Hydro-Ecological Responses of Arctic Tundra Lakes to Climate Change and Landscape Perturbation

Project Leader

Fred Wrona (University of Victoria)

Network Investigators

Ed McCauley (University of Calgary)
Daniel Peters, Terry Prowse (University of Victoria)

Collaborators

Steven Kokelj (Aboriginal Affairs and Northern Development Canada); Tom Carter, Laurent de Rham, Peter di Cenzo, Yonas Dibike, Jennifer Guay (Environment Canada); Spyros Beltaos (Environment Canada - National Water Research Institute); Barrie Bonsal (Environment Canada - Climate Impacts on Hydrology and Aquatic Ecosystems); Jim Reist (Fisheries and Oceans Canada - Central & Arctic Region); Tuomo Saloranta (Norwegian Water Resources and Energy); Terry Callaghan (University of Sheffield); Kirsten Brown, Peter Saint, Dane Campbell, Shannon McFadyen, Olaf Niemann (University of Victoria)

PhD Students

David Barrett (University of Victoria)

MSc Students

Benjamin Paquette-Struger (Queen’s University); Roxanne Ahmed, Erika Hille, Hayley Linton, Paul Moquin, Brandi Newton (University of Victoria)

Northern HQP

Jolie Gareis, William Hurst, Jolene Lennie, Don Ross (Aurora Research Institute)

Abstract

Average annual air temperatures in the Northern Hemisphere have been the warmest 30-year period of the last 800 years (IPCC 2013) and there is growing evidence that the Arctic terrestrial cryosphere is also being significantly altered and is highly susceptible to the effects of a rapidly changing and increasingly variable climate (ACIA 2005; IPCC 2007a,b, 2013; AMAP-SWIPA 2011). Permafrost temperatures have increased in the past few decades, and these increases have been attributed to increased air temperature and changes in the timing and thickness of snowcover (IPCC 2013). While freshwater systems and related hydro-ecological processes are particularly sensitive to changes in climate and related impacts on cryospheric components, the specific nature and the magnitudes of the effects on ecosystem structure and function are not well understood. The occurrence of lake shoreline retrogressive thaw slumping (SRTS) has been increasing in the western Canadian Arctic over the past several decades, as has the incidence of the slumping of steep hillside terrains of fluvial valleys (Kokelj et al. 2013). 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 applicable to cold regions/Arctic systems; 3) to evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources (lentic and lotic) and the occurrence of extreme hydrologic events in high-latitude western and northern Canada; and, 4) 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 is conducting 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 has utilized experimental mescocoms 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 in a network

of intensively studies upland tundra lakes representing a gradient of landscape disturbance associated with thawing permafrost.

- This project is evaluating how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada.
- As this project continues to expand its focus to include a broader range of type and size of lentic and lotic freshwater systems, it is providing a more comprehensive understanding of regional characteristics and responses in such systems to a changing climate.
- This project engages northern communities through community outreach activities, and through the training and hiring of northerners to assist with the field and laboratory work.
- 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

The strategic research objectives of the project are:

1. to characterize and improve our modelling capability for current and projected lake ice cover (under future climate change scenarios) in a latitudinal gradient and latitudinal distribution of Arctic lake sites;
2. to evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada;
3. to develop an improved process-based understanding and modelling capability of the changes in water quality (e.g. temperature, dissolved oxygen, carbon flux) in response to changing lake ice conditions under present and future climate regimes;
4. to improve understanding and modelling capability of the limnological and ecological relationships between aquatic productivity, nutrients, and geochemistry of Arctic lakes across a gradient of landscape perturbations; and,
5. to further develop an automated ice buoy and subsurface mooring system 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, temperature, oxygen levels, dissolved organic carbon). Data collected by this system contributes significantly to objectives 3, and 4 above.

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 (3.7ºC 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; AMAP-SWIPA 2011; AMBIO 2011; ABA 2013). 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 (AMAP-SWIPA 2011; ABA 2013). 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, climatological, and ecological field studies were established under the ArcticNet project “Hydro-ecological Responses 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. Specifically the reseach focuses on examining the effects of a regionally changing climate and cryosphere (ie., alterations in landscape permafrost and lake-ice dynamics) on the hydrological, geochemical and ecological (productivity) responses of small, upland Arctic lake systems.

As this project continues to expand its focus to include a broader range of type and size of lentic and lotic freshwater systems, it will provide a more comprehensive understanding of regional characteristics and responses in such systems to a changing climate. Additional scientific expertise, via collaborators and graduate students, will be utilized to enhance the expanding multidisciplinary scope of the various inter-linked studies.

The research priorities of the project are to: 1) characterize and improve our modelling capability for current and projected lake ice cover (under future climate change scenarios) in a latitudinal gradient and latitudinal distribution of Arctic lake sites; 2) evaluate how changes in atmospheric circulation and related hydro-climatic trends are affecting the spatial distribution of water resources and the occurrence of extreme hydrologic events in high-latitude western and northern Canada; 3) develop an improved process-based understanding and modelling capability of the changes in water quality (e.g. temperature, dissolved oxygen, carbon flux) in response to changing lake ice conditions under present and future climate regimes; 4) improve understanding and modelling capability of the limnological and ecological relationships between aquatic productivity, nutrients, and geochemistry of Arctic lakes across a gradient of landscape perturbations; and, 5) to further develop an automated ice buoy and subsurface mooring system 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, temperature, oxygen levels, dissolved organic carbon). Data collected by this system contributes significantly to 3, and 4 above.

Activities

Timeframe and study area: under this project, ongoing fieldwork has involved repeated annual sampling of a subset of a suite of 60+ tundra upland lakes (ranging from undisturbed to disturbed by permafrost thaw/ slumping) located between Inuvik and Tuktoyuktuk in the Mackenzie Upland Region east of the Mackenzie Delta, NT (Figure 1). In 2013, field investigations focused on a set of lakes, located in the Noell Lake catchment. A fully-automated ice buoy and mooring system installed into Noell Lake provided 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, temperature, oxygen levels).

The inception and development of a lake modelling and monitoring network (Prowse et al. 2009) was used for a fifth year of in-depth, field-based studies over the 2013 spring period. The network covers a latitudinal gradient from temperate southern regions to the far northern 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, Cornwallis Island, NU; Color Lake, Axel Heiberg Island, NU; Lake Hazen, Ellesmere Island, NU, and Lower Dumbell Lake, Alert, Ellesmere Island, NT (IRIS 2 - Eastern Arctic) and Ramsay Lake, Churchill, Manitoba (IRIS 3 - Hudson Bay). An additional site included in the network is Knob Lake, Schefferville, PQ (IRIS 4 Eastern Subarctic).

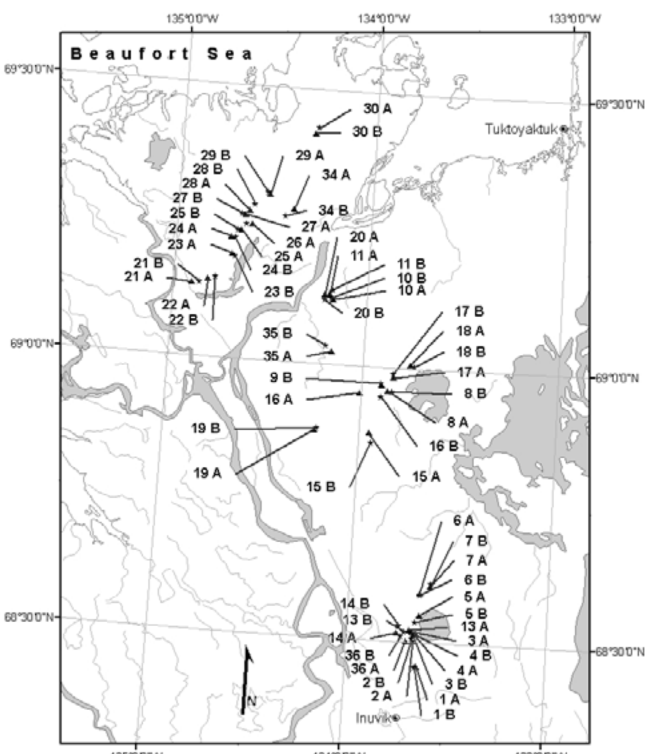

Figure 1. Map showing transect of 66+ study lakes.

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, Kokejl, Hille, Moquin, di Cenzo):

- This research component has focused 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). The two study watersheds were examined as part of a 60+ lake transect extending from near Inuvik to Richardson Island near Tuktoyaktuk, NT. All the fieldwork and laboratory data analyses for this work were completed in 2012. Interpretation of the data is nearly complete as part of an MSc thesis (E. Hille).
- Field reconnaissance was undertaken in 2013 to look at the degree and extent of tundra burn scars near some of our tundra study lakes (for which we have a considerable time-series of water geochemistry, biological and ecological

information), and to identify a small network of tundra lakes (comparable in size, contributing landscape, etc.) in the Noell Lake catchment (including slumped, unslumped, and lakes in the newly burned tundra area) for monitoring and assessment of the potential effects of burned tundra on lake water quality/geochemistry. The lakes identified for this investigation are shown in Figure 2.

- In late August, the Noell catchment study lakes were sampled for core water quality parameters (pH, temperature, DO, conductivity), chlorophyll-a, zooplankton, and water clarity measurements were made.
- Also, during August, Lakes 5A and 5B were instrumented with a vertical array of HOBO temperature loggers at 1m intervals, and with YSI water quality sondes (for temperature, pH, dissolved oxygen, specific conductivity and oxidation-reduction potential). The instrumentation was installed to freeze in over winter to provide us for the first time a detailed time-series of information on these small tundra lakes from the time of peak productivity (late August) through freeze-up, and under the winter ice cover until spring break-up and the return of the open water season.

Figure 2. Study lakes in the Noell Lake catchment sampled in 2013 for monitoring potential effects of tundra burns on lake geochemistry. Lakes 3B, 4B and 5B are affected by shoreline slumping; Lakes 5A, NSCL-3, NSCL-11 and NSCL-13 are unaffected by shoreline slumping; Lakes B1, B2 and B3 are located in the burnt tundra area and are unaffected by shoreline slumping.

- In early October (prior to freeze-up), the Noell catchment study lakes were sampled for water geochemistry. Water chemistry analyses were 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.

2. Modelling current and projected hydroclimatology, hydrology, river ice, lake ice and related limnological conditions in Arctic rivers and lakes (Prowse, de Rham, Dibike, Ahmed, Bawden, Linton, Newton):

- Continued field validations for modelled lake-ice composition at 13 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.
- Investigations on the spatial and temporal variation in the spring freshet of major circumpolar Arctic river systems.
- Analysis of spatial and temporal trends and patterns in runoff in cold-regions/Arctic rivers (northwestern Canada).
- Spatial and temporal analysis of hydroclimatic variables affecting streamflow in northwestern Canada.
- Generated four journal publications (3 accepted; 1 submitted) on hydroclimatic drivers and

analysis of spatial and temporal trends and patterns in runoff in northwestern Canada.

- A prototype ice-buoy and instrumented mooring system (developed in collaboration AXSY Technologies) installed into Noell Lake was removed from the lake and shipped south for refurbishing and recalibration of its instrumentation.
- Through our testing of the prototype system over the past several winters, we believe all the “bugs” have been identified and are now worked out of the prototype. We intend to deploy two systems during 2014 (one back into Noell Lake; the other into a suitable lake near Cambridge bay, NU).

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

- Pre-melt (May 2013) ice surveys on Noell Lake (for ice thickness, ice physical properties) for comparison with measurements made by the ASL ice-profiler (part of the automated buoy and subsurface mooring system), and with modelled ice thickness.
- Through the holes in the ice we collected under-ice water quality information (pH, Cond, colour, DOC/DIC and suite of ions) and isotopic (^{18}O, ^{2}H, ^{13}C DIC) parameters; pelagic samples where possible. This provided crucial information for investigating the role that lake ice plays on water quality and food webs.
- Replicate depth profiles of temperature, dissolved oxygen, specific conductivity and oxidation-reduction potential (ORP) were completed through the ice, and from a boat during the ice free season, at each Noell Lake water quality sampling location, for comparison with measurements made by the automated buoy and subsurface mooring system.
- Assessment of nutrient limitation mechanisms in Noell Lake using Nutrient Diffusing Substrates (NDSs).
- Water chemistry analyses were 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.
- Continued investigation/assessment of the limnological relationships between aquatic productivity, nutrients, and geochemistry across a gradient of lakes within the circumpolar Arctic in the context of a changing cryosphere.
- Continued data mining aquatic productivity information for circumpolar Arctic lakes (all ≥60°N; numerous lakes with multi-year data), increasing our dataset from ~500 to ~700 lakes.
- Generated a journal publication on the responses of benthic invertebrate communities to shoreline retrogressive thaw slumps in Arctic upland tundra lakes.
- Instrumented buoy and mooring system installed into Noell Lake provided crucial information on the major factors affecting food-web structure and function.

4. Developing a Unique Legacy Database of Freshwater Geochemistry, 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 critical 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

Hydrological and Geochemical Responses of Tundra Upland lakes to Landscape Perturbation:

All the fieldwork and laboratory data analyses were completed in 2012 as part of an MSc project at UVic (E. Hille). Ms. Hille is in the final stages of writing her thesis and is expected to defend her thesis by Spring 2014. The purpose of this research component was to investigate the hydrological and geochemical linkages between the contributing landscape and shallow tundra lakes in the upland region north-east of Inuvik for catchments both affected and not affected by Shoreline Retrogressive Thermokarst Slumping (SRTS). The specific objectives were to: (i) examine the hydro-climatic controls on key tundra lake water balance parameters and how the presence of SRTS is impacting catchment hydrology; and (ii) examine the geochemical signature of landscape runoff in order to assess the impacts SRTS on tundra lake geochemistry.

Investigations on tundra lake water balance for Lake 5A (unslumped) and Lake 5B (slumped) have yielded a number of results (Figure 3), some of which are highlighted below:

- the major hydrological event of the year was the melt of the spring snowpack and generation of runoff to the lake, resulting in a rapid rise of the lake levels and the runoff response at nearby Trail Valley Creek.
- the annual peak lake levels were influenced by snow/ice dam formation at the lake outlet - with temporary storage of water in the lake rapidly drained once outflow obstructions melted.
- the headwater tundra lakes in the study area "fill and spill" (as described in Spence and Woo, 2003) in response to the spring freshet. Following the spring freshet, the lake levels decreased via outflows until the spill elevation threshold was reached, after which evaporative losses during the long relatively warm summer days became an important control on lake level. Summer precipitation and resultant landscape runoff to the lakes act to partially replenish lake storage.
- in 2007, evaporation was greater than rainfall over the summer months, resulting in decreasing water levels through the summer up to the fall freeze-up.
- in 2009, large amounts of rainfall input to the lakes, and runoff generated from the surrounding

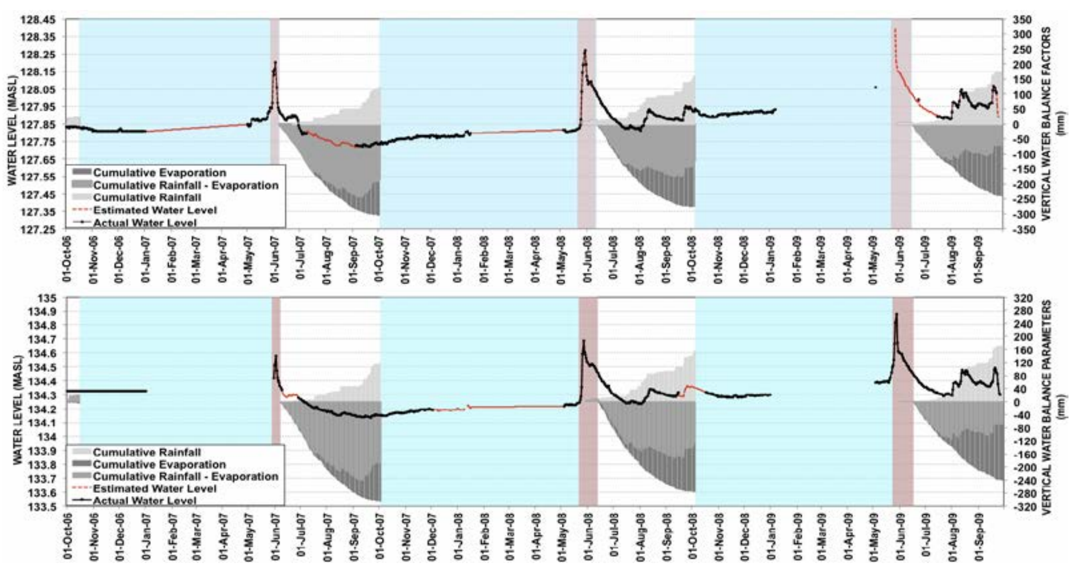

Figure 3. Water balance parameters (water level, rainfall, evaporation, precipitation minus evaporation) at study lakes 5A and 5B, along with runoff measured at nearby Trail Valley Creek.

landscape exceeded loss of water via evaporation and lake outflows, resulting in a significant rise in lake level over the summer months.

- examining the suite of hydrological processes that control lake water balance is not yet complete.
- the final results from this work will be presented as part of next year's report.

Comparison of lake geochemistry between lakes affected and not affected by SRTS was made using data obtained from our two primary study lakes (Lakes 5A and 5B), and 12 additional lakes located on Richards Island (8 lakes affected; 4 lakes unaffected). Figure 4 summarizes the difference in lake geochemistry over time between Lake 5A (unaffected) and Lake 5B (affected):

- lake geochemistry is strongly influenced by catchment hydrology (spring snowmelt and open water duration), and shoreline retrogressive thaw slumping.

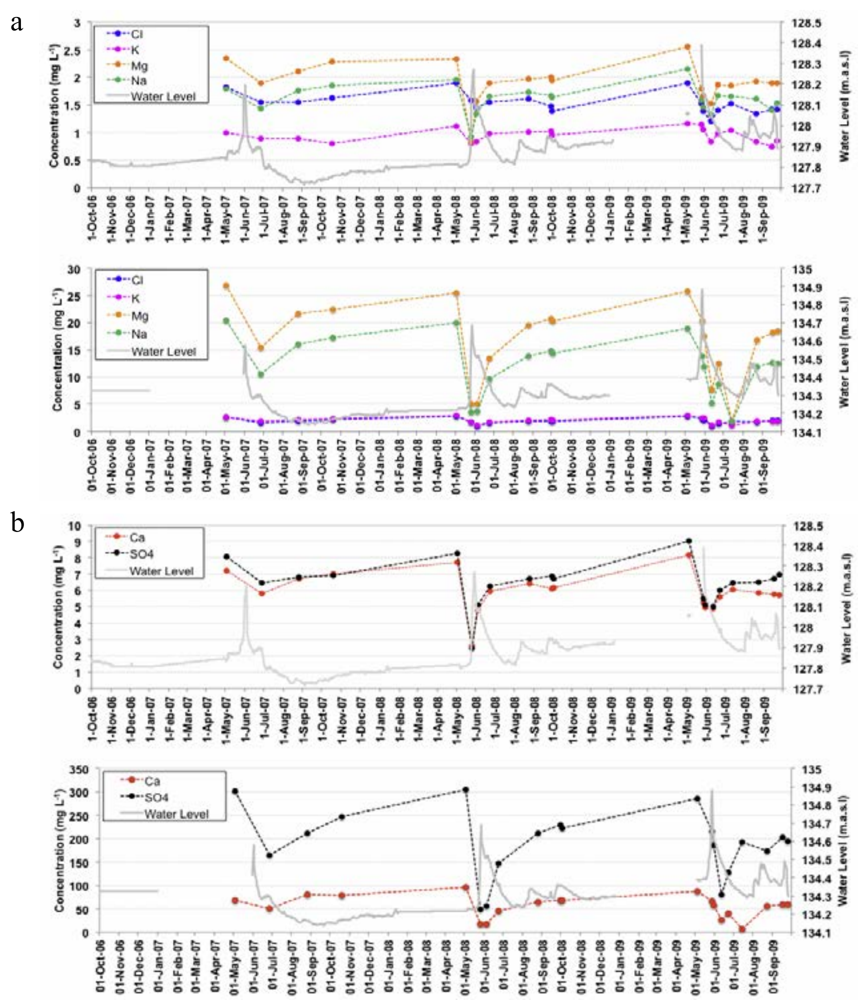

Figure 4. a) Comparison over time of Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-} concentrations and water levels in Lake 5A (unaffected by SRTS) and Lake 5B (affected by SRTS) and b), comparison over time of Ca+ and SO^{42-} concentrations and water levels in Lake 5A (unaffected by SRTS) and Lake 5B (affected by SRTS) b.

- in general, Lake 5B exhibits higher concentrations of Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-} than Lake 5A, statistically significant at alpha=0.05, both annually and seasonally.
- the concentrations of certain major ions (Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-}) 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 Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-} within the lake affected by SRTS (Lake 5B), and its inflows and outflows, were significantly 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 ions (particularly SO^{42-}) to the lake, especially during the summer months when the slump material is thawing and releasing its ions from storage to the lake.
- for both Lakes 5A and 5B, landscape overland flows (excluding flow from the slumps) showed no significant difference in concentrations of Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-}. Flow from the slumps, however, exhibited significantly higher concentrations in Cl-, Na+, Ca+, K+ and SO^{42-}. These results indicate that the observed effects of SRTS on shallow tundra lakes geochemistry is undoubtedly linked to landscape-level flow off the slump, particularly in mid- to late-summer.

Analysis of SRTS affected vs. unaffected lakes on Richards Island shows a similar pattern. SRTS affected lakes exhibit significantly higher concentrations of Ca^{2+}, K+, Mg^{2+} and SO^{42-} than the unaffected lakes. However, there was no significant difference in the observed concentrations of Cl- and Na+ in the lake water.

<u>The Effect of Tundra Burns on Small Tundra Lake Geochemistry:</u>

Field reconnaissance was undertaken in 2013 to identify a set of upland lakes (including unslumped, slumped, and lakes in the tundra burnt landscape) to monitor for effects of the burned area on lake geochemistry. These extensive tundra burns which occurred in June 2012 were the result of lightning strikes associated with convectional precipitation events. Such events are expected to increase with a warming climate – hence, we have a new analogue for a potential effect of a warming climate on tundra lake geochemistry and ecology – and a “natural laboratory” to look at these effects. Ten lakes (including 3 in the burnt tundra area) in the Noell Lake catchment were identified for monitoring (Figure 2).

This is the first year of this research component, and laboratory results from our 2013 sampling campaigns on this set of lakes (late August; early October) are still be QA/QC’d. In addition, two lakes (Lakes 5A and 5B) were instrumented with vertical profiling temperature arrays and water quality sondes to collect information on these lakes from the time of peak productivity (late August) through freeze-up, and under ice during winter until spring break-up. Data is being stored on the instruments themselves, and will not be available for analysis until the instruments are retrieved after break-up and the data downloaded. Hence, there are no results yet to report on this research activity. Results from this research component will be presented in next year’s report.

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

<u>Modelling Current and Projected Lake Ice:</u>

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 fifth year of in-depth field-based lake ice measurements over the 2013 spring period. 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. Data collected continue to be used for further development/ validation of lake ice and ecology models (including MyLake) for high latitude applications.

Spatial and Temporal Variation in the Spring Freshet of Major Circumpolar Arctic River Systems:

Spring freshet is the dominant hydrologic event occurring on nival Arctic river systems, with potential consequence to the Arctic Ocean freshwater balance. Freshwater flux to the Arctic Ocean has potential to influence global climate through modification of the intensity of the thermohaline circulation. Further, change in the freshwater flux (timing and magnitude) could have cascading effects on the ecology of the ocean via changes in associated nutrient fluxes and effects on local salinity levels. In addition, the timing and magnitude of the spring freshet and associated frequencies of river ice break-up and flooding has implications on delta lakes which rely on the flood waters to replenish nutrients and water levels in the lakes.

In last year's report, preliminary results were presented from R. Ahmed's MSc research on the timing and magnitude of the spring freshet in the four largest Arctic-draining watersheds (Mackenzie, Ob, Lena, Yenisei), and the climatic and atmospheric circulation patterns that control them. No previous research has collectively evaluated trends in the magnitude and sequential timing of spring freshets, the dominant hydrologic event occurring on these nival river systems, or examined the influence of climatic and atmospheric circulation patterns on such trends. New results on observed spring freshet trends arising from this research include:

- during 1980-2009, there is an increasing trend in Mackenzie-Ob-Lena-Yeniei total spring freshet volumetric contribution to the Arctic Ocean (Figure 5), amounting to an increase of about 30 km^3 per decade.

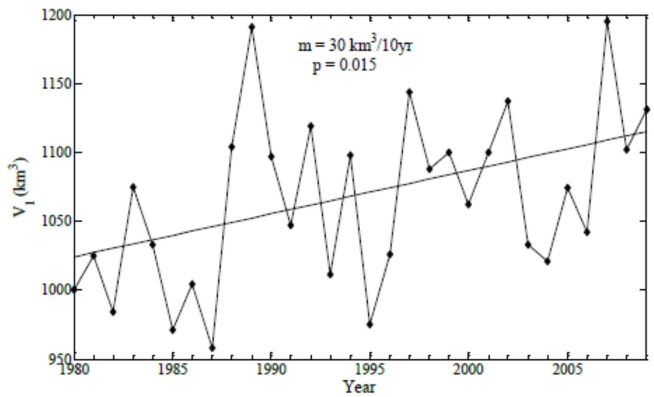

Figure 5. Trend in total spring freshet volumetric contribution by the Mackenzie, Ob, Lena, and Yeniei Rivers to the Arctic Ocean from 1980-2009.

- since 1980, freshet pulses tend to be occurring earlier, freshet volumes are increasing, and peak freshet magnitudes are decreasing.
- lower freshet volumes from the Mackenzie River are strongly linked to positive phases of North Atlantic Oscillation (NAO) and high El Nino Southern Oscillation (ENSO). Conversely, higher freshet volumes in Eurasia are strongly linked to negative NAO and low ENSO.

This research is ongoing, and future work will include: (i) running teleconnections with more seasonal lead times, under different seasons, and using more indices; (ii) obtain a better Eurasian climate dataset and re-run the climate correlations;(iii) analysis of travel time of freshet water from individual sub-basins within the four large basins (Mackenzie, Ob, Lena, Yenisei) to determine respective sub-basin contributions; and (iv) exploration of the effects of streamflow regulation on freshet characteristics.

Spatial and Temporal Analysis of Hydroclimatic Variables Affecting Streamflow in Northwestern Canada:

The overall goal of this MSc research project (H. Linton) is to determine the temporal and spatial variations in historical trends of hydro-climatic conditions affecting river flow to the Canadian Arctic region. Results pertaining to trends in precipitation and temperature, and effects on hydrology, were presented in last year's report. Under this project, an assessment of historical trends in snow accumulation and snowmelt across western Canada has now been completed. As a large portion of river flow to the Canadian Arctic originates in the mid-latitudes, this snow assessment covered 35 river basins in western Canada, from the west coast of British Columbia to western Manitoba and from the Canada-United States border to the Mackenzie River Delta in the northernmost reaches of the Mackenzie Basin.

Monthly Trends in Snow Accumulation – Winter snow accumulation during 1950-2010 has experienced statistically significant decreases across most of the study basins in most months of the year (Figure 6), attributed to less snow falling across most of the study area. Monthly rates of decreasing snow accumulation, expressed in snow water equivalents (SWE), range from less than -1 mm to -10 mm SWE. The only exceptions to the decreasing trends occur in January for the Pacific basins, and in March for the Fraser/ Columbia rivers, neither of which flow to the Arctic.

Monthly Trends in Snowmelt – Snowmelt during 1950-2010 throughout the study area experienced increasing trends for January through April, with

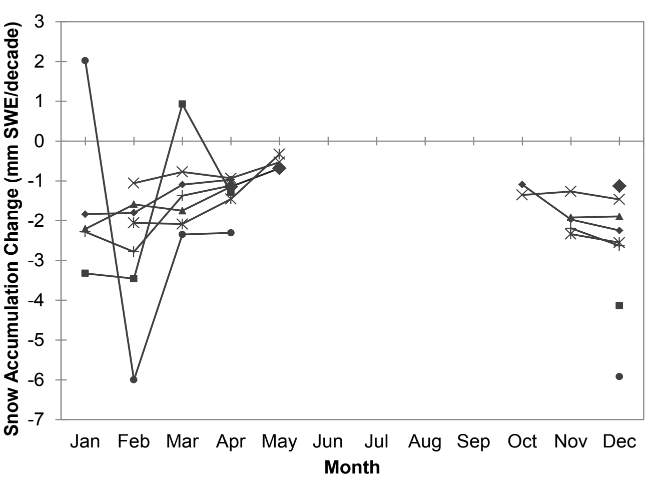

Figure 6. Rate of change of monthly total snow accumulation in mm SWE/decade, from 1950-2010.

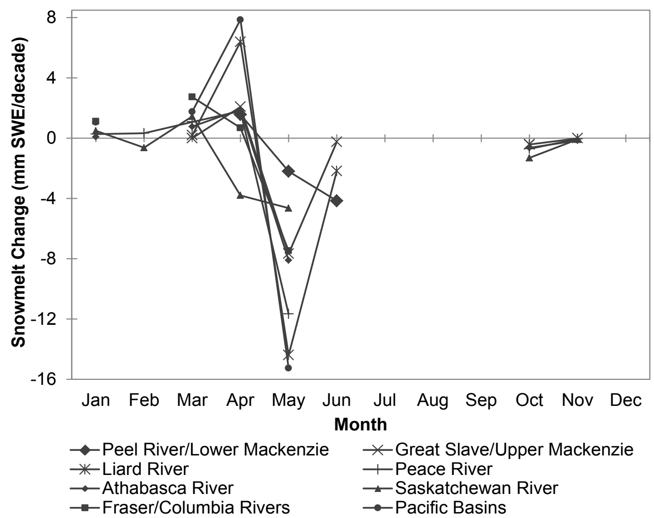

Figure 7. Rate of change of monthly snowmelt in mm SWE/ decade, from 1950-2010.

decreasing trends in May and June (Figure 7). January experienced increased snowmelt of 0.2-4 mm SWE/ decade at lower elevations. During February, some small areas also show increases in snowmelt of 0.3- 3 mm SWE/decade. These increases are at lower elevations and are likely due to increased instances of mid-winter melt. The largest statistically significant snowmelt increases occur in March and April. Decreases in snowmelt rates in May and June are the result of earlier onset of the spring freshet, and less snow remaining on the landscape to ablate.

This research is ongoing, next steps include:

- further identification of trends on a month to month basis, rather than cold-warm season basis.
- focusing on trend differences between regions.
- linking trends in climate variables to trends in synoptic patterns and trends in streamflow and freshet throughout the year.
- further exploring the cluster patterns provided by local spatial autocorrelation tests
- continuing analysis with an ensemble of climate scenarios from NARCCAP
- expanding the analysis to include other regions, such as northern and northeastern Canada.

Analysis of Synoptic Climatological Characteristics on Water Availability in Northwestern Canada (Mackenzie River Basin):

The overall goal of this research (MSc project, B. Newman) was to characterize and assess synoptic scale climatic conditions affecting river flow to the northwestern Canadian Arctic. Specifically, the objectives were to assess historical trends and spatial variability in climatic variables affecting river flows in the Mackenzie River Basin using interpolated, gridded data (precipitation, daily maximum and minimum temperature) on a monthly and annual basis for the time period 1950-2010.

Under this project, mid-tropospheric circulation, classified into 16 winter (Nov-Apr) and 12 summer (May-Oct) synoptic types using the SOM Toolbox for Matlab, were used in hydroclimatic analysis to determine the impacts of synoptic scale circulation on Rocky Mountain snowpack and snowmelt, and basin-wide summer water availability. SOM is a neural network process based on competitive and cooperative learning that cluster and project data onto a topologically ordered output array, and has been found to offer several advantages over traditional classification methods including principal components analysis.

Results from this work indicate that, during winter, above average precipitation and below average temperature are associated with a ridge of high pressure over the North Pacific Ocean, advecting cold Arctic air over the study region. Conversely, a ridge of high pressure over the western continent effectively blocks the intrusion of cold Arctic outbreaks, and is associated with above average temperatures and below average precipitation in the study region. Hence, the winter synoptic regime dictates conditions conducive to high or low winter snowpack development, which has profound implications on streamflow in the Mackenzie Basin as snowpack ablation in the mountains is a major source of water contributing to streamflow. In summer, the synoptic regime also effects temperature and water availability, where ridges of high pressure over the continent is associated with anomalously warm, dry conditions, and zonal flow across the continent is associated with anomalously cool, wet conditions.

It is notable that Ms. Newman successfully completed her MSc degree in December, 2013, and that two manuscripts from this research have been accepted for publication in the journal Hydrological Processes.

Analysis of Spatial and Temporal Trends and Patterns in Runoff in Cold Regions/Arctic Rivers:

Under this research activity (MSc project, A. Bawden), annual and seasonal trends in western and northwestern Canadian runoff (in 25 sub-catchments from the west coast of British Columbia to western Manitoba and from the Canada-United States border to the Mackenzie River Delta in the northernmost reaches of the Mackenzie Basin; utilizing historical records from 37 WSC hydromet stations) which were examined for the period of 1976-2010 using the Mann-Kendall (MK) test. Regional patterns of spatial variability were identified through a Principal Component Analysis (PCA) of the correlation matrix, and three hydrological regions were established representing watersheds in the upper, mid-, and lower latitudes of the study region.

Overall, runoff was found to have increased in most watersheds north of the 60th parallel, especially in the winter, while mid-latitude watersheds generally experienced decreased runoff, implying a northward shift in water availability from adjacent southerly basins. The lowest-latitude watersheds showed an even mix of both increasing and decreasing tendencies, suggesting the prediction that "low latitudes are becoming drier" is not applicable in all cases. For example, both the Pacific coast and western Prairies displayed increases in runoff for all seasons, implying this is not strictly a seasonally-dependent observation. Correlation analysis showed a significant yet weak relationship between runoff trends and latitude ($r \approx 0.5$), the result of which was largely affected by these conflicting increasing and decreasing trends in the southern basins.

PCA on runoff data revealed three regions of coherent hydrologic behaviour: the northern or UR, mid-latitude or MR, and southern or LR. Consistent with the results of watershed-scale trend analysis, the UR experienced increased runoff, the MR experienced decreased runoff, and the LR experienced a mix of seasonally-dependent increasing and decreasing trends for all runoff variables analyzed.

Results from this research indicates that there is a climatic redistribution of precipitation and shifting patterns of water availability in northwestern Canada, which is essential knowledge for assessment of climate variability and change effects on cold regions/Arctic freshwater systems, and has implications for future water management strategies.

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. In collaboration with AXYS Technologies (Sidney, BC), we have developed an Arctic Lake Monitoring System (ALMS) – a fully-automated Ice Buoy and Subsurface Smart Mooring System, described in detail in previous ArcticNet reports and ArcticNet ASMs, that comprises a fully-automated ice buoy and subsurface mooring system 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, temperature, oxygen levels).

Development of the Prototype ALMS - Challenges Overcome: To test and validate the prototype ALMS, the first of its kind, the system was deployed into Noell Lake, a medium-sized arctic tundra lake located about 20km NE of Inuvik, NT, in the Mackenzie Uplands Region. Noell Lake is one of our study lakes, and due to its proximity to Inuvik for relatively easy access for servicing, it was chosen as our test bed. Running the system over consecutive winters since 2010, and during the ice free seasons, a number of challenges had to be overcome before the system was deemed to be free of “bugs” and ready for deployment anywhere for scientific investigations and monitoring purposes.

Some examples of challenges overcome in developing the prototype:

- During the first deployment (2010-11), the battery compartment on one of the water quality sensors leaked causing the system to lose the data from that sensor. As all water quality sensors are bussed together, the other sensors eventually stopped working as well. Adjustments were made to the connections on the water quality sensors which corrected this problem for the second deployment.
- During the second deployment for the winter of 2011-12, the system experienced interruption in its telemetric communication during December. Although the ALMS is designed to automatically switch to a backup satellite telemetry when such a communication outage occurs, there was a problem with the programming scripts and some switch toggles being improperly set. This problem was rectified but necessitated a field visit by AXYS technicians in January 2012. Fortunately, the ALMS stores its data on the buoy and mooring until they are transmitted, and no data were lost during the communication outage.
- Towards the end of the 2011-12 winter season, the ALMS identified that the battery levels in the ice profiler had dropped lower than anticipated, ultimately resulting in loss of ice profiling data once the batteries ran out. This was unfortunate as the batteries failed before the lake ice reached its maximum thickness. Apparently, the manufacturer of the ice profiler had made

some hardware modifications (change in communications ports) to the unit which caused it to draw more power than the first sensor in the first deployment. The system has been modified to account for the extra power drain and the ice profiler battery levels are no longer an issue.

Validation and Application of the ALMS: As part of an MSc thesis (B. Paquette-Struger), data from the ALMS is being validated against other data collected from Noell Lake, either data measured by other scientific instrumentation, or with water grab samples collected and sent to laboratories for analyses. Although validation of the system is not fully complete, it is clearly evident that the system is now functioning properly, it is producing datasets as designed.

ALMS time-series data is contributing to our temporal understanding of Arctic lake ecosystems and is assisting in our development of hydro-ecological models for cold regions freshwater systems in the following research areas: landscape hydrology and geochemistry; lake-ice modeling; and aquatic productivity and ecosystem health. These models will be used to assess the vulnerability of Arctic lake ecosystems to disturbance, such as climate variability/ change and those related to Canada's and circumpolar northern regions.

Now that we are confident that all the “bugs” have been worked out of the prototype ALMS, we plan to deploy two systems in 2014 – one system will be redeployed into Noell Lake, and a second system will be deployed in a comparably-sized lake in the Central Arctic near Cambridge Bay, NU.

Application of the ALMS system is being considered for a pan-Canadian / pan-Arctic platform for long-term Arctic observing networks such as the Canadian High Arctic Research Station (CHARS) and the pan-Arctic initiative Sustaining Arctic Observing Networks (SAON).

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

Responses of Benthic Invertebrate Communities to Shoreline Retrogressive Thaw Slumps in Arctic Upland Tundra Lakes:

Permafrost disturbances in the form of shoreline retrogressive thaw slumping (SRTS) which leads to solute-rich terrestrial inputs to Arctic tundra lakes has been shown to change the biological, physical and geochemical properties of affected systems. Documented biological impacts include reductions in phytoplankton standing crop and increased macrophyte abundance as well as changes to the zooplankton and macrophyte community composition. Nine upland tundra lakes in the Inuvik region of the Northwest Territories, Canada (3 undisturbed lakes; 3 with active slumping; 3 that had active slumping but have now stabilized into inactive slumps) were sampled to assess the effects of SRTS disturbance on benthic invertebrate abundance and community structure.

A stratified, mixed-effects experimental design was used to examine whether SRTS activity had observable effects on abundance and community composition between undisturbed (U) and disturbed (D) lakes and to further assess whether localized effects in disturbed systems could be discriminated by comparing samples taken adjacent to the thermokarst disturbance (Da) to areas that were more distant (opposite) from the disturbance (Do). Significant differences in benthic community composition and abundance were found between U and D lakes (Figure 8). While the abundance of benthic macroinvertebrates was significantly greater in Da areas, no significant differences in community composition were observed between Do and Da areas. Macroinvertebrate mean abundance in D lakes was more than two times greater than in U lakes, with Ostracoda being the numerically dominant taxonomic group driving this pattern. Ostracoda mean abundance was four times greater in D compared to U systems and two times higher in Da compared to Do areas within disturbed systems. Correspondingly, Nematoda mean abundance was approximately 10 fold higher in D compared to U lakes, while in contrast, Chironomidae had significantly lower mean abundance in D lakes. Bivalvia and Oligocheata displayed similar abundance

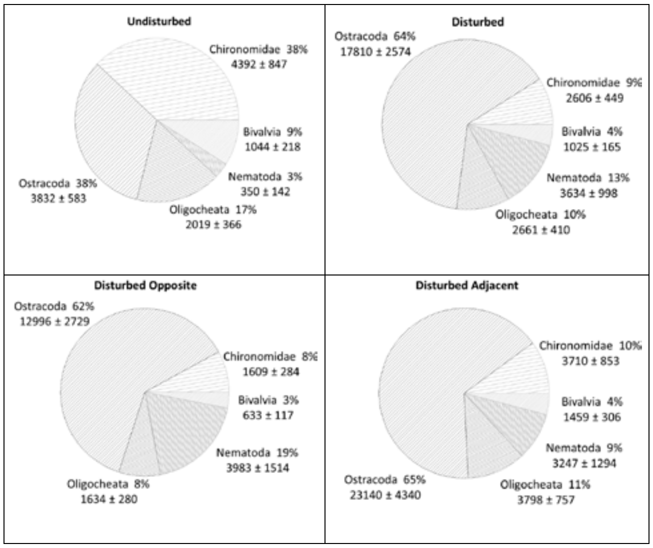

Figure 8. Community composition of numerically dominant macroinvertebrate taxa in lakes undisturbed (U) and disturbed (D) by a shoreline retrogressive thermokarst slump. While the community composition of U and D lakes were significantly different from each other, the differences between Do and Da areas were not significantly different.

patterns in both D and U systems, although mean densities of both groups were higher in Da compared to Do areas in SRTS disturbed systems.

Principle Component Analysis (PCA) of benthic macroinvertebrate abundance and composition patterns using sediment chemistry data (Figure 9) revealed the differentiation between U and D lakes was related primarily to increases in the concentrations of calcium in D lake sediments, and to higher organic carbon and organic nitrogen in U lakes. Correspondingly, Chironomidae abundance was found to be significantly negatively correlated with macrophyte standing crop biomass (which is higher in D lakes), while Ostracoda abundance was positively correlated with macrophyte biomass. This study contributes to previous findings under this ArcticNet project examining geochemical and pelagic food web alterations in thermokarst active lakes and further enhances our understanding of how present and projected climate change in the Arctic is resulting in cascading changes in the food web structure and ecological states in freshwater ecosystems.

SRTS is having a significant impact on benthic macroinvertebrate community structure and abundance with implications on cascading trophic effects. From this study, it appears that sediment chemistry alone does not fully explain the observed differences in benthic macroinvertebrate community structure. As shoreline slumping events are predicted to increase under a warming climate, understanding the impacts on trophic structure and ecosystem function is becoming increasingly important.

These are the first results reported from our study that is looking at second order effects of shoreline slumping on benthic macroinvertebrates. This research is ongoing - the next steps in this investigation are to conduct a Redundancy Analysis (RDA), and to examine the effects of sediment physical properties, water chemistry, and macrophytes, to further explain the effects of shoreline retrogressive thermokarst slumping on benthic macroinvertebrate abundance and composition patterns.

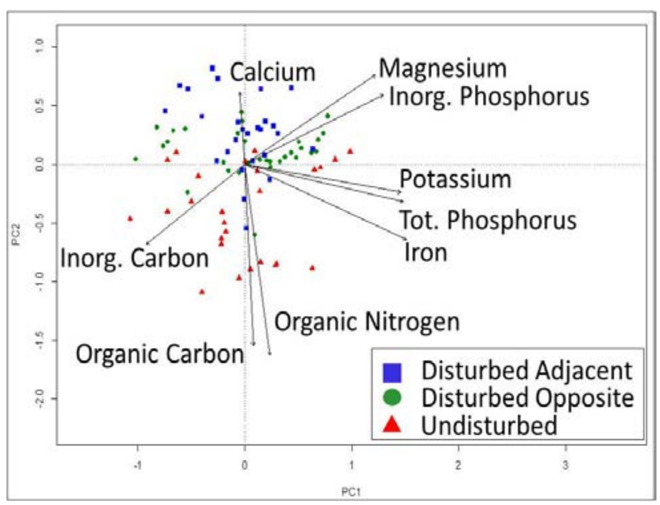

Figure 9. Plot of a principle component analysis based on sediment chemistry. Vectors are fit in the direction of ordination space towards which the environmental vector changes most rapidly and to which it has maximal correlation with the ordination configuration. Vector lengths are scaled by the strength of their correlation so that "weak" predictors have shorter arrows than "strong" predictors.

Geochemical, Biological and Limnological Responses of Arctic Lakes in Relation to a Changing Cryosphere:

The overall goal of this research (MSc project, B. Paquette-Struger) is to improve understanding of the limnological relationships between aquatic productivity, nutrients, and geochemistry across a gradient of lakes within the circumpolar Arctic in the context of a changing cryosphere (i.e., alterations in permafrost and lake-ice conditions). The specific objectives are to: (i) describe aquatic productivity relationships in the Arctic across spatial gradients in the 4 ACIA defined regions of the Arctic; (ii) test the applicability of Flannigan et al. (2003) mechanistic model for predicting algal biomass (Chl-a) from Total Phosphorous (TP) in Arctic lakes by including data from about 700 additional lakes (all ≥60°N; numerous lakes with multi-year data); (iii) validate data from the ALMS (ice buoy and instrumented mooring system) against other data collected from Noell Lake – either data measured by other scientific instrumentation, or with water grab samples collected and sent to laboratories for analyses; and (iv) characterize under-ice limnology of a typical upland Arctic tundra lake – Noell Lake which is located about 20km NE of Inuvik, NT.

Much progress has been made under this research activity this past year; however, most of the results are still preliminary and require additional QA/QC before reporting on them. It is expected that Mr. Paquette-Struger will complete this MSc research by fall 2014. Final results from this work will be presented in next year's report.

Discussion

Over the past 6 years we have been conducting a series of integrated hydrological and ecological field and experimental studies and modelling efforts assessing the effects of atmospheric, landscape and cryospheric (snow and freshwater ice) changes on the hydrology, geochemistry, and ecology of Arctic lakes and rivers. The most significant advances over the 2013-14 reporting period are highlighted below.

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

Significant progress was made in improving our understanding on the linkages between changes in catchment hydrology and corresponding geochemical responses in upland tundra lakes. Interannual replicate measurements revealed that the major hydrological event of the year was the melt of the spring snowpack and generation of runoff to the lake, resulting in a rapid rise of the lake levels. Annual peak lake levels were found to be influenced by snow/ice dam formation, with temporary storage of water in the lake being rapidly drained at the end of the freshet period. Evaporative losses during the summer period are the primary control on summer lake levels.

A comparison of lake geochemistry between lakes affected and not affected by SRTS revealed that lake geochemistry is strongly influenced by catchment hydrology (spring snowmelt and open water duration), and the effects of shoreline retrogressive thaw slumping. In general, unslumped systems have lower concentrations of major ions associated with marine sediments than slumped systems, most notably Cl-, Na+, Ca+, K+, Mg^{2+} and SO^{42-}. Furthermore, the concentrations of major ions were affected by seasonal patterns associated with the local lake hydrological regime.

Modelling current and projected river ice, lake ice and related limnological conditions in Arctic rivers and lakes

Analyses of spatial and temporal variation in the spring freshet of major circumpolar Arctic river systems have revealed new insights into the possible climatic and synoptic atmospheric patterns and drivers responsible for observed changes in the spatial and temporal trends in hydrological responses and regional water availability. For example, an increasing trend in Mackenzie-Ob-Lena-Yeniei total spring freshet amounting to about 30 km^3 per decade has been delineated. Furthermore, since the 1980s, freshet pulses tend to be occurring earlier, freshet volumes are increasing, and peak freshet magnitudes are decreasing. Lower freshet volumes from the Mackenzie River were found to be strongly correlated to positive phases of NAO and high ENSO.

Winter snow accumulation in northwestern Canada during 1950-2010 has experienced statistically significant decreases across most of the study basins in most months of the year, while snowmelt over the same period showed increasing trends for January through April, with decreasing trends in May and June. During winter, above average precipitation and below average temperature are associated with a ridge of high pressure over the North Pacific Ocean, advecting cold Arctic air over the study region. Conversely, a ridge of high pressure over the western continent effectively blocks the intrusion of cold Arctic outbreaks, and is associated with above average temperatures and below average precipitation in the study region. Hence, the winter synoptic regime dictates conditions conducive to high or low winter snowpack development, which has profound implications on streamflow in the Mackenzie Basin as snowpack ablation in the mountains is a major source of water contributing to streamflow. Finally, in general, runoff was found to have increased in most watersheds north of the 60th parallel, especially in the winter, while mid-latitude watersheds generally experienced decreased runoff, implying a northward shift in water availability from adjacent southerly basins.

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

Significant differences in benthic community composition and abundance were found between thermokarst thaw slumped lakes and undisturbed systems. Macroinvertebrate mean abundance in slumped lakes was more than two times greater than in unslumped lakes, with Ostracoda being the numerically dominant taxonomic group driving this pattern. The differentiation in benthic community structure between unslumped and slumped lakes was related primarily to increases in the concentrations of calcium in disturbed lakes, and to higher organic carbon and organic nitrogen in undistubed lakes. Correspondingly, Chironomidae abundance was negatively correlated with macrophyte standing crop biomass, while Ostracoda abundance was positively correlated.

Conclusion

Overall, the results of our suite of studies show that there are significant effects of climate variability and change on cold regions/Arctic freshwater hydrology and ecology. We continue to make significant progress in understanding the linkages and teleconnections between global, regional and local climate-related drivers and their local and regional effects on hydrological and cryospheric regimes and related water quality/geochemistry and aquatic ecosystem structure and function. Our 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.

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