High Arctic Hydrological, Landscape and Ecosystem Responses to Climate Change

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Abstract

Water is crucial for northern communities and ecosystems and plays a vital role, in conjunction with climate and permafrost, in the morphology and stability of arctic landscapes. To determine the impacts of climate change on freshwater quality and availability in the High Arctic, we created a watershed and landscape ecosystem observatory. The research is conducted primarily at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, near the Nunavut/NWT border, with additional work at Polar Bear Pass on Bathurst Island and the Apex River, Baffin Island. Research will investigate how climate change will affect rivers, permafrost, soils, vegetation, greenhouse gas emissions and the release of contaminants into High Arctic rivers, lakes and ponds.

Our integrated watershed network will provide an unprecedented understanding of the sensitivity and anticipated future effects of climate change to the High Arctic water, permafrost and ecosystem. By closely integrating related water and ecosystem process studies, this project will identify key environmental and societal vulnerabilities. Our goal is to develop impact models to assess linkages between anticipated environmental change and possible adaptations by communities and government agencies (clean water supply and ecological integrity) and industry (resource extraction, infrastructure protection).

Key Messages

- Climate changes at Cape Bounty during the melt season have been substantial, from 5-6°C since 2003. Runoff is 2-3 weeks earlier and the overall discharge from snowmelt has declined
- There is increasing evidence for the presence of subsurface hydrological pathways on land and below lakes, with the potential for substantial changes in water quality in late summer.
- Long term monitoring shows physical permafrost disturbances influence the flux of nitrogen, carbon, solutes and sediment, but specific responses depend on hydrological connectivity and processes like the occurrence of major rainfall.
- Reduced stream flow and channel storage dynamics have contributed to buffering sediment eroded from disturbances, hence downstream impacts are reduced.
- Hillslope streamflow regimes continue to be dominated by snowmelt but summer rainfall is becoming more important at some sites in generating flow. Seasonal water budgets for hillslope basins differ across scale, from one island to the next (i.e. Bathurst Island versus Melville Island) and when compared with previous streamflow studies (timing of runoff, peak runoff, and runoff ratios etc.).
- Organic matter composition and biogeochemistry varies with inputs from native plants as well as potential historic inputs from active layer detachments from permafrost melt.
- Permafrost-derived organic matter is entering biogeochemically active zones via active layer detachments.
- The composition of DOM as indicated by DOC/DON ratios and fluorescence analyses suggest that DOM composition in undisturbed catchments is fresher (less recalcitrant) then DOM from disturbed watersheds.
- Sediment samples were relatively low in concentrations of total mercury (THg) and relatively consistent across the different tributaries, streams and rivers at Cape Bounty.
- Cape Bounty is a small net sink for CO_2 in summer, consistent with a latitudinal gradient of other Arctic stations.
- Measures of net ecosystem carbon exchange from autochambers suggest good agreement with eddy covariance estimates, and variation within the mesic tundra vegetation type may be due to differences in soil moisture.

- When standardized according to global warming potential, carbon dioxide is the main gas (factor of 100) that influences the net greenhouse gas balance of High Arctic ecosystems.
- Permafrost disruption through formation of active-layer detachments leads to small change in soil trace gas fluxes, reducing production of nitrous oxide while increasing production of methane slightly in the highly disturbed areas.
- Concentrations of both CO_2 and CH_4 are low in the surface waters of East and West Lakes, resulting in low rates of net exchange with the atmosphere.
- Concentrations of both CO_2 and CH_4 are higher in the bottom waters of East and West lakes, suggesting that there is biological decomposition of organic matter in the sediments of these cold lakes, consuming O_2.

Objectives

Research in this project is divided into a series of collaborative sub-projects, all of which work closely with other sub-projects to develop comprehensive approaches, data sharing and training opportunities. The core objectives are as follows:

1. Analysis of spatial distribution of sources of watershed sedimentary, solute and nutrient fluxes (Lafrenière and Lamoureux)
2. Compare and contrast the inter, and intra-seasonal runoff processes between CBAWO and Polar Bear Pass (Young, Lamoureux, Lafrenière)
3. Analysis of the response of sedimentary, nutrients, inorganic ions, and dissolved organic matter fluxes from watersheds subject to varying degrees of permafrost disturbance (Lafrenière and Lamoureux)
4. Document and characterize the processes and impact of emergent subsurface hydrological pathways on the land and in water bodies (Lamoureux, Lafrenière)
5. To use advanced, molecular-level methods (organic matter biomarkers and nuclear magnetic resonance) to elucidate the organic matter composition and sensitivity in a High Arctic watershed, particularly in relation to permafrost disturbance (Simpson, Lafrenière, Lamoureux)
6. Quantification and identification of the age and lability of organic matter in Cape Bounty sediments (Simpson, Lamoureux, Lafrenière)
7. Comparison of hydrology, runoff, carbon and sediment fluxes, and macroinvertebrate diversity in polar desert and wetland ponds with diverse water sources and substrates (Young)
8. Analysis of frost table development in a range of arctic terrain (polar desert, pond, wet meadow) (Young)
9. Quantifying the export and fate of Hg from Arctic catchments experiencing rapid permafrost degradation (St. Louis, Kirk, Muir)
10. Quantify how interactions between vegetation type, disturbance, and climate change alter the net greenhouse gas balance of High Arctic ecosystems. Also exploring the various controls over greenhouse gas exchange at a range of temporal scales (Scott, Treitz).
11. Developing an operational method of determining soil moisture from Synthetic Aperture Radar (SAR) data across large areas of the High Arctic (Treitz)
12. Assessing the spatial variability in net ecosystem productivity (NEP) among high and low Arctic tundra ecosystems (Humphreys, Scott, Lafleur)
13. Quantifying the impacts of climate change on the net exchange of two greenhouse gases (GHGs: CO_2 and CH_4) from aquatic landscapes (St. Louis, Lamoureux)
14. Lake dynamics and biogeochemistry in response to changing ice cover, catchment inflows, and internal processes (Lamoureux, Lafrenière, St. Louis)
15. Characterising the response of flow and water quality to seasonal and long term hydroclimatological change in the Apex River (Lamoureux and Lafreniere)

Introduction

Human-induced climate change is altering polar eco-systems at unprecedented rates. Water is a crucial component of ecosystems and plays a vital role, in conjunction with climate and permafrost, in the stability of arctic landscapes and ecosystems. Projected climate changes are anticipated to substantially affect winter snowpack and melt season conditions that will in turn affect hydrological response, water quality, as well as permafrost and landscape stability. These changes will affect related watershed processes such as nutrient and contaminant cycling, soil erosion, net primary production of tundra vegetation and greenhouse gas exchange with the atmosphere. Collectively, these processes have important impacts on surface waters and landscapes. However, there is considerable scientific uncertainty, and few comprehensive datasets to assess the potential impacts of climate changes on water resources in the High Arctic. Predicted warming has already begun and was exemplified by 2007, the warmest melt season on record, which resulted in extensive permafrost degradation in many areas in the Arctic. As a result, the need is great for integrated research programs in the Arctic to quantify the changes in watershed processes and ecosystem response.

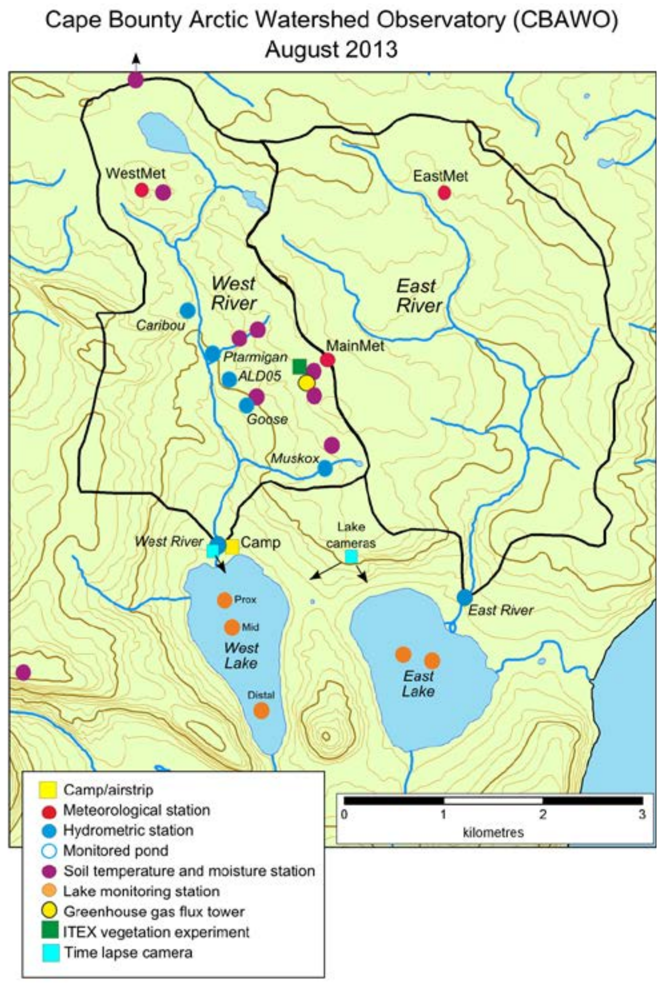

Figure 1. Site map of sample and station locations at the Cape Bounty Arctic Watershed Observatory (CBAWO).

This research has been conducted at the Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island, on the Northwest Passage near the Nunavut/NWT border. Since 2003 (with support from ArcticNet since 2005), research at CBAWO has focused on an integrated approach to identify the key processes that link watershed and landscape processes and to model their vulnerability and response to climate change. This location is the only comprehensive watershed monitoring observatory in the Canadian Arctic Archipelago and provides key insights into landscape and watershed processes in the western islands (Figure 1). The multidisciplinary research team has diverse expertise that has allowed them to develop an integrated approach to resolving uncertainties in the response of High Arctic watersheds to climate change. Sustained research at CBAWO has reached a decade, providing key insights into hydrological, terrestrial and atmospheric processes in the High Arctic.

Our research group has also undertaken parallel and complementary research at Polar Bear Pass, Bathurst Island and recently initiated a collaborative project with northern stakeholders on the Apex River, near Iqaluit, Baffin Island (Figure 2). These efforts are intended to transfer the knowledge gained by long term, integrated research at CBAWO to other areas of the Arctic and to work to address community and stakeholder knowledge needs for water management.

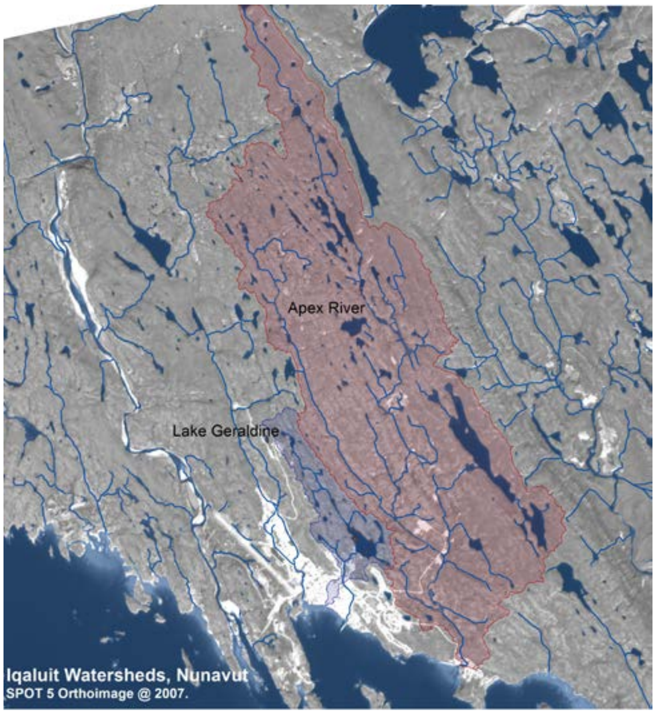

Figure 2. Apex River watershed and 2013 sampling locations, located adjacent to Iqaluit, Baffin Island.

Activities

Hydrological, limnological and biogeochemical dynamics:

Field activities extended from May 10-August 2 and focused on several key areas at CBAWO to refine our knowledge of hydrological, water quality and lake processes, including the continuation of multi-year data sets at the site. Field activities were closely coordinated by the research team to make efficient use aircraft and field personnel.

To support ongoing hydrological pathway research, frozen soil cores were extracted in May from representative vegetation sites and soil newly exposed by permafrost disturbance. These cores were returned to the laboratory frozen and analysed for water hydrochemical and stable isotopic composition, and a new collaboration with P. Grogan and V. Walker (Queen's) was initiated to assess the microbial communities in the frozen soil and upper permafrost. Results from these studies continue to emerge and were presented at the ASM in December 2013 (Christiansen et al.). Additionally, snow samples and lake profiles were collected as part of our long term monitoring of catchment water quality at CBAWO.

A series of 16 sediment samples taken along the West river catchment at the Cape Bounty Arctic Watershed Observatory (CBAWO) were examined for grain size and organic matter composition (see Figure 3). These samples were collected in the summer of 2011 and included samples from: undisturbed headwater (UW; blue circles), snowmelt dominated headwater (SW; white circles), main channel (MC; red circles), and disturbed subcatchment (DS; green circles).

Molecular-level geochemical analysis of organic matter of samples was conducted using solid-state ^{13}C NMR analysis of whole samples and a targeted approach that included the analysis of specific organic matter components (various microbial- and plant-derived lipids, lignin-derived phenols, and microbial-derived phospholipid fatty acids). These methods allow for the quantitative determination of organic matter sources and stage of diagenetic alteration.

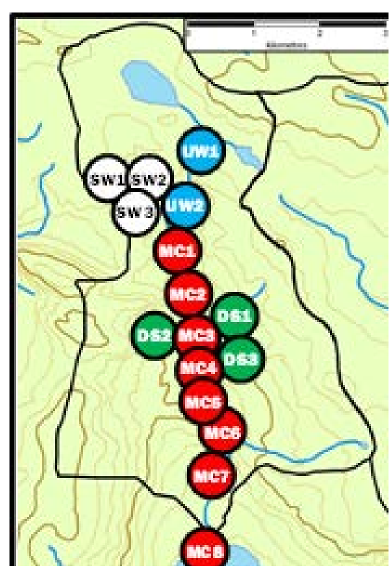

Figure 3. Sample locations along West River tributary system at CBAWO.

Summer 2013 programs also included soil and surface water sampling on experimental slope catchments, a longitudinal water and sediment sampling campaign on the West River (to replicate the 2011 sampling program) and installation of additional soil water samplers, soil temperature and moisture sensors, and recovery of data from our soil and permafrost monitoring network. Lake sampling and profiling was undertaken in both lakes to continue these long term records. In collaboration with researchers at U. Laval (P. Lajeunesse), side scan sonar and acoustic bottom profiling of the lakes was undertaken in late July, but was hampered by late ice cover. Most of the East Lake was completed, but ice cover on the West Lake precluded surveying.

Research was also undertaken at Polar Bear Pass (PBP), including detailed terrain-based snow surveys in late May, 2013 and monitoring snowmelt directly using ablation lines, as well as photographing the regional melt pattern, mid-June via helicopter. Detailed streamflow and water quality variables (conductivity, temperature, pH) were made at the eastern outlet stream of Polar Bear Pass (end of June to mid-July, 2013) and water level was monitored continuously until early August. The seasonal water budgets of hillslope streams was quantified and compared to catchments at CBAWO on Melville Island and other sites (Young et al. Hydrology Research, submitted). Additionally, the loss of semi-permanent snow across the arctic islands was examined (Woo and Young, J. of Glaciology, in press).

Finally, field research was initiated in collaboration with NRI researchers (J. Shirley) during the 2013 season, beginning with snow sampling in April-June, and systematic water sampling at stations in the catchment throughout the runoff period. Sampling was intensified for a four week-interval when M.Sc. student Elizabeta Kjikerkovska carried out detailed spatial sampling of water chemistry and stable isotopes to determine different water sources, and to compare with similar data collected in a study from 1983. Sampling continued with NRI personnel until freeze-up at the end of October. The available climate data from Iqaluit and the hydrometric data from the Apex River were also analysed to determine trends in climate and river flow.

Greenhouse gas and soil research:

The eddy covariance system was setup in early summer but due to a number of reasons, data collection was unsuccessful. Equipment was returned via sea lift and we are in the process of repairing and calibrating system components to help ensure successful campaigns in the future. The field season at Cape Bounty was shortened this year, and field visitation was restricted to late May and late June. When we arrived at Cape Bounty in May, expecting to install our autochamber systems to measure net carbon exchange in polar semi-desert communities, we found the landscape covered in snow and still frozen (Figure 4a). This provided an unexpected opportunity we usually

A

B

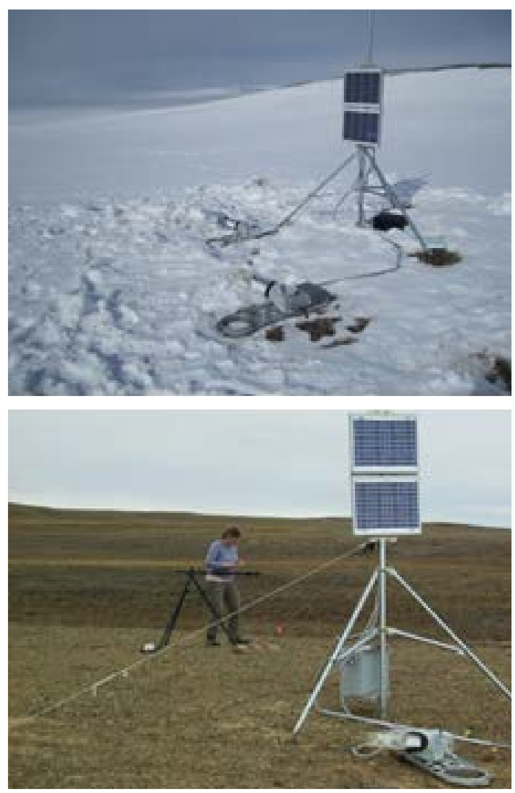

Figure 4. A) Automated ACE systems measuring carbon fluxes from frozen ground B) ACE system on polar semi-desert community with NDVI measurements in the background.

do not have – to measure net carbon exchange from the Cape Bounty landscape prior to the development of the active layer. We used three different techniques to measure these net carbon fluxes: ADC authochambers, static transparent CO_2 chambers used previously at Cape Bounty, and static (smaller) dark chambers commonly used for trace gas flux measurements. Results will be used to give us an estimate of winter-time carbon exchange with the atmosphere and its contribution to the annual landscape-scale carbon balance of this ecosystem. This work was largely carried out by HQP Andrew Mendelson.

The other major objective for 2013 was to carry out high-frequency measurements of net carbon fluxes from the polar semi-desert community at Cape Bounty (Figure 4b). This plant community type occupies roughly 40% of the landscape at CBAWO, yet the heterogeneous distribution of bare ground and vegetation makes it challenging to make enough measurements to quantify the total seasonal carbon balance of this vegetation type. We deployed 8 of the ADC ACE autochambers systems on both bare ground and vegetated areas in the polar semi-desert. We also carried out a series of measurements in late July to see if we could connect variation in net carbon flux to percent cover of vegetation, and how this related to the satellite-based vegetation index, the NDVI. Our goal was to see if we could relate percent plant cover both to the net carbon balance and to the NDV, which would allow for satellite-based estimates of net carbon flux to be carried out over a wide area. This work was largely done by HQP Emma Buckley.

Biogeochemical Cycling of Mercury (Hg)

St. Louis, Kirk and Muir have been examining climate induced alterations to the mercury (Hg) cycle in West and East lakes and the impact of these alterations on concentrations of Hg in Arctic char. From 2007-2012 river and lake water samples were collected bi-weekly in Teflon or glass bottles during the summer using ultra-clean sampling techniques for analysis of filtered and unfiltered concentrations of THg and MeHg. Muir and Kirk have also been studying the bioaccumulation of MeHg through the West and East Lake food webs beginning in 2008, and quantifying the THg and MeHg lake pools beginning in 2009.

Field work in 2013 focussed again on collection and analysis of water from the lakes for analysis of total Hg (THg) and MeHg. Landlocked arctic char were collected from East and West Lake in late July. THg and MeHg in all water food web and water samples were determined at Environment Canada labs in Burlington, ON using standard U.S. Environmental Protection Agency analytical protocols.

Remote Sensing:

Research was expanded to examine biophysical variables (i.e., aboveground phytomass (AGP), percent vegetation cover (PVC), leaf area index (LAI)) across a latitudinal gradient, corresponding to a climatic (i.e., 10ºC mean-July temperature gradient) and vegetation gradient [a surrogate continuum for anticipated changes that will be observed under a warming climate (i.e., “greening of the Arctic”]. This research is being conducted at Sabine Peninsula (77ºN) and Cape Bounty (75ºN), Melville Island; Boothia Peninsula (71ºN); and Apex River, Baffin Island (63ºN), Nunavut. In 2013, Treitz established a new study site near Iqaluit, Nunavut (i.e., the Apex River Watershed). This study site represents the southern limit of his latitudinal gradient. It also represents an important source of water for the city of Iqaluit (as the population of Iqaluit continues to increase at a dramatic rate). Satellite data were collected for the establishment of baseline conditions. Vegetation communities were sampled and with the satellite data, a network of representative plots can be established for more detailed sampling over the next three years.

Results

Hydrology and biogeochemistry:

Ongoing analysis of the impact of permafrost disturbance at CBAWO has demonstrated key distinctions between physical disturbance caused by localized slumps, compared to catchment-wide thermal perturbation caused by one or more years of warm conditions that result in deep thaw and changes in downstream water quality. Lafrenière and Lamoureux (2013) note that the impact of physical disturbance on downstream dissolved load is measurable and proportionate to the area of disturbance. However, they also note that areas not subject to physical disturbance showed a substantial increase in downstream solute loads, indicating that catchment-wide thermal perturbation has an important, if largely invisible impact on water quality compared to localized slumps and failures. Results also indicate the importance of rainfall events for flushing of solutes (Figure 5), and provide additional evidence for catchment-scale results reported by Lewis et al. (2012). These results further provide important evidence for sustained water quality changes after a period (or single year) of permafrost perturbation, with implications for modelling and predicting downstream water quality.

By contrast, erosion of particulate material from slumps is initially proportionate to the size of the slump and rapidly declines with time (Lamoureux

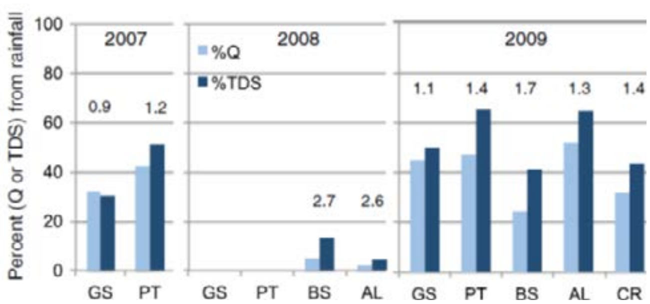

*Figure 5. Percentage of total discharge derived from rainfall (pluvial) (%Q =Qpluvial/Qtotal*100) and the percentage of seasonal total dissolved solute (TDS) load (kg) derived from rainfall runoff (%TDS = TDSpluvial/TDStotal) for 2007–09. The numbers represent the fraction of the TDS (kg) derived from pluvial runoff (TDSpluvial) over the fraction of runoff volume (mm) derived from pluvial runoff (Qpluvial) or the pluvial solute ratio (PSR = (TDSPluvial/TDStotal)/(QPluvial/Qtotal)). GS = Goose; PT = Ptarmigan; BS = Big Slide; AL = ALD05; CR= Caribou. From Lafrenière and Lamoureux, 2013.*

et al. submitted). Results from CBAWO indicate that differences in geomorphology and hydrological connectivity result in divergent recoveries for individual disturbances, and it is hypothesized that these differences result in long term catchment heterogeneity of sediment erosion on the landscape. These results will aid in developing landscape based modelling approaches for sediment erosion and predicting downstream water quality changes, and natural variability constraints for baseline environmental data.

Investigations of the disturbance impacts on fluvial nitrogen (N) dynamics (MSc Louiseize) also clearly illustrate that disburbances have a significant impact on N fluxes, especially nitrate (NO^{3-}) fluxes. A comparison of seasonal N fluxes (including NO^{3--}, ammonium (NH^{4+}), dissolved inorganic N (DON), and total dissolved N (TDN)) in the undisturbed Goose (GS) catchment, and the disturbed Ptarmigan catchement (PT), withing the West river watershed. These results clearly illustrate that NO3- concentrations and fluxes are significantly higher compared to pre-disturbance conditions (2007) in this catchment, and also compared to the undisturbed Goose catchment in 2012 (Figure 6). The mean seasonal NO^{3-} concentrations in GS and PT in 2007 were 0.001 and 0.002 ppm N, respectively, while in 2012 the mean seasonal concentration of NO^{3-} was 0.002 for GS and 0.064 ppm N for PT, more than 30 times higher than in 2007. The increases in NO^{3-} are however most readily apparent following stormflow. For example, the mean stormflow NO^{3-} concentrations in 2012 were 0.001 ppm and 0.149 ppm N for GS and PT, respectively. These results are consistent with those reported by Lafrenière and Lamoureux (2013) and Lewis et al. (2012) for total dissolved ion concentrations. Investigations of the stable isotopic composition of the NO^{3-} ($\delta^{15}N$ and $\delta^{18}O$ of NO^{3-}) in streamwaters (in collaboration with M. Hastings, Brown University) indicate that this NO^{3-} is not atmospheric NO^{3-}, but is rather microbially derived (mineralized from organic N, and nitrified from NH^{4+}).

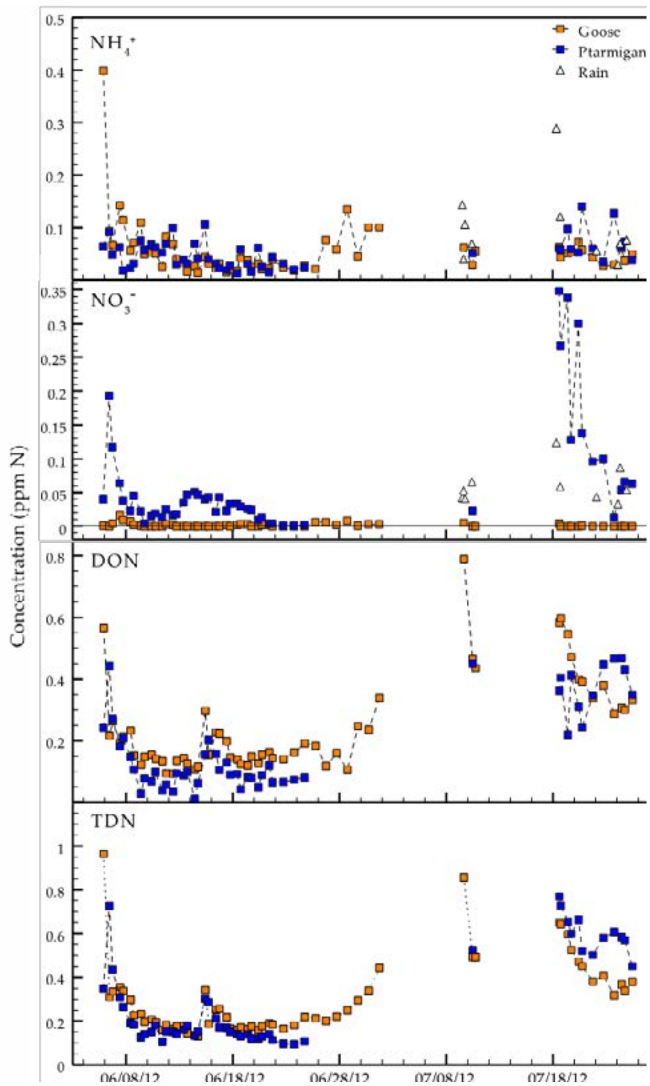

Figure 6 . Streamwater concentrations of NH^{4+}, NO^{3-}, DON, and TDN in GS and PT in 2012. The solid black line in the NO^{3-} panel delineates detection limit.

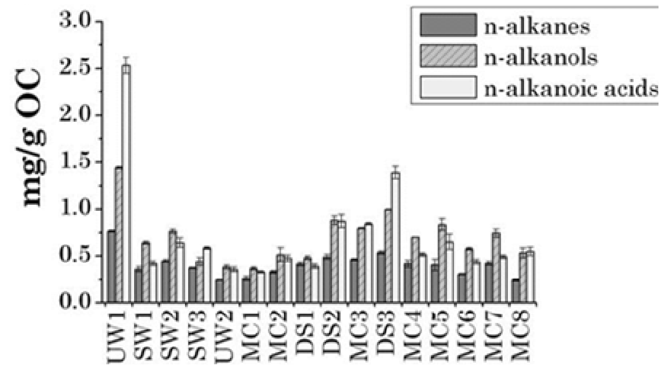

Figure 7. Distribution of aliphatic lipids in sediment samples from CBAWO.

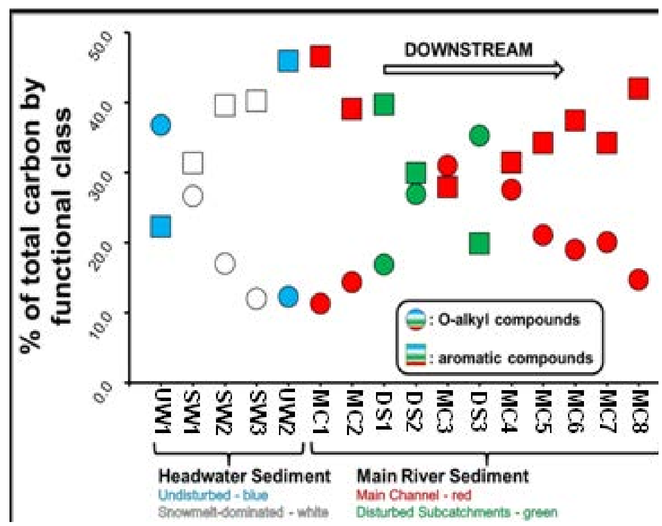

Figure 8: O-alkyl (labile) and aromatic (recalcitrant) functionalities measured using solid state ^{13}C NMR.

In related biogeochemical investigations, we found evidence for the addition of plant-derived organic matter from disturbed sites along the sub-catchment. Figure 7 shows high concentrations of lipids at the headwater (UW1) and the disturbed sites (DS1-DS3). Long-chain alkanes are characteristic of plant-derived organic matter. Based on these results, we hypothesized that old plant-derived organic matter previously preserved in permafrost is entering the catchment through active layer detachments.

Solid-state ^{13}C NMR analysis similarly shows high concentrations of labile organic matter, consistent with plant inputs, entering the catchment at the headwaters and disturbed sites (Figure 8). Plant-derived organic matter will be enriched in carbohydrates and peptides which will result in a high O-alkyl signal in the ^{13}C NMR spectrum. The O-alkyl concentration increases near the headwaters and then decreases downstream, likely due to microbial degradation. However, there are additional contributions near disturbed sites again suggesting that active layer detachments release plant-derived organic matter into the subcatchment.

To date, we have completed organic geochemical analysis of the mud ejections to better understand the source of this material and are currently analyzing this data. The preliminary results suggest that this material is devoid of labile organic matter and is diagenetically altered.

At Polar Bear Pass (PBP), relatively deep snow and cold conditions in 2013 resulted in a late start to streamflow out of the wetland and discharge did not peak until early July about 3 weeks later than in 2012. While melt runoff was 11 days in 2012, it persisted for much longer in 2013 (27 days), and was much lower in magnitude. Multiple peaks in the stream hydrograph follow the pattern where the north side of the Pass melts out first and then is followed by the southern end (Assini and Young, 2012).

Initial results from the Apex River project provide insights into climate change and hydrological impacts in a setting close to a large community and where residents use the river intensively for many activities. Iqaluit has substantially warmed since the late 1990s, particularly in the autumn months (Sept-November), resulting in a longer streamflow period. Initial analysis of stable isotopes in the river water indicate a consistent shift towards enrichment but further incorporation of water chemistry data is necessary to interpret potential changes in water sources in the catchment. Thee analyses are underway and we anticipate developing a 2014 field program to extend this research.

Greenhouse gases:

One of the key goals was to try and relate variability in plant cover in the polar semi-desert communities to NDVI values. NDVI is commonly used in carbon exchange models to drive plant productivity, yet little work to date has linked NDVI values to variation in plant cover and carbon exchange. The semi-desert communities are highly variable, and the vegetated areas can be occupied by a range of vegetation including mosses up to Salix arctica. Figure 9 shows calculated % plant cover and the NDVI values.

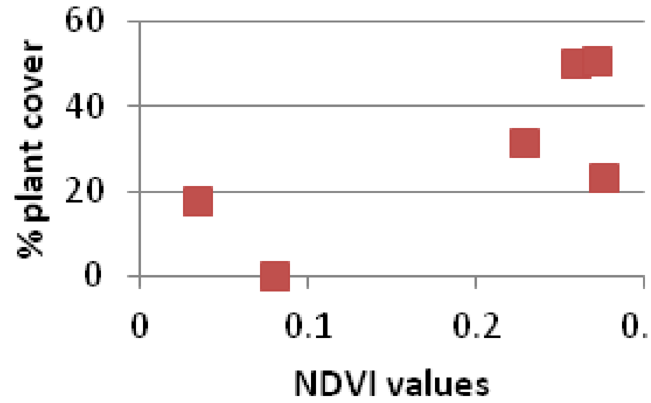

Figure 9. Relationship between NDVI and % plant cover in the polar semi-desert communities.

Based on a preliminary look at the data, NDVI values appear to be positively correlated with % cover (Figure 9), although there is significant variability. These data are from the autochamber sample sites – we also surveyed, over a much broader area, the variability in plant cover and NDVI for this plant community type. The final results of this work should provide us with scaling algorithms that allow us to link NDVI more directly to carbon exchange data from the autochambers, and to explore how other factors (e.g. temperature, soil moisture, and PAR) influence carbon exchange in this very heterogeneous vegetation type.

Results from the autochamber systems that functioned throughout the summer months showed some very interesting results. In spite of having significant vegetation cover, vegetated areas from the polar semi-desert were largely carbon sources throughout the growing season (Figure 10a). 2013 was a relatively cool year, and this is reflected in our measurements of carbon exchange. Over the entire growing season, ecosystem respiration dominated the carbon flux, and was strongly (non-linearly) linked to soil temperature (R2=0.57). Near the middle of July, temperatures finally increased (Figure 10b), and this seemed to suddenly stimulate GPP, as the ecosystem very quickly became a net carbon sink (Figure 10a). This would make sense if there was some sort of temperature threshold required for photosynthesis to increase enough to offset ecosystem respiration. Temperatures

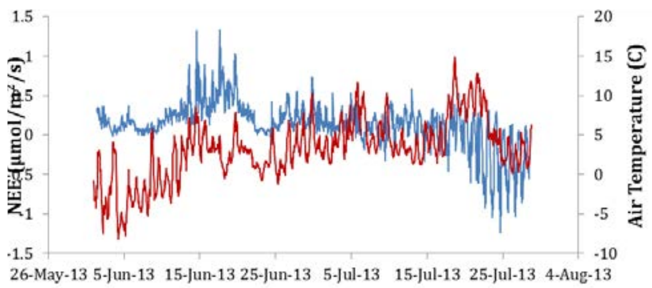

Figure 10. A) Variation in net ecosystem carbon exchange (blue line), air temperature (red line). B) Variation in Ecosystem respiration.

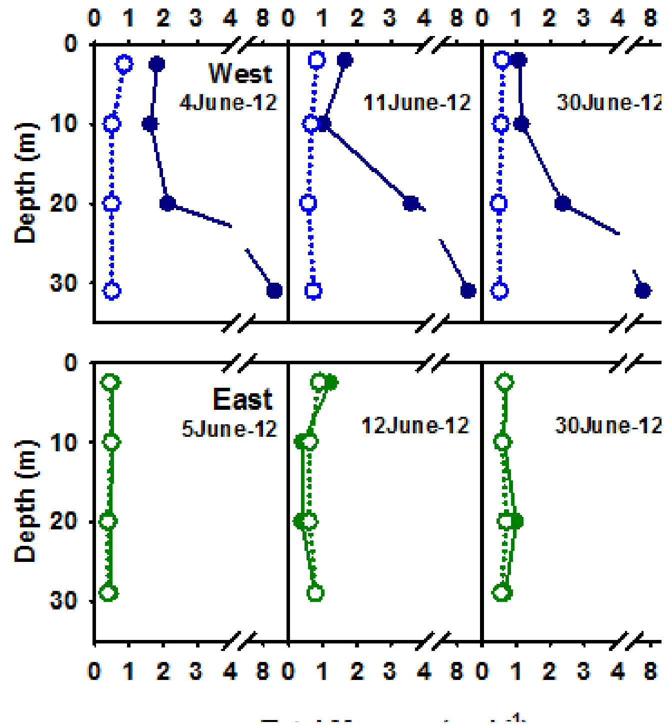

Figure 11. Unfiltered and filtered THg concentrations in West and East lakes over summer 2012.

remained high for a little over a week, after which they began to fall, and NEE began to approach zero again. Interestingly, over the entire growing season NEE related very poorly to PAR values collected at each autochamber site ($R^2<0.01$). However, one the temperature increased and NEE became negative (net carbon uptake occurring), NEE correlated very well with PAR ($R^2=0.46$). The system seemed to shift from being dominated by ecosystem respiration to be dominated by GPP, at least for the time when temperatures remained high.

Mercury dynamics:

Between 2007-2012 (results for 2013 are pending), average THg concentrations in West and East rivers were comparable (6.8±4.7 and 7.1±4.1 ng L^{-1}) and followed stream hydrology, reaching over 20 ng L^{-1} during high flow periods. MeHg concentrations were low in both rivers (0.04±0.02 and 0.05±0.03 ng L^{-1}). Most of the THg in West and East rivers was particulate-bound (60±20 and 60±21%) and in West River, particulate-bound THg (pTHg) was highly correlated with total suspended solids ($R^2=0.74$, $p<0.001$) demonstrating that catchment erosion is resulting in the transport of pTHg terrestrial Hg to West Lake. THg exports to West Lake were ~20% higher than those to East, except in 2007 when sampling during West River's high flow period was not carried out. THg concentrations in West lake were >three times those in East (2.2±2.4 and 0.7±0.4 ng L^{-1}) (Figure 11). These concentration differences were due to high concentrations of pTHg (7.1-9.4 ng L^{-1}) at the bottom of the water column in 2012 in West Lake, which are indicative of pTHg sinking and/or resuspension. MeHg concentrations were extremely low and almost identical in the two lakes (0.01±0.01 ng L^{-1}). In both 2010 and 2012, unfiltered and filtered THg and MeHg pools increased in mid-June during the high river flow period, demonstrating that catchment Hg inputs did increases lake Hg pools. In 2010, THg and MeHg pools decreased after the high flow period river indicating that Hg inputs did not mix into the lake but instead flowed through the lake and out the outflow. These results highlight the importance of mixing processes in dictating the impact of catchment Hg inputs on downstream lakes.

Arctic char collections from East and West Lake now extend over the period 2008 to 2013. $\delta^{13}C$ in char muscle was consistently more depleted in East Lake compared with West Lake except for samples from 2009, indicating carbon in West Lake fish is of more terrestrial origin. $\delta^{15}N$ was significantly higher in East

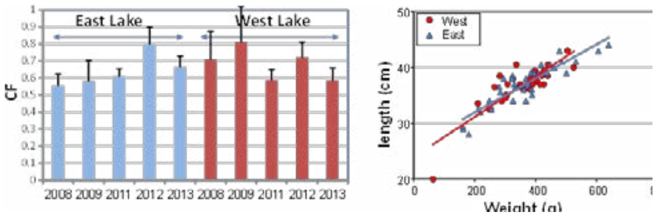

Figure 12. Condition factors for char in East and West Lake and length weight relationships for char from 2012 and 2013.

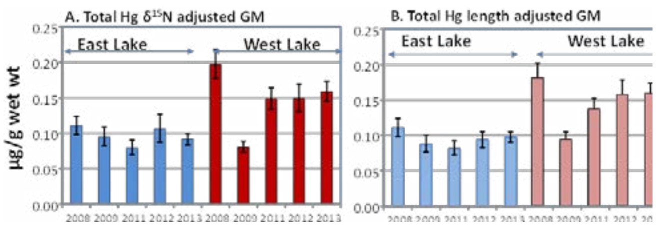

Figure 13. Geometric mean (± 95% CI) concentrations of THg in muscle of Arctic char from East Lake and West Lake. A. Adjusted using $\delta^{15}N$ based on analysis of covariance model, B. Adjusted using length.

Lake char (mean±95% CI, all years, 11.22±0.12‰ vs 10.02±0.20‰) suggesting differences in food sources. Mean δ15N values from 2008 to 2013 did not change significantly. Condition factors (cg/cm^3) in the char have increased in East Lake while declining in West Lake (Figure 12). West lake fish were generally longer for a given weight, especially in 2012 and 2013. CFs of ~0.7 are typical of char in other high Arctic lakes while values <0.6 may imply a low food supply or other stressors.

Mean THg concentrations in West lake char were generally significantly greater than those in East lake except in 2009 when char were feeding on more pelagic carbon (Figure 12). Adjustment for trophic level of the char using $\delta^{15}N$ to take into account differences between lakes had minimal overall effect compared to length adjusted results (Figure 13).

Remote Sensing:

We have conducted field experiments and analysed remote sensing data to determine the potential for: (i) high spatial resolution optical data for characterizing arctic vegetation composition and biophysical variables (Laidler et al., 2008; Atkinson and Treitz 2012; 2014); and (ii) synthetic aperture radar (SAR) data for characterizing surface roughness (Collingwood et al., 2013), vegetation (Collingwood et al., submitted); and surface moisture (Wall et al., 2010; Collingwood et al., submitted). This body of work has demonstrated great potential for monitoring vegetation response and moisture regimes of high arctic environments through a changing climate at watershed scales. To date, we am not aware of any other researchers examining the linkages between high spatial resolution satellite data and arctic vegetation composition, structure and function in the Canadian High Arctic for extension to landscape and regional scales. Our field campaigns have been extensive and are integral to our understanding of vegetation responses to environmental change and are critical for scaling up to local and regional scales using satellite remote sensing data. Our research in the Arctic also includes the examination of snow cover using remote sensing data for determining impacts of snow cover on arctic ungulates (Maher et al., 2012). This aspect of our research aims to develop methods for examining the effects of a changing climate (i.e., increased snowfall and/or freezing rain events) on access to vegetation for grazing arctic ungulates. In addition, specific to the Arctic and permafrost environments, we are now extending our analysis to include change detection, particularly in the context of hazard susceptibility and permafrost degradation (Rudy et al., 2013).

Discussion

Hydrology and biogeochemistry:

Hydrological research at CBAWO has revealed considerable insights into the impact of short term permafrost disturbance in the High Arctic, and the longer term impact this disturbance has on downstream sediment, dissolved loads and important nutrients. This knowledge will be particularly important for the development of realistic watershed water quality models to predict future responses to projected climate changes, and will substantially extend first efforts to model sediment load (Lewis and Lamoureux, 2010) in this large region. Continued refinement of subsurface pathways research will begin to address key questions about how water quality evolves on the land and how changes in summer thaw depth will likely influence water quality.

Biomarker analysis of the sedimentary organic matter from Cape Bounty revealed a predominance of plant-derived compounds which likely originate from permafrost-derived organic matter released by active layer detachments including long-chain aliphatic lipids, sterols, cutin, suberin, and lignin. Organic matter biomarker degradation proxies of sediments near active layer detachments revealed less alteration in aliphatic lipids while constituents such as sterols cutin, suberin, and lignin were found in a relatively advanced stage of degradation. Phospholipid fatty acid analysis indicated that microbial activity was higher near active layer detachments than downstream and microbial substrate limitation was prevalent within in the disturbed regions. This study provides evidence suggesting that active layer disturbances in the High Arctic provide a readily available source of organic matter to the active pool of cycling carbon upon transport into hydrological ecosystems.

The recent work by Young et al. (submitted) document the response of streamflow in hillslope catchments at Polar Bear Pass and Cape Bounty in relation to previous studies across the Queen Elizabeth Islands (70's/80's). This research showed that the timing of runoff, peak response at PBP and CB was significantly earlier than these previous studies and can be tied to a warming climate since 2000. However, if one considers the 2013 preliminary data from the outlet stream at PBP, the timing, runoff duration are more reflective of these earlier basin studies. The 2013 year, may be a one year anomaly as the Arctic continues to warm, but these extreme conditions, whether exceptionally warm or cold deserve more attention as to better understand how they impact on basins (i.e. cumulative responses).

Research at CBAWO has resulted in a new efforts at the Apex River to transfer knowledge from ArcticNet research to address community interests and concerns about climate change impacts on water. While our efforts at Iqaluit are in the early stages, with much of our effort directed at building partnerships and collaborations with NRI, AANDC and the City of Iqaluit, we anticipate that the key hydrological research questions addressed by these two watershed programs will advance the state of knowledge in the Canadian Arctic and will contribute to better water management in the region.

Greenhouse gases:

Changes in climate, both temperature and precipitation, may cause changes in the spatial patterns and extent of different vegetation types. These changes may alter the net carbon balance of high Arctic ecosystems, potentially leading to either positive or negative feedbacks on the climate system. At present, models of the arctic carbon balance often are parameterized assuming a single vegetation type, yet our past results suggest significant differences in the processes controlling net carbon exchange in the different vegetation types. In order to understand the future impact of these changes on the climate system, we need to understand the different processes in the different plant community types, and develop ways to scale local studies to the broader arctic region.

Our results for the polar semi-desert communities from last year suggest some interesting results showing the existence of a temperature threshold for initiation of various carbon cycling processes. Once the remote sensing work from this past year is completed, we should have a much more robust way of scaling these results up to a larger area to better understand the impact of vegetation distribution on the carbon balance. Our results also suggest that at least for some years, the polar semi-desert communities that occupy over 40% of the landscape are significant carbon sources to the atmosphere, yet with warming might become stronger carbon sinks as suggested by the data. Furthermore, our winter-time carbon flux data should give us a much better picture of what is happening over the entire year at Cape Bounty instead of just during the summer season when active layer development is taking place. By contrast, research demonstrates that oncentrations of both CO_2 and CH_4 are low in the surface waters of East and West Lakes, resulting in their net exchange with the atmosphere also being low. Concentrations of both CO_2 and CH_4 are higher in the bottom waters of East and West lakes, clearly showing that there is biological decomposition of organic matter in the sediments of these cold lakes producing these GHGs and consuming O_2.

Mercury dynamics:

Greater inputs of terrestrial carbon to West Lake, along with higher THg in lake water, may explain higher THg in char in West Lake. However, lake water and periphyton MeHg were similar among the two lakes suggesting that differences in char THg are not related to MeHg availability at the base of the food web, but instead to differences in feeding behaviors. The presence of amphipods in the diet of West Lake char may provide additional Hg not available to East Lake char. Much higher turbidity in West Lake in 2009 (Dugan et al. 2012) and 2010 (Lamoureux, unpublished data) compared to 2008, may have caused food web shifts and reduced food availability to char in 2011. Continued sampling of food web organisms as well as $\delta^{13}C$ and $\delta^{15}N$ and multi-element analyses should help us understand the factors driving the difference in char Hg among the two lakes.

Remote Sensing:

Research related to the spectral and spatial variability of surface reflectance over arctic tundra vegetation indicates that the normalized difference vegetation index (NDVI) is well suited to the prediction of biophysical variables, at least at coarse spatial resolutions between bioclimatic zones (Raynolds et al., 2012; Johansen and Tømmervik, 2013). However, we have observed that the relationships are less clear at high spatial resolutions within bioclimatic zones (Laidler et al. 2008; Atkinson and Treitz, 2013). And further, although it is well known that surface moisture is a key driver of vegetation productivity, surface moisture is difficult to extract through conventional means since it is influenced by active layer depth and permanent snow fields rather than directly by precipitation. However, using Radarsat SAR data we have been able to characterize moisture differences across watersheds in the High Arctic (Wall et al., 2010; Collingwood et al., submitted). In addition, we are examining vegetation disturbance to model areas susceptible to permafrost disturbance using remote sensing (e.g., Rudy et al., 2013). My research not only examines ecological classification of vegetation communities (Atkinson and Treitz 2012; Middleton et al., 2012) and biophysical variables (Laidler et al., 2008; Atkinson and Treitz, 2013), but also includes processes involving carbon fluxes (Atkinson et al., in prep.). Hence, one of the goals of our ongoing research is to expand our understanding of carbon fluxes across vegetation communities and latitudes.

Conclusion

Research at CBAWO and PBP represents an integrated effort to identify the impact of climate change on landscape and water processes in the High Arctic. Through comprehensive field and leading-edge analytical approaches, this project has identified key direct and indirect impacts of climate change on the terrestrial Arctic system. Key outcomes contribute new knowledge to our understanding of the hydrology, geomorphology and ecology of the High Arctic, and provide substantial process linkages associated with material fluxes, cycling and fate. This knowledge will be disseminated through conventional scientific literature and will also be integrated into the preparation of the IRIS reports for regions 1 and 2 that are currently underway.

Based on the success of this approach and interest by community stakeholders and decision makers, we have expanded this research to the Apex River near Iqaluit. This location will allow our research to more closely meet and respond to the interests of northerners. Hence, we aim to continue our work at CBAWO and PBP to develop primary process knowledge and build baseline records in remote, pristine settings, while at the same time transferring our knowledge and experience to the Apex River.

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