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. 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.
- Frost table development (ponds, wet meadows) is showing progressive deepening from 2007 to 2010; conditions that may be attributed to increasing summer temperatures and summer precipitation amounts.
- 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.
- Rainfall is becoming an important input in seasonal water budgets for hillslope catchments, but due to elevated evaporation losses, snowmelt remains an important driver of streamflow.
- 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.
- Organic matter composition and biogeochemistry varies with inputs from native plants as well as potential historic inputs from active layer detachments from permafrost melt.
- The composition of dissolved organic matter (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.

• Streams have high concentrations of both CO₂ and dissolved organic carbon, but virtually no CH₄.

• Concentrations of both CO₂ and CH₄ are low in the surface waters of the East and West Lakes, resulting in low net exchange with the atmosphere, while both CO₂ and CH₄ are higher in the bottom waters, suggesting that there is biological decomposition of organic matter in the sediments of these cold lakes, consuming O₂.

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. Analyze 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. Analyse 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. 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. Quantify and identify the age and lability of organic matter in Cape Bounty sediments (Simpson, Lamoureux, Lafrenière).

7. Compare the hydrology, runoff, carbon and sediment fluxes, and macroinvertebrate diversity in polar desert and wetland ponds with diverse water sources and substrates (Young).

8. Analyse frost table development in a range of arctic terrain (polar desert, pond, wet meadow) (Young).

9. Quantify 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 to explore the various controls over greenhouse gas exchange at a range of temporal scales (Scott, Treitz).

11. Develop an operational method of determining soil moisture from Synthetic Aperture Radar (SAR) data across large areas of the High Arctic (Treitz).

12. Assess the spatial variability in net ecosystem productivity (NEP) among high and low Arctic tundra ecosystems (Humphreys, Scott, Lafleur).

13. Quantify the impacts of climate change on the net exchange of two greenhouse gases (GHGs: CO₂ and CH₄) from aquatic landscapes (St. Louis, Lamoureux).

14. Assess lake dynamics and biogeochemistry in response to changing ice cover, catchment inflows, and internal processes (Lamoureux, Lafrenière, St. Louis).

Introduction

Human-induced climate change is altering polar ecosystems 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.

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 (Fig. 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.

Activities

The research activities primarily took place at the Cape Bounty Arctic Watershed Observatory (CBAWO), Melville Island, NU (74.5°N, 109.5°W) during the 2012 field season. The season extended from June 1-July 28, and was delayed by 11 days due to poor weather conditions. The team was able to rebuild the camp at the airstrip and activities during 2012 were carried out as expected. There were up to 11 team members in the field at once. Additionally, part of our 2012 field research activities included a small camp at Polar Bear Pass (PBP), Bathurst Island (75°40’N, 98°30’N). This research substantially extends the hydrological and biogeochemical dimensions of research at CBAWO.
In addition to our extensive field research activities, we continued to advance synthesis of our large data sets and publish research from the group. A number of graduate students also completed theses and a number of new students were in the field in 2012. Additionally, we are contributing to the writing of the IRIS 1 report (Lamoureux) and have taken roles in the IRIS 2 report, including chapter authorship by Lamoureux and Lafreniere. Both participated in the IRIS 2 workshop in Iqaluit in November 2012, and a number of key linkages and exchanges were initiated or furthered with northern decision makers. In particular, the IRIS 2 process and consultation has resulted in a new research initiative on the Apex River, near Iqaluit, that will be undertaken through this project. This new project has already developed close synergies and partnerships with northern stakeholders, and promises to provide an ideal location to engage a northern community in integrated hydrological research. Details about this project are indicated in our plans for 2013-14.

Further, we have maintained ongoing contact with the Resolute community to develop a better understanding of the community interests and concerns and to generate open communications.

**Hydrological and climate related observations**

A key element of our research program includes the systematic collection of snow, weather, river and related biogeochemical, contaminants and terrestrial ecosystem data sets necessary to support the broader research objectives. Despite early delays in fieldwork, we were able to collect a full set of climate and hydrometric data from CBAWO for the 2012 melt season, with the exception of the catchment snow surveys. We continued to collect meteorological and soil temperature data from expanded station networks deployed in 2011, and continued year-round limnological instruments. Further, we successfully drilled two 7 m bore holes and instrumented them with thermistors to monitor permafrost in the years to come. Similarly, we obtained the first permafrost cores from CBAWO and we are currently undertaking detailed sediment, organic matter, microbial and soil water analyses from these cores.

At PBP, detailed streamflow and suspended sediment measurements were made (June - end of August, 2012) and ongoing research to quantify hillslope stream discharge and downslope pond water levels (linked, unlinked ponds) has continued. We are quantifying the water budgets of hillslope stream catchments at PBP (2007, 2008, 2009, 2010, 2012) and will compare them to results at Cape Bounty (CB), Melville Island, and Resolute Bay, Nunavut, in order to explore variation in water resources across the Queen Elizabeth Islands (QEI). We anticipate that this information will be presented at the 19th NRB, Alaska, August 2013.

**River and stream biogeochemical research**

Building on our efforts to decipher the sediment budget and impact of recent (2007) permafrost disturbance and based on successful work in 2010, we carried out more detailed sediment budget work on the West River in 2012. This research was conducted by MSc student Elena Favaro and results demonstrate clearly that the majority of the sediment that enters the river system from disturbances and slopes is stored in the channel, particularly later in the runoff season. This suggests that the river system is buffering the impact of permafrost disturbances, and that the channel system may be a location where eroded nutrients and sediment accumulate and may contribute to aquatic ecosystem. We continued to monitor and sample two rivers and a number of disturbed and undisturbed subcatchments for sediment and hydrochemical fluxes following permafrost disturbance, including work by MSc student Nicole Louiseize. Additionally, wet (rainfall) and dry deposition along with stream runoff in disturbed and undisturbed catchments were analysed for N species (DON, NO\textsubscript{3}\textsuperscript{-} and NH\textsubscript{4}\textsuperscript{+}), NO\textsubscript{3}\textsuperscript{-} isotopes, water isotopes, dissolved organic concentrations (DOC) and DOC fluorescence. Additionally, new PhD student Daniel Lamhonwah initiated a detailed soil moisture, water stable isotope and hydrochemical study to evaluate slope hydrological processes and pathways. This research is intended to provide a key means to advance modelling of surface water and hydrochemical systems in the High Arctic.
Simpson and PhD student David Grewer have also been analysing a network of sediment samples collected in the summer of 2011 along the catchment of the West River (see Fig. 2). The collected sediments include 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 analysis of organic matter from CBAWO sediment samples was conducted using a complementary approach. This included solid-state $^{13}$C NMR analysis of whole sediments and a targeted approach that included the analysis of specific organic matter components (various 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 decomposition.

**Lake research**

The physical limnology of the lakes at CBAWO has been intensively studied since 2003, likely the longest comprehensive data sets available for lakes in the High Arctic. Lakes at CBAWO were instrumented with advanced acoustic doppler current profiler (ADCP), conductivity, temperature, depth (CTD) and temperature logging instruments to document the linkages between changing river inflows, lake ice cover, and water column dynamics. CTD moorings left to overwinter from August 2011 were recovered in June 2012 and continue to reveal substantial information on sub-ice, winter conditions in the lake. As was the case in previous winter, the winter CTD mooring in West Lake (2011-12) revealed significant sediment, oxygen and conductivity excursions at the lake bottom after the runoff period had ended, including two major events in December 2011 and February 2012. Further evidence for hydrochemical change in the lakes was collected, and we are continuing to attempt to constrain these underwater processes that appear to change the chemistry of the lake overwinter. Deployment of lake mooring instruments in 2012-13 was carried out and will provide further data to investigate the winter dynamics of these lakes.

Postdoctoral fellow Dr. Philip Bonnaventure also compiled and has analysed the water temperature record from the CBAWO lakes. This data shows strong seasonal asymmetry of heat gain and loss rates, and his work has further shown important limitations to multi-year heat gain in these lakes.

Finally, we deployed fixed time-lapse cameras at each lake at CBAWO to document the decay and removal of ice cover in the spring, as well as the formation of ice cover in the autumn.

**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. In 2007, they began quantifying export of total mercury (THg; all forms of Hg in a sample) and methyl mercury (MeHg; the toxic and bioaccumulative form of Hg) from the East and West catchments at CBAWO, as well as from a few smaller tributaries on the landscape, some of which have been impacted by major permafrost disturbances. 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 2012 focussed again on collection and analysis of water from the lakes and their inflows 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 the University of Alberta Biogeochemistry Laboratory (UABL) and the Environment Canada labs in Burlington, ON using standard U.S. Environmental Protection Agency analytical protocols. Fluxes and pools of THg and MeHg to and in the lakes are calculated using measured THg and MeHg concentrations, aerial water discharge volumes from the landscape, and detailed lake bathymetry.

Terrestrial vegetation dynamics and GHG fluxes

For the fourth year, we deployed an eddy covariance flux tower to measure CO$_2$ fluxes at CBAWO (Humphreys and Lafleur). The flux tower measuring energy budget terms and CO$_2$ fluxes was setup in early June and captured the 4th snow-melt/summer period. This station is located in the upper Goose subcatchment (Fig. 1), a location where intensive terrestrial and hydrological activity is underway. The tower provides a key tool for scaling up the landscape CO$_2$ fluxes at CBAWO.

In 2012, we established eight ADC automated carbon exchange (ACE) Autochamber systems (Fig. 3) in the Goose catchment (Fig. 1). These autochambers measure CO$_2$ production (either ecosystem respiration (dark lid) or net ecosystem production (transparent lid). Each autochamber runs independently, containing its own gas analyzer and data logger. This means that individual chambers can be deployed across the landscape in any location, making them ideal to measure CO$_2$ fluxes from the different vegetation types across the landscape. However, before running the autochambers in the different vegetation types, we decided to first compare results from the autochamber systems to those from the flux tower so that we would have confidence that the different technologies were giving us similar results. As a result, in 2012, we ran four autochambers in the mesic tundra vegetation type, with four measuring net ecosystem productivity and four measuring ecosystem respiration. Measurements were made every 30 minutes for a seven week period starting in early June and continuing until the end of July. We then compared our results both to measured NEP from the flux tower, and also calculated ecosystem respiration from the flux tower.

We are also quantifying the impacts of climate change on the net exchange of two greenhouse gases (CO$_2$ and CH$_4$) from aquatic landscapes at Cape Bounty.
This research began in 2008, and we now have data pertaining to this aspect of the research project for 2008, 2009, 2010 and 2012. This ongoing project has already yielded some interesting long-term information on the concentrations and fluxes of GHGs from rivers and lakes at the site. Throughout the open water season, dissolved GHG samples were collected from the East and West rivers, just prior to entering East and West lakes. Surface dissolved GHG samples were also collected in East and West lakes to calculate the net ecosystem exchange of these GHGs with the atmosphere. We also did depth profiles of these GHGs in both East and West lake to determine zones of production and decomposition.

**Permafrost disturbances**

Mapping of active layer detachments (ALD) that occurred in 2007-8 was undertaken again in 2012, and further delineation of exposed bare soil within disturbances was also completed. Most of the disturbances have stabilized, with only one still showing evidence for retrogressive headward expansion.

Mapping was also necessary to verify the performance of a remote sensing protocol to identify disturbances. Results from this research by PhD candidate Ashley Rudy demonstrates a high degree of accuracy for large, elongate disturbances, and this method is currently being applied to other areas of the Arctic to determine if it can be broadly used for disturbance mapping.

**Remote sensing**

The 2011-12 research activity has been directed at developing an operational method of determining soil moisture from Synthetic Aperture Radar (SAR) data across large areas of the High Arctic (PhD student A. Collingwood). The use of the Canadian RADARSAT-2 fully polarimetric SAR satellite should allow for better discrimination of soil moisture, surface roughness, and vegetation characteristics than is possible with current single-polarization space-borne SAR solutions. Fully polarimetric data will also allow for operational methods of soil moisture estimation to be developed that preclude the need for expensive field data collection. An accurate method of determining important biophysical parameters such as soil moisture in arctic environments over the long term is very important for future climate and hydrological studies as they impact evaporation and water storage. These methods are being calibrated and validated from data collected at the CBAWO in 2009 and 2010, and further validated from data collected in 2011 at Drake Point, Sabine Peninsula, Melville Island. It is important to be able to extrapolate models developed for one year, to other years at the same site, as well as to different sites, and to make comparisons of soil moisture across islands and landscape terrain (e.g. CBAWO versus PBP). The field work so far has resulted in several thousand soil moisture measurements and nearly 1500 surface roughness measurements taken at more than 130 sample locations, as well as measurements of other biophysical parameters such as vegetation cover, rock fraction, and soil properties. Most of this field data has been processed and dozens of RADARSAT-2 SAR images have been acquired in support of this field work at both study sites. An analysis and model of surface roughness parameters is complete, and Mr. Collingwood is beginning to work on change detection of surface soil moisture, as a precursor to a full model that is capable of estimating soil moisture, surface roughness and vegetation cover from SAR data. These RADARSAT-2 SAR data for this project are being provided by the Canadian Space Agency’s Science and Operational Applications Research (SOAR) program.

**Results**

**General**

A full season of field research was carried out at CBAWO, and a wide range of hydrological research at PBP. Research themes included ongoing meteorological, hydrological and limnological measurement programs. Due to poor weather at the beginning of the season, planned snow surveys were
not possible. A number of new instrument stations were deployed in 2012, including time lapse cameras for lake ice monitoring, soil moisture/conductivity/temperature profiling stations, and two boreholes that were instrumented to 7 m depth with thermistors.

**Hydrology**

Discharge in 2012 was muted compared to previous years. In part, this was due to warm conditions during May, prior to thaw, that likely resulted in high sublimation rates and snow loss. Ongoing analysis of meteorological data is underway to assess this possibility. Flow began June 10 and peak flow was on June 12 in the West and East Rivers, nearly three weeks earlier than in 2003 when measurements began. Sediment load was similarly reduced compared to previous years, and resulted in an overall low suspended sediment flux for the 2012 season. Sediment budget work carried out for the West River revealed persistent storage in most reaches of the river, consistent with patterns observed in 2010 (MSc research, Elena Favaro).

Subcatchment flow and sediment transport was also early and of low intensity. Most subcatchments stopped flowing late June when snowcover was exhausted. Rainfall rejuvenated flow, but notably, a high intensity event in early July resulted in exceptionally low runoff (runoff ratio of 0.02). This lack of response was due to exceptional drying of the catchment soils in late June and early July, resulting in antecedent conditions that retained the vast majority of rain water and generated minimal runoff or sediment transport (MSc work, Elena Favaro).

Detailed slope soil moisture research by PhD candidate Daniel Lamhonwah revealed complex soil water patterns during drying and rewetting phases of the season. Surface water samples collected from a dense network of sites at 3-day intervals are currently being analysed for water stable isotopes and hydrochemistry, with the goal of determining water sources and pathways with end-member mixing models.

At Polar Bear Pass (PBP), preliminary results from 2012 streamflow research (eastern edge of PBP) suggest that meltwaters from the northern part of the Pass produce the first major peak in the streamflow record, while a second pulse, delayed by a few days comes from the southern part of the Pass. This confirms our earlier snowmelt and modelling efforts (Assini and Young, 2012; Young et al. submitted). Surprisingly, this pattern differs in the western portion of PBP. Here, water drainage from the central part of the wetland activates early streamflow peaks, and it is only much later (late June) that deep valley snowpacks in sheltered caverns (northwest part of the Pass) melt-out, producing elevated, and sustained flow. Clearly, the processes underlying these streamflow variations require further exploration.

Preliminary work on water budgets for hillslope catchments at PBP suggest that in recent years (e.g., 2008, 2009), summer rains can account for a larger proportion of the seasonal precipitation inputs than snowfall. Snowmelt however, continues to be an important driver of streamflow, as evaporation losses typically track seasonal rainfall inputs.

**Catchment hydrochemistry**

Preliminary analysis of the nitrogen concentrations in the snowpack and precipitation indicate that the concentrations of nitrate (NO$_3^-$) and ammonium (NH$_4^+$) in rainfall and late winter snowpack samples are similar in range, and that the total atmospheric deposition of N from rain (total N ~ 8 kg/km$^2$) was only slightly greater than that in the snowpack (~7 kg/km$^2$) over the season of monitoring (Fig. 4, MSc work Louiseize). These first estimates of total wet deposition of N at Cape Bounty (approximately 15 kg/km$^2$) are much higher than previously published dissolved inorganic nitrogen (DIN) fluxes from the West and East rivers, which were on the order of 3-6 kg/km$^2$ (Fig. 3, Lafrenière and Lamoureux, 2008; Lewis et al., 2012).

The results of the flux calculations are supported by the results of analyses of the stable isotopes of
NO$_3^-$ (δ15N and δ18O of NO$_3^-$) in streams, which indicate that following the initial snowmelt runoff period, the NO$_3^-$ exported in stream runoff was not derived directly from atmospheric sources, but was the result of microbial cycling of N within the watershed (mineralization and nitrification reactions). Figure 5 shows that late in the season NO$_3^-$ in the Goose and Ptarmigan streams is significantly depleted in δ18O-NO$_3^-$ and enriched in δ15N-NO$_3^-$. The depletion of δ18O and enrichment of δ15N of NO$_3^-$ is indicative of NO$_3^-$ that has been formed as a result of microbial mineralization and nitrification (Kendall, 1998).

The composition of dissolved nitrogen in the Goose and Ptarmigan watersheds in 2012 indicates that the concentrations of the dissolved N species are similar overall in the two catchments. The primary difference between the two watersheds is that the N in runoff in Goose watershed was dominated by DON, while runoff from the disturbed Ptarmigan catchment had greater amounts of dissolved inorganic nitrogen (DIN, which consists of NO$_3^-$ plus NH$_4^+$). The prime difference in the seasonal fluxes was that there was greater N flux from the Goose watershed overall, due to melt water production and runoff being supported by the large and deep snowbanks in this watershed, when runoff in Ptarmigan has ceased, due to persistent dry conditions in July. The other distinction that can be made between the two catchments is that there was a large increase in the concentration and flux of NO$_3^-$ from the disturbed Ptarmigan catchment following the large rainfall event on July 18 (MSc work, Louiseize).

Preliminary analysis of the composition of dissolved organic carbon (DOC) in the watersheds at Cape Bounty indicates that late summer rainfall events can yield important DOC fluxes from watershed late in the season when flow volumes and DOC concentrations are typically at their minimum. In general DOC concentrations are always higher in the undisturbed Goose catchment, while dissolved inorganic carbon (DIC) concentrations are higher in the disturbed watershed. DIC and DOC concentrations in the Goose streams are approximately equal in concentration, while DIC concentrations are between 2 to 7 times higher in runoff from the disturbed Ptarmigan watershed. The concentrations of DOC increase in both the undisturbed and disturbed streams following summer rainfall, but DOC concentrations are higher for the undisturbed catchment, while rainfall runoff yields extremely high concentrations from the disturbed watershed. The DOC/DON ratio, which is an indication of the freshness of lability of the dissolved organic matter (DOM), is higher in the disturbed Ptarmigan catchment, indicating that the DOM in the disturbed watershed is more degraded than that coming from the Goose watershed. Although the data are only too preliminary to show here, the initial analyses of
the fluorescence composition of the dissolved organic matter (DOM) by the fluorescence excitation emission matrices (EEMs) also indicate there are differences in the composition of the DOM emanating from the disturbed Ptarmigan watershed and the undisturbed Goose watershed, and that the DOM in the Ptarmigan watershed may be more degraded than that in Goose (BSc student Rutherford).

**Sediment biogeochemistry**

Organic carbon content varied in the sediments analysed. Total organic carbon analysis displays a trend of downstream accumulation of suspended organic carbon inputs (Fig. 6). Sites situated along and downstream of disturbed subcatchments show a significant increase of total organic carbon. This suggests additional carbon inputs from permafrost disturbance.

Solid-state 13C NMR analysis shows varying organic matter composition in the sediment samples (Fig. 7). Aromatic concentrations are generally greater than O-alkyl concentrations upstream; disturbed subcatchments show an increased input of O-alkyl organic matter which is consistent with an introduction of fresh or previously preserved undegraded organic matter from permafrost.

As material from the disturbed subcatchments travels along the main channel, the labile organic matter degrades or becomes solubilized and is no longer concentrated within the sediments. We also examined the ratio of alkyl/O-alkyl carbon which typically increases with progressive biodegradation. The highest degradation ratios occur in the sediments near headwaters and along the disturbed catchments. This suggests that accelerated microbial activity due to carbon inputs near permafrost disturbances (labile organic matter inputs).

Organic biomarker data have been collected and are now being tabulated. One notable observation is the occurrence of nonacosan-10-ol which is believed to be derived from the waxes of pine needles. This biomarker was observed in all sediments and we are currently assessing the potential for this to be derived from historic organic matter inputs.

**Lake research**

Systematic sampling of both lakes for water column chemistry and sediment load indicated that the lakes had substantially enhanced SO$_4^{2-}$ concentrations, representing near doubling of concentrations from 2010, and four-fold increases from pre-2009. These data, together with mooring data of dynamic winter conditions under ice cover in the West Lake, suggest multiple processes are occurring. First, high

![Figure 6. Total organic carbon of sediment samples from CBAWO. Sample locations correspond to sites in Figure 2.](image1)

![Figure 7. O-alkyl (labile) and aromatic (recalcitrant) functionalities quantified using solid state 13C NMR relative to total organic carbon.](image2)
turbidity events in the West Lake during December and February were consistent with turbidites and left substantial residual sediment in the lower water column (Fig. 8). By comparison, the water column of the East Lake remained essentially clear. Despite the differences in the turbidity of the lakes, the water chemistry, particularly SO$_4^{2-}$, had increased throughout the water column compared to 2010, suggesting that another mechanism was contributing to lake chemical changes. Given the lack of fluvial inputs over winter, seepage or other internal processes are likely mechanisms we are currently assessing with aquatic gas data and further analysis of the mooring and hydrochemical records.

**Mercury research**

Average THg concentrations in the West and East rivers were comparable (7.8±4.0 & 7.2±4.8 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 in West Lake and

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Figure 8. Water samples from West Lake June 4 showing late winter turbidity in the lower water column.

Figure 9. Hg concentrations and flow in West & East Rivers in summers of 2007-10. Results from 2011 and 2012 samples are pending.
0.05±0.03 ng L\(^{-1}\)). Most of the THg in West and East rivers was particulate-bound (66±15 & 66±18%) and in West River, particulate-bound THg (pTHg) was highly corrected 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 (Fig. 9). 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 ~double those in East (1.3±0.6 & 0.8±0.4 ng L\(^{-1}\)). MeHg concentrations were extremely low and almost identical in the two lakes (0.01±0.01 ng L\(^{-1}\)). Calculation of lake Hg pools over summer 2010 demonstrated that unfiltered and filtered THg and MeHg pools increased in mid June during the high river flow period, then decreased. These results suggest that in 2010, river Hg inputs did not mix into the lake but instead flowed through the lake and out the outflow; however mixing may occur in other years.

Arctic char collections from East and West Lake now extend over the period 2008 to 2012. \(\delta^{13}C\) 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 Lake char (10.98±0.35‰ vs. 9.99±0.79‰), suggesting differences in food sources. Mean \(\delta^{15}N\) values from 2008 to 2012 did not change significantly. 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 (Fig. 10). Adjustment for trophic level of the char using \(\delta^{15}N\) to take into account differences between lakes had minimal overall effect; it raised 2009 THg concentrations ~3%. (Fig. 10).

MeHg concentrations in periphyton (2.5 ng g\(^{-1}\) dw in both lakes), chironomids (E = 41; W = 47 ng g\(^{-1}\)) and juvenile char (E=98; W=83 ng g\(^{-1}\)) are similar in the two lakes. West Lake amphipods had relatively high concentrations of MeHg (83 ng g\(^{-1}\)). No amphipods have been found in East Lake. The presence of amphipods may help explain the higher Hg concentrations in the char in West Lake.

The results of this study also provide additional information on THg in landlocked char for the High Arctic region, which may be useful for communities in the region. THg is lower in char in East and West Lakes compared to most lakes in the Cornwallis Island area but similar to those in the Kent Peninsula and Victoria Island area.

Greater inputs of terrestrial carbon and THg to West Lake, along with higher THg in 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) & 2010 (Lamoureux, unpublished data) compared to 2008 may have caused food web shifts (e.g. char to shift to a more pelagic diet or reduced amphipod abundance). Continued sampling of food web organisms for Hg and δ13C and δ15N, as well as multi-element analyses, should help us understand the factors driving the difference in char Hg among the two lakes.

**Greenhouse gas research**

We deployed an eddy flux town to measure CO₂ fluxes at CBAWO (Humphreys and Lafleur). The eddy flux tower measuring energy budget terms and CO₂ fluxes captured the fourth snow-melt/summer period. 2012 was a banner year for CO₂ uptake. Over an uncommonly warm and dry 50 day period (June 4 - July 23), the tundra was a sink for 27 g C/m² in 2012 while in 2008 - 2010, uptake varied from 2 to 7 g C/m² (Fig. 11). Warm spring and summer temperatures (Fig. 11) enhanced plant growth and photosynthetic uptake of CO₂ to a greater extent than respiration processes.

The landscape at Cape Bounty is dominated by three key vegetation types: polar semi-desert, mesic tundra, and wet-sedge meadows. Polar semi-desert and mesic tundra are the main types, occupying over 90% of the landscape. These vegetation types are distributed along soil moisture gradients. If changes in precipitation occur in the future, it is possible that the relative abundance of these vegetation types could change, altering the net GHG balance of the landscape if there are differences in GHG fluxes from the different vegetation types.

Our previous work over the past four years has utilized static chambers to compare net carbon exchange (Fig.

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**Figure 11.** Daily air temperature (top) and net ecosystem exchange (NEE) of CO₂ (bottom) at the Cape Bounty flux tower site.

**Figure 12.** Carbon flux in three high-Arctic vegetation types at Cape Bounty in 2008 and 2009. NEP = net ecosystem production; RE = ecosystem respiration; GEP = gross ecosystem production.
measurements have painted a relatively clear picture about differences in GHG fluxes for these different vegetation types. Wet sedge meadows are generally the strongest carbon sinks across the landscape, followed by the vegetated areas of polar semi-desert (Fig. 12). At the same time, there are clear differences in the fluxes of trace gases from the different vegetation types (Fig. 13). Wet sedge meadows are clearly sources of all of the trace gases in both years, as is the mesic tundra, although in some years (e.g. 2009 for methane) the net flux is very close to zero. In contrast, both bare soil and vegetation portions of polar semi-desert are significant methane sinks when averaged across the growing season, and very weak sources of nitrous oxide (very low fluxes) (Fig. 13).

These results (Fig. 12 and 13) can be scaled up to the entire growing season and to the entire landscape at Cape Bounty using our vegetation map that shows the relative abundance of these different vegetation types. To determine the relative importance of the different GHG fluxes to a net GHG balance for the landscape, we applied the different global warming potentials (GWP) for each gas (CO₂, CH₄, N₂O) to express results on a CO₂-equivalent basis. It is clear (Fig. 14) that fluxes of CO₂ dominate the net GHG balance of the landscape, in spite
of the fact that the polar semi-desert systems are strong methane sinks similar in magnitude to tundra ecosystems further south.

With the help of our collaborator Elyn Humphreys, we now have completed a footprint analysis around the tower that shows the dominant vegetation type that contributes to the measured carbon flux showing how this would vary depending on the wind direction. Although there is variation in the vegetation around the tower site (Fig. 15), preliminary data suggest that the cumulative fluxes from the different “sectors” differ very little. Clearly, there are still some questions to be answered about the seasonal contribution of the different vegetation types to landscape-scale C fluxes, which we hope to address with our autochamber work.

Deployment of automatic chambers during the 2012 field season provided highly detailed time series of ecosystem respiration and exchange. Both NEE and ecosystem respiration showed a very strong diurnal signal, linked strongly to temperature ($R^2=0.50$) but poorly to photosynthetically active radiation (PAR) ($R^2=0.01$). During the later parts of the growing season, the relationship between ecosystem respiration and temperature became even stronger, suggesting that...
high moisture content early in the growing season may have altered the impact of temperature on respiration rates. The strong diurnal signal in both fluxes (Figs. 16 and 17) suggest a strong dependence on temperature fluctuations. Future work will explore in more detail the scale dependency of the relationship between temperature and ecosystem respiration. Overall, we found relatively good agreement between growing season sums of NEE and ecosystem respiration. The autochambers located closest to the tower provided measurements of NEE that were very similar to those measured by the flux tower. These results give us confidence in the comparability of the two techniques for measuring carbon fluxes, and will allow us to deploy the autochambers across a wider range of vegetation types in the near future. To our knowledge, these are the first applications of these autochamber systems in the High Arctic of Canada, and perhaps some of the first high frequency direct measurements of ecosystem respiration.

Over the past three years, we have completed two years of static chamber measurements quantifying the impacts of active-layer detachments (ALD’s) on net carbon fluxes, and two years of measurements of trace gas production. Year two of the trace gas data was collected in 2012, but the gas samples have not yet been analyzed. Results from the first year of trace gas flux measurements showed some interesting patterns across a disturbance gradient (Fig. 18). For nitrous oxide production, the highest fluxes came from the control site and the lowest from the disturbed site. Nitrous oxide fluxes from the highly disturbed site were intermediate. Methane fluxes did not differ significantly between sites (p=0.22), although it was interesting to note that the highly disturbed site acted as a methane source, while the other two sites were both methane sinks. Once our second year of data is in hand, we will be able to calculate full GHG budgets across this disturbance gradient, and gain a better understanding of how permafrost thawing and disturbance features like ALDs might alter the GHG balance of High Arctic landscapes.

Finally, systematic sampling for GHG demonstrate that both the East and West rivers have high concentrations of both CO₂ and dissolved organic carbon, but virtually no CH₄. Concentrations of both CO₂ and CH₄ are low in the surface waters of East and West Lakes. Concentrations of both CO₂ and CH₄ are higher in the bottom waters of East and West lakes. These results will contribute to catchment-scale carbon and GHG budgets, and represent a long term data set from CBAWO.

**Remote sensing**

Adam Collingwood (PhD candidate) is developing an operational method determining soil moisture from Synthetic Aperture Radar (SAR) data across large areas of the High Arctic (at Cape Bounty and the Sabine Peninsula). These methods are being calibrated and validated from data collected at the CBAWO in 2009 and 2010 and are being validated with data collected in 2011 at Cape Collingwood, Sabine Peninsula, Melville Island. It is important in order to extrapolate models developed for one year to other years as well as within and between sites. The field data have been processed and the analyses of these extensive datasets are complete. Dozens of RADARSAT-2 SAR images have been acquired in support of this field work at both study sites. An analysis and model of surface roughness, vegetation
and soil moisture parameters is complete. The candidate is now in the writing phase of his research. The RADARSAT-2 SAR data for this project are being provided by the Canadian Space Agency’s Science and Operational Applications Research (SOAR) program. This represents a significant in-kind contribution by CSA. Mr. Collingwood has completed three extensive field seasons and will spend 2012-13 writing his PhD thesis. It is anticipated that he will defend his PhD in September 2013.

Biophysical remote sensing of High Arctic vegetation has typically relied heavily upon the Normalized Difference Vegetation Index (NDVI). It is indisputable that NDVI has shown strong and robust relationships with many High Arctic vegetation biophysical variables. However, until recently, it has not been possible to test indices fundamentally different from NDVI in the High Arctic at both a large spatial extent and a fine spatial scale. As such, the objectives of this research are to take advantage of the increased spectral resolution of the WorldView-2 multispectral sensor to: 1) develop and test new spectral vegetation indices well-suited to capture the sparse and fragmented nature of High Arctic vegetation community composition and cover; and 2) characterize vegetation community composition and cover for the Sabine Peninsula, Melville Island, Nunavut (76°27' N, 108°33' W).

A stratified random sampling scheme was developed from descriptive vegetation observations and an unsupervised classification of WorldView-2 multispectral imagery (2 m spatial resolution), collected in July 2010. Five vegetation classes were identified by the unsupervised classification: polar desert, dry-mesic tundra, mesic tundra, wet-mesic tundra and wet sedge/mosses. These vegetation classes were sampled throughout July and August 2011, coincident with a WorldView-2 multispectral dataset collected on July 16, 2011. Plant species composition and cover for all classes were sampled using 1 m² quadrats (n = 49) according to International Tundra Experiment (ITEX) protocols for community baseline measurements: species, height, and status (live, dead, standing dead, or inflorescence). Vegetation reflectance measurements were collected for 29 of these quadrats with an ASD FieldSpec Pro spectroradiometer. We then resampled these field reflectance spectra to approximate the spectral response functions of the eight WorldView-2 spectral channels (MSc Allux).

In 2012-13, regression analyses are being used to relate cover and abundance data, grouped by plant functional type, to spectral vegetation indices. Two approaches are being used to develop a wide range of vegetation indices well-suited for High Arctic vegetation: a combinatorial approach, testing all possible combinations of normalized two-band indices similar in form to NDVI; and a biophysical approach based on known relationships between absorption features and foliar chemical concentrations. These indices will be tested in regression models to identify those with significant statistical relationships with plant functional group cover and abundance. From this pool, a subset of indices that minimize multicollinearity and maximize predictive power will be selected as explanatory variables for a multivariate analysis. Ultimately, we will upscale the regression models developed at the plot scale to the satellite imagery to obtain high-resolution maps of plant functional group cover, total vegetation cover, and vegetation community type.

Discussion

Our integrated research activity has been focused on understanding the processes and linkages between the land and water at CBAWO to demonstrate the sensitive elements of these systems with respect to climate change. Each year, our work has advanced this research theme through coordinated field research, sampling and analysis activity. Hence, we view ArcticNet as a key to support a dynamic and productive team that carries out diverse research, student training, and community engagement.
We have had limited capacity to bring residents from Resolute to our field camp but have endeavoured to do so, including in 2012. Through the direct involvement of residents, and discussions with the community, we are seeking to share our knowledge and to learn about the interests, concerns and implications of this research on northern communities. Further, we intend to expand our research activities to the Apex River near Iqaluit, to increase our interaction with northern residents and decision makers, while contributing to knowledge generation and sharing associated with this heavily used watershed. We anticipate this new partnership will leverage our strength in integrated hydrological research at CBAWO and PBP and bring it to an important new audience of northerners.

Our work has demonstrated the critical role of water availability and hydrological connectivity over hydrological fluxes of all types. Reliable estimates of snowcover for arctic basins are still required to quantify water budgets and to elucidate the factors which lead to the resilience or alteration/demise of these ecosystems to extreme events (drought periods) or a changing climate. Hence, temperature change has a less direct influence on these processes compared to the dominant effect of altered water from snow and rain. Results clearly show that the High Arctic hydrological system is currently at the threshold between snowmelt and rainfall dominance. The research literature has emphasized the role of snowmelt and runoff on most catchment processes. Our work demonstrates that in some years, when sufficiently intense rainfall occurs, the latter constitutes a major, if not dominant hydrological driver that is responsible for the majority of seasonal fluxes like water, sediment, solutes and nutrients. The occurrence of rainfall sufficient to dominate these processes has only occurred once (2009) in the eight years of work at CBAWO. Research in 2012 demonstrated that heavy rainfall alone will not generate a runoff response, hence, antecedent conditions (particularly soil moisture) play important roles as well. Years with reduced, but hydrologically important rainfall occurred in 2007-8. Notably, the early years (2003-5) were cooler and had little rainfall and were more typical of a snowmelt dominated system, while later years (2007-9) were wetter and warmer. Hence, our results suggest that rainfall has become more important for watershed processes in recent, warmer years.

It remains too early to suggest that this may represent a likely change in hydroclimatolgy associated with regional warming, but it does indicate the need to account for substantial changes in water timing and runoff processes in this region. Our most recent work, supported by past observations, suggests a key conceptual addition to this hydrological framework. Increasingly during the late melt season, water that is likely supplied by the melting of ground ice is contributing to baseflow in rivers and ponding on the surface. The chemical composition of this water is distinct from meteoric (rain and snow) sources, and represents an important linkage between the deeper soil and increasing summer thaw. In future years, we plan to direct a considerable amount of our time to investigate these processes and impacts, as they appear to be a potential change that is recent. Characterizing these processes across the heterogeneous arctic landscape is a key research challenge, particularly to develop effective modelling approaches. Our 2012 research has begun to evaluate the spatial patterns in hydrological systems at CBAWO and we plan to develop this more extensively in the 2013-14 period.

Our research has identified that organic matter near areas that have experienced active layer detachments from permafrost melt is distinctly different and is predominantly in labile form. These inputs may accelerate microbial activity and may alter organic matter biogeochemistry in the High Arctic. Comparisons of the dissolved N and C composition at CBAWO indicates that disturbance results in enhanced export of inorganic N and C especially following rainfall events. Additionally, the fluorescence analyses and C/N ratios of the DOM, indicate that DOM exported from the disturbed watershed was more recalcitrant than DOM from the undisturbed catchment. Further, our initial results suggest that overall these High Arctic watersheds are sinks for atmospherically deposited N. This conclusion is also supported by the results of the nitrate isotope
analyses, which indicate that most of the nitrate leaving watersheds is derived from, or has been subject to, nitrification within catchment soils prior to export in runoff.

While downstream water quality changes may be subtle, the integrated, potentially cumulative change of these altered fluxes is most evident in the lakes, where water chemistry has systematically changed through progressively higher ionic concentrations since disturbance in 2007. The higher THg in arctic char from West Lake also is consistent with the higher fluxes of Hg although not with observed MeHg in lake waters. These processes, which are complex, require further research on which to elaborate. We note, however, the research team and effort to date provides an exceptionally suitable context and capacity to undertake this research. Results from river Hg research will be used in conjunction with the lake Hg research to create a mass balance budget of both THg and MeHg in two high Arctic lakes.

Additionally, the river Hg research is also revealing how legacy Hg, stored on the landscape in permafrost, is being released to downstream lakes as human-induced climate warming accelerates permafrost melt. Higher Hg concentrations in the outflow from disturbed catchments provide a clear indication of the potential for increased Hg release from these terrestrial systems.

Overall results of the greenhouse gas research at CBAWO point to the potential for climate change to alter the greenhouse gas balance of High Arctic ecosystems. The magnitude of CO$_2$ sequestration at the CBAWO mesic tundra site is relatively small compared to sites in the southern Arctic or High Arctic sites dominated by wetland ecosystems. These results suggest considerable variability in daily CO$_2$ exchange rates within and among years. Changes in soil moisture regimes could lead to changes in the distribution of plant communities that are distributed along soil moisture gradients.

Methane can both be consumed and lost from terrestrial ecosystems, but initial estimates suggest these fluxes are small compared to CO$_2$ fluxes, and may not greatly impact the overall C balance. Similarly, both East and West Rivers have high concentrations of both CO$_2$ and dissolved organic carbon, as would be expected draining a landscape with carbonate geology and some vegetative covering. Because the rivers are well oxygenated, there was virtually no dissolved CH$_4$ in the rivers. Concentrations 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$_2$. This type of information is critical to understand whether climate change will result in positive or negative feedbacks to the global climate system.

Overall, these results demonstrate many of the key elements of response by High Arctic land and water to a rapidly changing climate. Continued research to further integrate and incorporate these findings into modelling frameworks will improve our ability to predict how these environments will respond to future change and provide decision makers with important insights to constrain and balance policy.

**Conclusion**

Research at CBAWO represents a directed, 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 plan to expand this research to the Apex River near Iqaluit. This location provides excellent logistical support, and most importantly, will permit 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.

Acknowledgements

Additional funding was provided by NSERC through individual Discovery Grants, and funding from NSERC Discovery Frontiers ADAPT to SFL, MJL and MJS. Student support was provided by the Northern Scientific Training Program, AANDC. Environment Canada provided in-kind support for analysis of THg and MeHg as well as direct support for travel costs of Kirk (2011) to CBAWO, shipping of sampling gear, and hiring of Debbie Iqaluk of Resolute Bay. Polar Continental Shelf Program provided invaluable logistical support. Campbell Scientific Canada Inc., continues to provide valuable support to the automatic weather station at Polar Bear Pass, Bathurst Island. A number of students associated with CBAWO were supported by scholarships from NSERC, the Garfield Weston Foundation, Queen’s University, and the Ontario Graduate Scholarship programs. Undergraduate student research at CBAWO has also been supported by the Queen’s University Summer Work Experience Program (SWEP). Our partnership with the Canadian Space Agency continues to support this research through provision of remote sensing imagery.

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