of an MSc thesis (S. von de Wall) which was successfully completed in November 2011. Two journal manuscripts from this work will be forthcoming.
Table 3. Percentages of significant ($\alpha=0.05$) spearman correlation coefficients in Canada’s climatic regions between timing of break-up initiation (TB), peak-break-up water level (TM), B and the mean 1 month, 2 month and 3 month SOI, PNA, AO and NAO indices. Note: the asterisk indicates a low sample size (n = 2) for the Southern BC Mountain climate region. From von de Wall 2011.

<table>
<thead>
<tr>
<th>Climate Region</th>
<th>SOI</th>
<th>PNA</th>
<th>AO</th>
<th>NAO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_B</td>
<td>T_M</td>
<td>B</td>
<td>T_B</td>
</tr>
<tr>
<td>Southern BC Mountains*</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Yukon/North BC Mountain</td>
<td>17</td>
<td>14</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>25</td>
<td>0</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Northwest Forest</td>
<td>13</td>
<td>19</td>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>Prairie</td>
<td>0</td>
<td>15</td>
<td>7</td>
<td>44</td>
</tr>
<tr>
<td>Arctic Tundra</td>
<td>0</td>
<td>40</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Northeastern Forest</td>
<td>10</td>
<td>12</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Atlantic</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Southern BC Mountains*</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Yukon/North BC Mountain</td>
<td>17</td>
<td>43</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>25</td>
<td>0</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>Northwest Forest</td>
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<td>23</td>
<td>56</td>
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<td>Prairie</td>
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<td>23</td>
<td>21</td>
<td>55</td>
</tr>
<tr>
<td>Arctic Tundra</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Northeastern Forest</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Atlantic</td>
<td>0</td>
<td>14</td>
<td>28</td>
<td>0</td>
</tr>
</tbody>
</table>

(*) denotes small sample size
Development of an Ice Buoy and Subsurface Smart Mooring System:

A major difficulty in monitoring hydro-ecology of lakes in the Arctic is that many locations are very remote, often only accessible by helicopter or float plane. This makes visiting these sites frequently for monitoring purposes very difficult due to the high cost of conducting research in the North. In addition, bad weather in summer and harsh winter conditions interfere with planned field trips to research sites and compromise programs for gathering sets of time-series environmental data. To overcome these challenges, in collaboration with AXYS Technologies (Sidney, BC), we continue to further develop an Arctic Lake Monitoring System (ALMS) – a prototype fully-automated Ice Buoy and Subsurface Smart Mooring System described in detail in last year’s report.

The prototype ALMS was installed into Noell Lake prior to freeze-up in September 2010 (Figure 8), and functioned reasonably well through its first winter (2010/11). However, in 2011, we did encounter some difficulties that had to be overcome. Firstly, we had difficulty in retrieving the system from the lake for annual servicing (swapping out YSI sondes and internal batteries). Many lessons were learned which should make

![Figure 7. Results of the Mann-Kendall test (α=0.1) of a) HB and b) HM for the 1969-2006 period. Regulated rivers are indicated with black dots. From von de Wall 2011.](image)

![Figure 8. Deployment of the ice buoy into Noell Lake involved (i) transport of the pre-assembled buoy from Inuvik by helicopter and deployed into the lake near the shore (top left), and (ii) towing the buoy by boat to its mooring location (top right and bottom left). The buoy froze into the lake ice as planned with no damage and with instruments intact (bottom right). Photo credit: courtesy of Environment Canada.](image)
system retrieval in subsequent years much easier to deal with. Secondly, we had logistical difficulty in arranging a helicopter with sufficient lift capacity to remove and redeploy the buoy. Thirdly, after redeploying the system in late summer all instrumentation was functioning within normal parameters, until November when the system ceased its satellite telemetric transmission of its data. This problem could not be resolved remotely, and necessitated a troubleshooting field trip to Noell Lake where the Buoy had already been frozen into the lake for some time. It was discovered that the transmission problem was due to migration to a 4G system for the region, and the modem on the Buoy had to be reprogrammed to overcome this problem. After this fix, the entire system continues to be fully operational – no data was lost while the data transmission was down as the data continued to be collected and stored in the Buoy datalogger.

It was planned to install a second buoy/mooring system into a lake near Cambridge Bay, NU during 2011. However, these plans were put on hold until 2012 or 2013 – it was deemed prudent to get the prototype system installed in Noell Lake running seamlessly before installing the second system into an even more remote location.

3. Assessing and modelling changes in food-web structure and productivity of tundra lake systems to present and future climate regimes

Arctic Tundra Lake Food-Webs: Evaluating Fish Presence/Absence in Small Upland Tundra Lakes:

As part of our ongoing study on food-web structure, we had reported last year that in 2010 assessed eight lakes along an elevation gradient and eight lakes within sub-catchments of Noell Lake (Figure 9). Of the 16 lakes, 11 appeared to be fish-less, while three hosted *N. stickleback* and two both *N. pike* and *N. stickleback*. The three lakes hosting *N. stickleback* were small, shallow, and connected to each other. One lake with a mixed population of *N. pike* and stickleback was located higher in the watershed. The second lake with *N. pike* and *N. stickleback* populations, drained directly into Noell Lake and was larger and possibly deeper, allowing for *N. pike* to be present. This suggested that lake size/depth and location on the landscape may play a role in distribution fish in lakes situated at high elevations in watersheds. Upon further investigation, in the Noell Lake catchment, elevation gradient appears to be a factor – no fish were found >22m above Noell Lake (Table 4).

Work on characterizing the aquatic food-web for the tundra study lakes using stable isotope signatures of δ15N and δ13C, and the degree to which fish (where present) act as a “top-down” control on the food-web, is ongoing. Preliminary results indicate that food-webs in the small tundra lakes are simplistic compared to lakes in other more temperate regions, and that fish (where present) do act as a “top-down” control in these tundra lake systems. This work is not yet complete as we are still receiving laboratory isotope signature data for the food-web components.
Dr. Ganter, who led this work, completed his NSERC Government of Canada Visiting Fellowship and has moved to a new position as a Banting Scholar at the University of Victoria.

Mesocosm Experiment – Impacts of Shoreline Retrogressive Thermokarst Slumping on Productivity:

Using the experimental mesocosm approach described above, part of this study was a first ever attempt to assess how varying levels of thermokarst slumping affect pelagic and benthic autotrophic and heterotrophic production. An innovative light and dark bottle measurement system was developed and implemented and used simultaneously with radio-labelled leucine uptake incubations to assess the relative importance of autotrophic and bacterioplankton production.

In general, the addition of thermokarst sediments resulted in decreases in pelagic autotrophic and heterotrophic production while benthic heterotrophic production increased. Furthermore, decreases in pelagic production even as nutrients increased, indicate that factors other than nutrient availability govern the observed reductions in pelagic productivity. These other factors are likely to include the chemical binding of nutrients, DOC and light availability.

Table 4. Elevation gradient versus fish species for select lakes in the Noell Lake catchment.

<table>
<thead>
<tr>
<th>Lake</th>
<th>m above Noell</th>
<th># of fish species</th>
<th>Lake depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>5B</td>
<td>55</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>3B</td>
<td>54</td>
<td>0</td>
<td>10.5</td>
</tr>
<tr>
<td>NSCL 2</td>
<td>50</td>
<td>0</td>
<td>6.5</td>
</tr>
<tr>
<td>4B</td>
<td>48</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>SA</td>
<td>43</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>NSCL 7</td>
<td>35</td>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>NSCL 9</td>
<td>32</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>NSCL 8</td>
<td>25</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>NSCL 10</td>
<td>24</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>NSCL 5</td>
<td>22</td>
<td>2</td>
<td>5.1</td>
</tr>
<tr>
<td>NSCL 13</td>
<td>22</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>NSCL 4</td>
<td>20</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td>NSCL 11</td>
<td>18</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>NSCL 6</td>
<td>15</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>NSCL 3</td>
<td>9</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>NSCL 12</td>
<td>9</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

No fish found >22m above Noell Lake (<6m asl)

Autotrophic Primary Productivity:

Pelagic – Sediment additions were associated with decreases in rates of Primary Productivity (PP) in the pelagic zone. Probability values from the three parameter mixed effects model including treatment, time and treatment-time interactions are presented in Table 5 and percentage change relative to the control are presented in Table 6. Decreases in PP were apparent in decreased concentrations of chlorophyll a, decreased rates of Net Productivity (NP) at both depths, and Gross Primary Productivity at 0.5m depth (GPP<sub>0.5</sub>). Rates of Gross Primary Productivity at mesocosm bottom (GPP<sub>b1</sub>) were generally lower than GPP<sub>0.5</sub> but no significant treatment effect was found.

GPP was weaker than respiration, leading to negative values of NP in all treatments. NP and GPP decreased with depth. In the control mesocosms, the difference between NP<sub>0.5</sub> and NP<sub>b1</sub> was not significantly different from the difference between GPP<sub>0.5</sub> and GPP<sub>b1</sub> (t-test, t=0.68, p=0.50). In contrast, these differences were significant in the treated Mesocosms (t-test, t=2.23, p=0.028) indicating that decreases in GPP accounted for the decreases in NP in the control but not in the treated Mesocosms. This suggests that respiration rates increased with depth in the treated Mesocosms although they did not vary significantly with treatment.

There was a significant interaction of time and treatment (p<0.001) in chlorophyll a concentration. This interaction resulted from the control and low treatments increasing in levels throughout the experiment (though low is subdued relative to the control), while the medium and high treatment levels did not vary with time and remained at low levels. NP<sub>b1</sub> increased significantly over time while the increase in NP<sub>0.5</sub> was marginally non significant (p=0.051). Neither GPP nor respiration varied significantly over time.

Pelagic autotrophic primary production was found to be the dominant energy pathway for carbon into the food web regardless of sediment treatment level. Autotrophic primary production decreased with increasing treatment level while the biomass of Daphnia, which represented
the majority of the zooplankton biomass, increased with increasing addition of sediments. An increase in pelagic secondary productivity with increasing sediment treatment indicates that the overall effect of thermokarst disturbance is an enrichment of the system, and supports the hypothesis that a “top-down” predator-prey interaction is primarily responsible for regulating the abundance of phytoplankton in these systems.

Benthic – No significant treatment effects were found in NPben, GPPben, or Rben; however, they all changed significantly over time.

Bacterial Production – Pelagic Bacterial Production (BP) decreased significantly with sediment addition and benthic BP increased with sediment additions. Both pelagic and benthic BP changed significantly over time (Figures 10, 11).

### Table 5. Summary table of probability values from a series of three-parameter mixed-effects models for primary productivity and bacterial productivity. The model included: treatment level, time in weeks and an interaction term of treatment and time. Significant p values (p<0.05) are shaded with grey. For parameters that varied over time, the direction of the change is in parenthesis after the p value. The final column represents the direction of the trend with increasing treatment level for each parameter. From Moquin 2011.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fig. #</th>
<th>Significance of Time</th>
<th>Contrasts Relative to Control</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Chl’a</td>
<td>4.4</td>
<td>&lt;0.0001 (+)</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
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<tr>
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<td>0.051</td>
<td>0.98</td>
<td>0.28</td>
</tr>
<tr>
<td>NP&lt;sub&gt;bot&lt;/sub&gt;</td>
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<td>0.0017 (+)</td>
<td>0.47</td>
<td>0.022</td>
</tr>
<tr>
<td>GPP&lt;sub&gt;0.5&lt;/sub&gt;</td>
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<td>0.48</td>
<td>0.62</td>
<td>0.033</td>
</tr>
<tr>
<td>GPP&lt;sub&gt;bot&lt;/sub&gt;</td>
<td>NA</td>
<td>0.47</td>
<td>0.89</td>
<td>0.12</td>
</tr>
<tr>
<td>R&lt;sub&gt;pel&lt;/sub&gt;</td>
<td>NA</td>
<td>&lt;0.0001 (-)</td>
<td>0.44</td>
<td>0.80</td>
</tr>
<tr>
<td>NP&lt;sub&gt;ben&lt;/sub&gt;</td>
<td>4.7</td>
<td>&lt;0.0001 (+)</td>
<td>0.24</td>
<td>0.92</td>
</tr>
<tr>
<td>R&lt;sub&gt;ben&lt;/sub&gt;</td>
<td>4.7</td>
<td>&lt;0.0001 (-)</td>
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<td>0.85</td>
</tr>
<tr>
<td>GPP&lt;sub&gt;ben&lt;/sub&gt;</td>
<td>4.7</td>
<td>0.035 (-)</td>
<td>0.53</td>
<td>0.29</td>
</tr>
<tr>
<td>BP&lt;sub&gt;gel&lt;/sub&gt;</td>
<td>4.8</td>
<td>&lt;0.0001 (-)</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
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<td>4.9</td>
<td>0.0165 (+)</td>
<td>0.027</td>
<td>0.0020</td>
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</table>

Table 6. Treatment effect expressed in mean percentage change relative to the control. Calculated as: Treated – Control / Control. Significant changes (p<0.05) are shaded with grey. From Moquin 2011.

<table>
<thead>
<tr>
<th>Process</th>
<th>Mean % change relative to the control</th>
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</thead>
<tbody>
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<td></td>
<td>Low</td>
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<tr>
<td>Chl’a</td>
<td>-38</td>
</tr>
<tr>
<td>NP&lt;sub&gt;0.5&lt;/sub&gt;</td>
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</tr>
<tr>
<td>NP&lt;sub&gt;bot&lt;/sub&gt;</td>
<td>-28</td>
</tr>
<tr>
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<td>-16</td>
</tr>
<tr>
<td>BP&lt;sub&gt;gel&lt;/sub&gt;</td>
<td>-37</td>
</tr>
<tr>
<td>BP&lt;sub&gt;ben&lt;/sub&gt;</td>
<td>44</td>
</tr>
</tbody>
</table>
Benthic versus Pelagic – Autotrophic production was greater than heterotrophic production in both the benthic and pelagic zones regardless of treatment. Pelagic-based autotrophic processes were greater than benthic-based autotrophic processes. In heterotrophic production, pelagic production increased with treatment and surpassed pelagic processes in the high treatment.

Zooplankton Production:

The objective of this research component was to use the experimental (mesocosm) approach to assess the responses, relative importance and role(s) of the zooplankton community (structure, density and biomass) in relation to sediment additions mimicking shoreline...
retrogressive thaw slumps (SRTS) associated with permafrost melt. Using fishless mesocosm systems, zooplankton are consumers as well as top predators, phytoplankton and bacterioplankton are the producers while nutrients are the resource.

Zooplankton were categorized into three broad taxonomic groups: Cladocera, Rotifera and Copepoda. A multivariate analysis of variance (MANOVA) on the percentage composition of taxon density (individuals per litre) within each group was conducted to determine if group composition changed significantly with treatment. Data were arcsine transformed to deal with the bound nature of percentage data (Crawley 2007). A significant result (p<0.05) for a given species (last column of Table 7) indicates that the species composition changed significantly with treatment. The p-value for the overall MANOVA (last row of each group, shaded in grey) indicates whether or not overall changes in taxonomic composition with treatment were statistically significant for the group.

Within the Cladocera assemblage, percentage taxon composition changed significantly with treatment (e.g., *Daphnia middenorffiana* abundance was depressed with increasing treatment relative to the control). Taxonomic composition of Rotifera and Copepoda did not change significantly with treatment (p>0.05), though some individual taxa did change significantly with treatment (i.e., *Asplancha* spp., *Cyclops scitifer*). However, these taxa did not exhibit any consistent trends with treatment suggesting that treatment effects are not likely responsible for the observed differences.

This work was part of an MSc thesis (P. Moquin) which was successfully completed in December 2011. Several journal manuscripts from this work will be forthcoming.

**Ice Buoy and Subsurface Smart Mooring System:**
Time-series data from the Arctic Lake Monitoring System (described above) continues to provide an improved temporal process-based understanding of Arctic lake ecosystems, and assist in the development and improvement of hydro-ecological models for Arctic lake systems in the following research areas: (i) the effects of landscape hydrology and geochemistry linkages on Arctic lake water quantity and quality; (ii) lake ice processes and modelling; and (iii) intra- and inter-seasonal changes in pelagic and benthic food-webs (structure and productivity) and carbon dynamics. This improved knowledge and modelling capability will contribute significantly to our ability to assess the vulnerability of Arctic lake ecosystems to landscape disturbance and climate variability/change.

**DISCUSSION**
Over the past 4 years we have been conducting a series of integrated hydrological and ecological field and experimental studies and modeling efforts assessing the impacts of landscape and lake-ice related cryospheric changes on the hydrology, geochemistry, and food web responses of upland Arctic lakes. In particular, using lake shoreline permafrost “slumping” as an analogue for climate change-induced landscape effects, we have utilized these systems to assess the relative importance of external subsidization of nutrients, major anions and cations and allochthonous organic carbon on pelagic
and benthic productivity relationships and trophic/food-web responses. Much of the work is still ongoing with results being preliminary. The following discussion pertains to aspects of this integrated research program that have now been completed.

Much of the preliminary work on the impacts of thermokarst activity has focused on the geochemical contrasts between slumped and unslumped lakes. A number of multi-lake comparative studies have found that mean concentrations of major cations and anions such as Ca, Mg and SO₄ are over an order of magnitude higher in slumped lakes compared to unslumped lakes while mean levels of water colour and dissolved organic carbon (DOC) are lower in affected lakes (Kokelj et al. 2005, 2009a,b, Thompson 2009). Furthermore, increases in ion concentration and decreases in DOC and colour were proportional to the percentage of total basin area influenced by thermokarst disturbance (Kokelj et al. 2005). Experimental work by Thompson et al. (2008) suggests that the “clear” pelagic water observed in slumped lakes may be a result of interactions between coloured humic matter and permafrost-related sediments released from thermokarst disturbance. They proposed that charged particles such as ions and clays associated with thermokarst disturbance interact with the organic particles in the water column to form heavier compounds, which settle to the lake bottom. The theory is based on evidence that has shown that such interactions readily occur in the pelagic (Stumm and Morgan 1981, Rasmussen et al. 1989) and benthic (Hobbie et al. 1999) environments. Since large portions of the compounds in humic matter are coloured (Jones 1992), this leads to a clearing of the water column.

Results from our mesocosm experiment showed that additions of permafrost-related sediments were associated with significant increases in nutrient concentrations within treated mesocosms. All phosphorus parameters, potassium and ammonia increased with sediment treatment. These results are contrary to expectations. This may be a result of the relative fresh nature of the simulated slumping event in the mesocosms. In a synoptic study of 60 tundra lakes, Thompson (2009) found no increases in nutrient concentration related to thermokarst activity – temporal data from this study indicate that most nutrient concentrations decreased throughout the length of the experiment. While Thompson’s (2009) study included active slumps, it also included lakes with stable but recently active slumps and ancient slumps making a comparison to these mesocosms tenuous. There are a number of processes that may sequester nutrients from the water column over time. They include biological uptake (Levine and Schindler 1989), binding directly with sediments (Hobbie et al. 1999) as well as various settling processes (Forsberg 1989). In particular, the binding and settling of nutrients to inorganic particles in suspension such as fine silts and clays (Stumm and Morgan 1981) which are also part of the slump material, may be an important mechanism sequestering nutrients from the water column. These processes may have continued to function reducing nutrient concentrations to background levels given a longer experimental length.

In general, the addition of thermokarst sediments to the mesocosms resulted in decreases in pelagic autotrophic and heterotrophic production while benthic heterotrophic production increased. Furthermore, decreases in pelagic production even as nutrients increased, indicate that factors other than nutrient availability govern the observed reductions in pelagic productivity. These other factors are likely to include the chemical binding of nutrients, DOC and light availability. Because trends were shown to differ by environment (benthic vs. pelagic), how a lake is impacted by permafrost degradation likely depends as much on physical parameters such as depth and volume to benthic area ratios as the geochemical properties of the impacted lake. For example the impact of slumping to shallow lakes, in which benthic production is known to be the most important carbon support for food webs (Vadeboncoeur et al. 2002, Rautio and Vincent 2006) will be different than the impact to deep lakes with pelagic-based food webs. The dramatic increase in benthic heterotrophic activity and the absence of any significant changes in benthic primary production were unexpected relative to observations by Mesquita (2008) who reported that slumped lakes had greater benthic primary productivity than unslumped lakes. Results showing stimulated benthic heterotrophic productivity raises the provocative possibility that such
increased activity is the first step in a succession leading to the proliferation of benthic production as observed in slumped lakes.

Additions of permafrost-related sediments were also associated with (i) increases in secondary production – in particular via increases in Cladocera, (ii) shifts in the size structure of the zooplankton community, and (iii) dietary shifts for Copepoda and rotifers. These results likely reflect fundamental shifts in the basal components of the food web and suggest that the addition of permafrost-related sediments may have far-reaching effects on the structure and function of affected aquatic ecosystems.

Our mesocosm experiment results underscore the importance of investigating multiple trophic levels when exploring questions of productivity. As such, studies should tailor their sampling regime to their specific questions and include all trophic levels that may surround the specific questions. For example in this study, trophic interactions as a cause for the decreases in BP with increasing treatment cannot be ruled-out because a group of protozoan, called heterotrophic nanoflagellates (HNF), who feed on bacteria (Kalff 2001) were not assessed. It is therefore recommended that HNF be included in future studies particularly when knowledge surrounding the fate of allochthonous carbon is sought. Future studies should also include Amphipoda as they have been observed to be numerically abundant in numerous upland Arctic lakes in the Mackenzie Delta. Amphipoda are known detritivores and their diet also includes bacteria, algae and fungi as well as non-living substances (Hargrave 1970). Amphipoda represent an important outlet of carbon to higher trophic levels as exemplified in temperate lakes (Schindler and Scheuerr 2002) as well as in northern systems such as the Mackenzie River basin (Hesslein et al. 1991).

Though a great deal of insight into how lakes may be impacted by retrogressive thaw slumping has been achieved in this mesocosm experiment, a longer (inter-annual) experimental period is recommended to better understand how these systems change over time. Reductions in turbidity and the settling of larger particulate complexes in the water column that would likely occur after a season under ice would certainly have revealed a better understanding of the effects of permafrost thaw slumping in these cryospherically dominated systems. Many of the significant time effects found in this study were seasonal, yielding little information of treatment effects over time. It is likely that many of the effects of a major change in such an environment develop over multiple years, especially when the environment is frozen for a better part or the year.

The spring break-up of river ice is a critical period for river environments in cold regions as river ice is as a dominant control of annual, peak water levels on cold-region rivers. Break-up is responsible not only for ecological and morphological effects, but also has significant socio-economic implications. In some northern/arctic environments, such as in the Mackenzie Delta, ice-jam flooding is the primary mechanism through which small arctic lakes have their water and nutrients replenished. Arctic freshwater systems (lakes and rivers) are directly and indirectly (2nd and 3rd order impacts) affected by cryospheric responses to climate variability and change. In light of the importance that river ice break-up (both timing and magnitude) can have on freshwater systems in the arctic, our research program partially supported the MSc project (S. von der Wall) on assessing the river ice break-up season across Canada, including its northern/arctic regions. The following is a discussion on new results from this work over the past year that were not mentioned in last year’s report.

The mean timing of river ice break-up initiation ($T_B$) and the spring 0°C isotherm reveals a close correspondence in spatial patterns between both events. Notably, the influence of the Pacific Ocean on the climate of western Canada is reflected in the spring 0°C isotherm, where unlike the rest of the country, spring air temperatures do not increase uniformly with latitude. This is also reflected in the timing of $T_B$, where the distinct differences for comparable latitudes were previously noted by Prowse and Onclin (1987). For example, it is evident that break-up initiation begins earliest in south-central British Columbia (mid to end of January) whereas those in Atlantic Canada and southern Manitoba break-up
towards the middle to end of March. Generally speaking, initiation advances north-east for most of western Canada and occurs the latest in the western and central Arctic towards the end of June. Although variable across the country, the mean difference between $T_B$ and the spring $0^\circ C$ isotherm indicates that above $0^\circ C$ temperatures precede break-up initiation on average by 11 days. Although the timing of spring break-up is affected by a number of hydro-climatic variables at multiple spatial and temporal scales, its strong correlation with the spring $0^\circ C$ isotherm indicates that air temperature is a dominant control, and hence able to explain the observed spatial patterns between these two variables. This is also consistent with the fact that the majority of significantly earlier break-ups occur in the western regions of Canada where spring temperatures have increased the most (Zhang et al. 2000).

The strong relationship between the spring $0^\circ C$ isotherm and break-up timing, combined with trends of earlier break-up and reduced water levels, suggest a greater occurrence of thermal break-ups. In contrast to break-up timing, which is primarily controlled by air temperature, other hydro-climatic factors such as the rate of spring snowmelt, resisting forces provided by the ice cover (strength, composition and attachment to channel banks) and, more importantly, the freeze-up stage can affect the type of break-up and the magnitude of break-up water levels (Beltaos 2003). Governed by hydro-climatic conditions of the preceding autumn (e.g., precipitation and temperature), a higher (lower) freeze-up stage would be more likely to contribute to a thermal (dynamic) break-up as more (less) discharge is required to dislodge and break the ice cover. It follows that in order to substantiate reduced break-up water levels additional analysis of the freeze-up stage and its effects on break-up water levels is required. Unfortunately, these data are currently unavailable.

The influence of the inter-annual variability of temperature, as mediated by ocean/atmosphere circulation patterns, on the timing of river ice break-up was also examined. Although the strengths of correlations are weak to moderate, distinct spatial signatures are evident. The strongest effects on break-up are observed in most of western/nothwestern Canada, where the positive (negative) PNA phase generates earlier (later) break-ups in the season due to warmer (colder) than normal temperatures. Similarly, a significant and strong positive correlation with a similar spatial extent is found between ENSO, as measured by the Southern Oscillation Index (SOI). In other words, river ice break-up generally occurs later in the season during a positive SOI year (i.e., La Niña) while it is delayed during negative (El Niño) phases. Both, the Arctic and North Atlantic Oscillations show fewer significant, weak to moderately positive associations with the break-up season in the climatic regions of eastern Canada. Positive AO/NAO indices are indicative of more frequent arctic air mass intrusions which delay break-up to later than normal.

Overall, this research shows that the spatial and temporal variability of the river ice break-up season is largely dependent on the variability of spring air temperature. Accordingly, any changes in air temperatures via an increase in climate variability and change will also modify the break-up regimes of cold region/arctic rivers as well as their socio-economic effects. Based on these findings, future work should: (1) increase the spatial and temporal coverage of the hydrometric station database such that the influence of air temperature on break-up dynamics can be assessed across all of Canada, as currently, the Northern/Arctic and Atlantic regions are underrepresented; and (2) evaluate specific hydro-climatic controls of break-up water levels such as the rate of springtime warming and subsequent melt as well as components that contribute to the ice cover strength and, in particular, the freeze-up stage. This would aid in determining whether break-up has in fact become more thermal in response to warmer spring air temperatures.

The results of the studies discussed above, along with preliminary results from our other studies still ongoing, show that there are significant effects of climate variability and change on cold region/arctic freshwater hydrology and ecology. Landscape permafrost degradation as measured by increased thermokarst slumping significantly affects the observed complexity of aquatic food webs (structure and function), pelagic and benthic geochemistry and primary productivity. Lake-ice meas-
urements and modelling, and river break-up assessments, indicate cryospheric sensitivities to regional and synoptic changes in climate result in a delay of freeze-up, earlier break-up (hence reducing lake and river ice duration), and a reduction in lake ice thickness with a somewhat greater thickness in white ice in most locations. Our completed and ongoing studies reiterate that understanding climate-cryosphere-ecosystem interactions are necessary to predict the future responses and sensitivities of aquatic ecosystems to climate variability and change.

CONCLUSION

Climate models predict increasing mean temperatures for the majority of the globe with disproportionate increases in Arctic Polar regions. Unsurprisingly, incidences of permafrost degradation are also predicted to increase. Results of our mesocosm experiment suggest that the productivity of arctic tundra lakes will increase with increasing thermokarst activity. Following predictions from the exploitation model, increased productivity should increase the number of trophic levels that can be supported within the system. As such, slumped lakes are predicted to have more suitable habitat conditions conducive to hosting higher trophic levels including fish. Furthermore, our observed increases in the size structure of Cladocera may also increase the potential of an aquatic ecosystem to host fish as fish recruitment success is positively correlated with the size of available zooplankton.

Our studies underscore the importance of investigating multiple trophic levels when exploring questions of productivity. Studies should tailor their sampling regime to their specific questions and include all trophic levels that may surround the specific questions. For example, in our mesocosm experiment, trophic interactions as a cause for the decreases in BP with increasing treatment cannot be ruled-out because a group of protozoan, called heterotrophic nanoflagelates (HNF), who feed on bacteria were not assessed. It is therefore recommended that HNF be included in future studies particularly when knowledge surrounding the fate of allochthonous carbon is sought. Future studies should also include Amphipoda as they have been observed to be numerically abundant in numerous upland Arctic lakes in the Mackenzie Delta. Amphipoda are known detritivores and their diet also includes bacteria, algae and fungi as well as non-living substance. Amphipoda represent an important outlet of carbon to higher trophic levels as exemplified in temperate lakes as well as in northern systems such as the Mackenzie River Basin.

Overall, the results of the river ice break-up assessment provide several valuable contributions to the field of cold-regions river hydrology. The peak water-level river-regime classification illustrates, for the first time, the effects of river-ice on annual peak water-levels across Canada, while the subsequent analysis has shown that physical controls contribute to break-up magnitudes. In addition, the spatial and temporal assessment of spring break-up provides a first ever quantification of break-up using hydrometric timing variables previously not assessed at this scale, and more importantly break-up water levels. It is anticipated that these contributions will further aid the advances of river ice hydrology in the face of increasing climate variability and change.

The integrated studies being conducted in our overall ArcticNet project are ongoing, and continue to advance our process-level understanding and predictive capability of the relationships and interactions between climate-cryosphere-landscape hydrology and their combined effects on the structure, function and productivity of aquatic ecosystems. Knowledge obtained from this research will be directly applicable to the development of adaptation options for the conservation, protection and management of Arctic freshwater ecosystems to present and future climate variability and change.

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