Instability of Coastal Landscapes in Arctic Communities and Regions

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Abstract

Future climate scenarios and impacts modeling predict changes in climate variables that may increase coastal landscape instability and hazard risk. Projecting the future response of the coastal land system to these changes in climate forcing is a prerequisite for an effective adaptation strategy and forms the core of this ArcticNet project. Through improved understanding of changes in climate, sea-level, sea ice, storms and wave climate, seasonal thaw depths, and other aspects of environmental forcing we will assess integrated impacts on coastal landscape stability, including flooding, erosion, habitat integrity, and community vulnerability. Together with northern communities and partners we plan to integrate local and external research and knowledge on climate-change trends and impacts in order to provide a common basis for decision-making at all levels, thereby enhancing community adaptive capacity. Ultimately the goal is to promote informed choices of adaptation measures and enhanced resilience in northern coastal communities.

Key Messages

- The 2013 multibeam mapping program in partnership with UNB (ArcticNet project 2.6) using the GN research vessel MV Nuliajuk mapped previously uncharted coastal waters, including navigational hazards and safe anchorages, clam habitat, submerged shoreline features and marine geohazards between Qikiqtarjuaq and Pangnirtung, NU.
- Multibeam mapping along outer Cumberland Peninsula established a new Holocene sea-level minimum at ~50 m below present and confirmed the magnitude and pattern of submergence along the eastern fringe of Baffin Island.
- The nature and sensitivity of nearshore marine habitats near Qikiqtarjuaq, NU, on Baffin Island were explored through marine habitat mapping and characterization, focusing on two areas surrounding the community, including areas that could host harvestable quantities of clams.
- Our summer fieldwork expands the knowledge of the benthic macrofauna of the Qikiqtarjuaq region, including commercially valuable populations of marine molluscs, notably the Arctic soft-shell clam, Mya truncata, and the Greenland cockle, Serripes groenlandicus.
- Arctic Bay coralline algae growth is light-dependent and their growth rates have been shown to be inversely related to sea-ice cover. The rapid decline in sea ice in the past 150 years is unprecedented during the >600 year record of the algae from Arctic Bay and northern Labrador analyzed in our study.
- Radiocarbon dating of samples collected near Arviat on the western shores of Hudson Bay has allowed much tighter constraint on the poorly known late Holocene sea-level history of the region. In addition, a campaign GPS site installed in Arviat has yielded the first preliminary GPS-measured uplift rate for the coastal Kivalliq region.
- The Canadian Beaufort Sea coast, including Herschel Island, Richards Island, and other islands north of the Mackenzie Delta, has some of the most dynamic coastlines in the Canadian Arctic due to the unlithified soil properties and the large amounts of ice buried within the sediments.
- High Arctic coasts reflect a very different set of littoral processes, particularly in the inner channels of Eureka Sound and the fiords of western Axel Heiberg Island. In both cases sea-level rise is outpacing erosion and sea-ice conditions display little change and appear not to be a factor.
- Shorelines, backshore and coastal lowland areas along Eureka Sound are being reshaped by thermokarst, which is also contributing to increased sediment flux into the nearshore zone.

- Fog is very locallized in occurrence and is a function of synoptic situation, local wind speed and direction, sea-ice state, water and air temperature, snow cover, and ground moisture. This can make its prediction challenging.
- Numerical methods for predicting fog occurrence have shown limited success. This is especially true where the occurrence of fog is dominated by non-dynamic processes. Diagnostic methods remain the most effective approach, guided typically by physical processes as well as empirical relationships rooted in statistical analysis.
- Co-design of research on the vulnerability of subsistence infrastructure with the Inuvialuit Land Administration identified key target areas, facilitated two-way sharing of quantitative geomatics data and traditional knowledge, and identified the form of information delivery most appropriate for the project stakeholders.
- Analysis of the risks to camps and other facilities identified some sites below historical limits of storm-surge flooding and others potentially at risk with rising sea levels, as well as areas where the potential exists for rapid local acceleration of coastal retreat. Coastal erosion also poses a serious risk to the survival of some archaeological sites along the coast.
- New measurements in the Mackenzie Delta indicate that negligible sedimentation combined with enhanced shallow subsidence in parts of the outer delta are contributing, in combination with sea-level rise, to gradual submergence at the same time as the outer edge is being eaten away by waves. This raises serious concern for the conservation of nesting habitat for the large numbers of swans, geese, cranes, and other bird species utilizing the delta. It also has important implications for development should the natural gas reserves in the delta re-attract interest in the future.
- Completion of a project on coastal hazards in the City of Iqaluit provides scientific support for sustainability planning and the next iteration of the general plan. While most private and municipal infrastructure along the waterfront appears to be high enough for the time being, a minor rise in sea level combined with an increase in wave energy, with reduced sea ice, would require some facilities to be raised in the future.
- The most vulnerable component of land use along the Iqaluit waterfront is the subsistence infrastructure built mostly along the top of the beach and well below the limits of past extreme water levels. The presence of other buildings immediately to landward along much of the shore limits the opportunity for this infrastructure to shift landward to higher ground.
- Our Digial Information for Sustainable Communities (DISC) program is producing planning constraint maps for Nunatsiavut communities that identify available, suitable areas for development across a range of land uses and under current and projected future climate states.
- Municipal plans and development regulations that are based on community values, needs and concerns and informed by the most current planning constraint data, including climate and landscape hazards, are excellent tools to guide local councils in making day-to-day land use and development decisions that build long-term sustainable, climate adapted communities.
- In partnership with the Nunatsiavut Government, our project was represented on the Arctic Inspiration Prize winning team for a knowledge-to-action plan to design and build healthy homes in Nunatsiavut.

Objectives

- To improve understanding of changes in climate, sea levels, sea ice, storms and wave climate, seasonal thaw, permafrost and ground ice, and other aspects of environmental forcing as a basis for assessing integrated impacts on coastal landscape stability, including flooding, erosion, thermokarst activity, habitat degradation and community vulnerability, particularly in areas of high sensitivity and cultural significance.

- To improve our understanding of the effects of changes in climate on Arctic coastal environments, particularly pertaining to coastal and landscape instability, other natural hazards, and community vulnerability.
- To work with stakeholders in the Inuvialuit Settlement Region, Nunavut, and Nunatsiavut to develop improved adaptive management strategies to address changes in both physical and human systems and support sustainable development of safe and healthy communities.
- To integrate local and external research and knowledge on climate-change trends and impacts in order to provide a common basis for decision-making at all levels, thereby enhancing community adaptive capacity. Ultimately, the goal is to support and promote informed choices of adaptation measures and enhanced resilience in northern coastal communities.
- The project has evolved to focus on key knowledge gaps identified in the State of the Arctic Coast 2010 report. These include more robust projections of local sea-level change in Arctic communities, better understanding of the effects of a changing sea-ice regime on Arctic coasts, more detailed studies of Arctic storms and changing storm climatology, consideration of the fate of Arctic deltas and intertidal systems under changing sea level, wave energy and development pressures, and renewed efforts to develop integrated monitoring strategies in the context of a circumpolar Arctic Coastal Communities Observatory Network.

Introduction

Northern communities and community lands, generally located on permafrost in coastal environments, are exposed to a harsh climate, with strong seasonal contrasts in temperature, wind, precipitation, and ice conditions. Under a constant climate, seasonal changes in the landscape and extreme weather events create instability and hazards, including flooding, landslides, thaw failure and subsidence, coastal ice push, storm surges, and coastal erosion. Emerging evidence of climate change in the north and a growing global consensus point to significant changes leading to more severe environmental hazards in the future.

Coastal landscape change in the Arctic has been ongoing for thousands of years and human adaptation has been a constant imperative for Inuit occupying this region. The evolution of Inuit culture is a clear demonstration of adaptation to extreme climatic conditions, but limits to adaptation are seen in the demise of the Thule culture and early European agrarian settlement in Greenland, both due at least in part to climate cooling. The former occupation of parts of the northern Canadian Arctic Archipelago that were later abandoned, as well as early paleo-Eskimo expansion southward to Newfoundland, demonstrates a capacity on the part of northern people to adapt in the past through migration, taking advantage of opportunities to access resources or withdrawing if resources became scarce. More recently, as people have become more dependent on community services available only through hamlets and larger settlements, moving is no longer an acceptable response to environmental change.

The Inuit lifestyle is closely tied to marine resources. Long experience on the land and coastal ocean has allowed the development of traditional knowledge of the physical environment and living resources in a region, as well as an understanding of the range of climate variability expected over timescales of a few generations. This knowledge base provided an understanding of safe practices or routes, such as areas of reliable ice, or of particular environmental hazards. Over the past few decades, and particularly in recent years, the extent of climate variability and change has begun to challenge the limits of traditional knowledge. At the same time, climate change is forcing adjustments in building and infrastructure engineering practices in communities and driving a recognition of the need for adaptation at all levels from individuals to communities, regions, and territorial governments. It is expected that the pace of change will increase in the future, with some of the earliest and most severe changes occurring at high latitudes. The greatest warming in recent decades has occurred in the western Arctic, while climate warming has been slower to occur and less clear in Nunavut, Nunavik, and Labrador. However, there is now widespread evidence across the Canadian Arctic for climate warming affecting glaciers and ice caps, vegetation and other living resources, permafrost and seasonal depth of thaw, slope stability, coastal sea-ice conditions, wave energy, sea level and coastal flooding and erosion hazards, among other factors posing increased risk to northern coastal communities and habitats.

Virtually all Inuvialuit, Nunavut, Nunavik, and Nunatsiavut communities are coastal and many emerging resource developments are either located on the coast or, more commonly, require shipping access with coastal implications. Thus coastal infrastructure is a critical issue for northern governments and communities (Ford et al., 2010). The emerging evidence for climate warming in the Arctic is pointing to changes already apparent in coastal ice extent, form, and safety as a hunting platform, sea-level changes, increased wave action and erosion even in communities with rapid uplift and falling relative sea levels, and changes in species composition with implications for coastal habitat integrity and communities dependent on country food. There is a high demand on the part of communities and territorial governments for information on these emerging issues (Catto and Parewick, 2010). The objectives of this project include the acquisition and appropriate consultative distribution of scientific information to support adaptation efforts.

Activities

Milestone 1: Coastal erosion and response to changes in forcing and sea levels

Coastal geoscience and sea levels

- As part of the Beaufort Regional Environmental Assessment (BREA) program, with additional support from the Geological Survey of Canada and the Polar Continental Shelf Program (Natural Resources Canada – NRCan), the Alfred Wegener Institute for Polar and Marine Research (AWI), Parks Canada, ArcticNet, and other sources, work continued on a synthesis of 40 years of coastal geoscience data acquired along the Beaufort Sea coast (NI Forbes with Manson, Couture, Whalen, Fraser, Lantuit, and German student).
- Nearshore bathymetric and underwater camera surveys using chartered local boat in Broughton Channel near Qikiqtarjuaq NU (Figure 1) provided detailed profiles and bottom characterization for submerged boulder barricade marking the presumed postglacial lowstand of relative sea level in that area (Cowan, NIs Bell and Aitken with NI Forbes).
- In collaboration with Government of Nunavut (GN) and the University of New Brunswick (UNB) Ocean Mapping Group (link to Project 2.6), more extensive Kongsberg EM3002 multibeam surveys using the GN research vessel MV Nuliajuk revealed new sites with submerged deltas and spillover terraces marking the postglacial lowstand of relative sea level (Figure 2) (NIs Bell and Forbes, with Hughes Clarke and Cowan).

Figure 1. Survey vessel (locally chartered freighter canoe) used for coastal and benthic surveys in the vicinity of Qikiqtarjuaq (Broughton Island) in 2013. Research assistant Jenna Munden on the bow and Broughton Channel in background. Note sampling frame with block and single-beam sounder with transom-mounted transducer (photo credit: Beth Cowan).

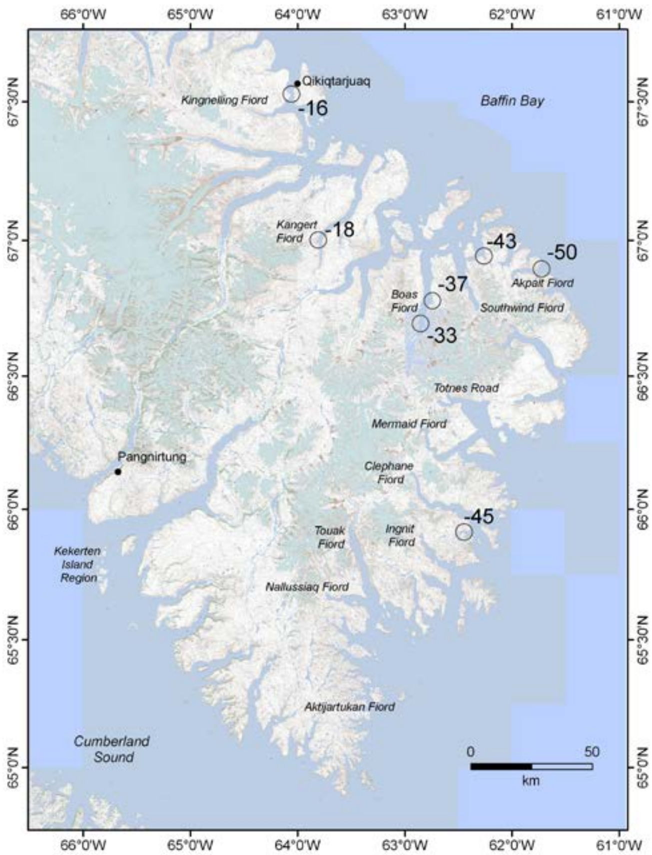

Figure 2. Study area on Cumberland Peninsula, Baffin Island, showing sites (circled) where multibeam surveys revealed submerged indicators of former sea levels (nearshore benches, boulder barricades, deltas, and sill terraces). The numbers at each site are preliminary estimates of the associated lowstand sea level in metres relative to mean sea level today. Qikiqtarjuaq is located on Broughton Island with Broughton Channel to the west. The benthic habitat work described in this report was carried out in that area.

Figure 3. Evidence for barrier overtopping on the tombolo beach across from Qikiqtarjuaq in the storm of 10 September 2013 (photo credit: Beth Cowan).

Coastal impacts of sea ice, storms (waves and surges) and other weather

- Real-time kinematic (RTK) GPS surveys of active beach systems in the vicinity of Qikiqtarjuaq and Broughton Channel, eastern Baffin Island, provided information on the limits of contemporary storm wave runup (Figure 3) and a comparison of present-day coastal dynamics on exposed and protected shores with conditions at the time of the local sea-level lowstand approximately 16 m below present datum (Cowan, NIs Bell and Forbes).
- Assembled a literature review of fog and low visibilty in general and, to the limited extent available, as pertains to Arctic regions; and completed a report overviewing fog and the prediction of fog. Commenced analysis of fog and low visibility in ice-covered marine areas, using data from Canadian northern communities. It is apparent that the observational data available for climatology development work are limited (NI Atkinson with Khalilian).
- Work proceeded on projections of storminess at the seasonal timeframe, explicitly tuned to end-user needs (shipping in Alaskan waters) but applicable to ArcticNet objectives in the longer term. Developing novel approaches to link storm activity response to climate drivers such as the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO), gainging skill using a novel sub-domain partitioning approach, and moving into use of non-linear methods (Shippee with NI Atkinson).
- Partnered with colleagues from Moscow State University, Zubov State Oceanographic Institute, the University Centre in Svalbard, and the Alfred Wegener Institute in an analysis of ice scour hazards to seabed installations (natural gas pipelines) and coastal infrastructure in Baydaratskaya Bay, southern Kara Sea. Data acquisition included marine geophysics (sidescan

sonar and subbottom profilers), global navigation satellite systems (GNSS) and laser total stations for coastal surveys, and diving observations. Produced a map showing seven classes of ice-seabed hazards in the bay (NI Forbes with Russian and German colleagues).

Milestone 2: Coastal change detection (shorelines and habitats)

Scoping for sentinel sites and coastal observatories

- With support under the BREA program in partnership with Natural Resources Canada (NRCan), we reoccupied a number of coastal survey sites dating back as much as 30 years along the Beaufort Sea coast from Shingle Point YT to Cape Dalhousie NWT at the eastern end of the Tuktoyaktuk Peninsula (Figure 4) (Whalen, Fraser with NI Forbes).
- Also with BREA and NRCan funding, monitoring of threats to indigenous infrastructure (camps and other structures) and archaeological sites was undertaken through field visits to Shingle Point YT, Hendrickson Island and Kittigazuit NWT, and by digital photogrammetric analysis of high-resolution satellite imagery in the Inuvialuit Settlement Region (Whalen, Fraser with NI Forbes).
- The network of continuous GNSS sites was maintained and expanded, including sites co-located with tide gauges, providing the nucleus for community-based coastal observatories at sites across the Arctic from Tuktoyaktuk NWT to Qikiqtarjuaq NU amd from Churchill MB to Nain NL (Craymer, Henton with NIs James and Forbes).
- The conceptual framework for a circum-polar Arctic Coastal Communities Observatory Network (AC-CON) was formulated and developed to guide the planning process for integrated (social and biophysical) change detection and adaptive response in Arctic coastal communities (NIs Forbes and Bell with Nymand Larsen, Couture, Overduin).

Seabed and benthic habitat mapping

- In collaboration with Government of Nunavut (GN) and the UNB Ocean Mapping Group (link to Project 2.6), expanded multibeam surveys using the GN research vessel MV Nuliajuk included new surveys of potential clam harvesting sites around the Cumberland Peninsula, Baffin Island, from the vicinity of Qikiqtarjuaq to Pangnirtung, NU (NIs Bell, Aitken, Edinger and Hughes Clarke).
- Ground-truthing of the 2012 multibeam bathymetric and acoustic backscatter data in Broughton Channel near Qikiqtarjuaq, NU, was undertaken in the summer of 2013 using a chartered local boat (freighter canoe) outfitted for single-beam sounding, grab and dredge sampling, and underwater video imaging (Figures 1 and 5). This work involved the selection of stations at which samples of bottom sediments and benthic macrofauna and megafauna were obtained. Three priority sampling areas were identified based on previous research related to bivalve mollusc abundance (Siferd, 2005): outer coast of Baffin Island north of Qikiqtarjuaq, Broughton Harbour, and the southern shore of Broughton Island (Figure 2). In each sampling area, ten sites were chosen for study. Weather conditions and sea state over the study period August 26 to September 4 restricted sampling to the two inner study areas (NIs Aitken, Bell, Edinger with Cowan).
- NI Edinger published a high-impact paper on sea-ice cover reconstruction from the combined growth and Mg/Ca ratios in the skeleton of corraline algae collected from Arctic Bay during sampling for marine habitat mapping in community waters (Halfar et al. 2013).

Sea-level change and vertical motion

- Time-series of GNSS subsidence measurements in the outer Mackenzie Delta was extended by

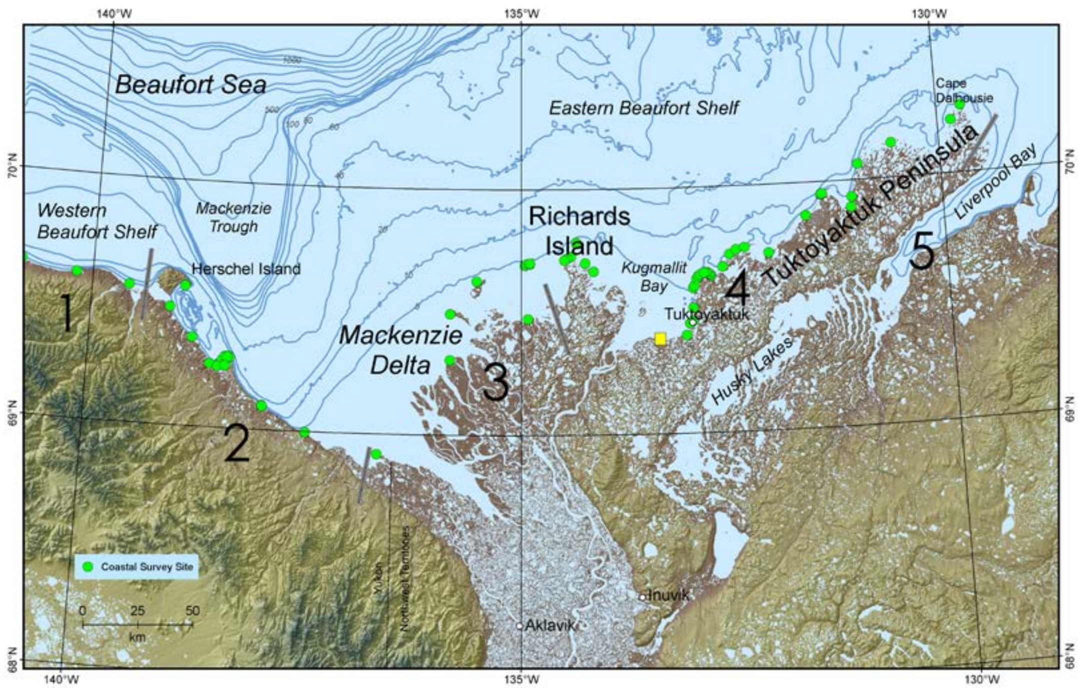

Figure 4. Canadian Beaufort Sea coast with regional divisions (after Forbes et al., 2014b), showing locations of Herschel Island, Mackenzie Delta, Tuktoyaktuk, and Cape Dalhousie. Green circles are coastal monitoring survey sites of the Geological Survey of Canada. Partially obscured site symbol at left-hand margin is the Canada-USA boundary site. Yellow square on the south shore of Kugmallit Bay is location of Figure 11.

re-occupation of monuments at five sites and one additional year of continuous measurements at an autonomous station on the outer delta (Figure 4) (Craymer, Whalen, Fraser with NI Forbes).

- Additional measurements of sedimentation and shallow thaw subsidence in the outer delta were acquired using SET device for microtopographic measurements tied to GNSS monuments and by measurement of sediment accumulation over marker horizons (Whalen, Fraser with NI Forbes).
- In partnership with Natural Resources Canada (GSC-Pacific) and the University of Victoria, data on ages of former raised sea levels in western Hudson Bay and campaign GPS data from Arviat (site ARVI) were processed and interpreted. The results of this analysis were summarized in a paper submitted to Quaternary Research (Simon et al., in revision). The data from the Arviat area were subsequently integrated into a much larger regional dataset of relative sea level measurements and present-day GPS vertical land motion rates in order to constrain ongoing glacial isostatic adjustment modelling studies throughout northern Canada (Simon, Dyke, with NIs James and Forbes).

Coastal landscapes and terrestrial habitat

- Data collection of phenological markers for both flower and leaf growth were obtained following National Phenological Network protocols in one thermokarst site on Ellesmere Island, Nunavut (79.85°N, 85.37°W). PGLS (phylogenetic least squares regression) analysis of first leaf and first flowering dates was undertaken using R statistical software. Hourly soil temperatures were documented at 10 cm depth. A representative phylogeny of vascular plants was developed using rbcl and matk genes in a Bayesian framework (Chisholm and Becker with NI Pollard).

- Data collection on Herschel Island, Qikiqtaruk Territorial Park, Yukon coast, including permafrost cores using SIPRE core drills, ground ice sampling, vegetation, soil sampling, active layer surveys and peat cores for polygon genesis reconstruction, discharge measurements using cut-throat flumes at retrogressive thaw slump outlets, water sampling using water autosamplers, micrometeorology using mobile weather stations (Lantuit and students with NI Pollard).

Milestone 3: Science for sustainability in Arctic coastal communities

Inuvialuit Settlement Region

- Using photographic and anecdotal data on Mackenzie Delta and Beaufort Sea coastal ice conditions, combined with on-line water level data (courtesy of Environment Canada), MODIS imagery, and Radarsat-2 SAR imagery, a daily record of Mackenzie-Beaufort breakup was compiled again in 2013 and circulated to a mailing list of almost 300, with support from Natural Resources Canada, the Aurora Research Institute, and stakeholders in the Inuvialuit Settlement Region (Fraser and Whalen with NI Forbes).
- In partnership with Natural Resources Canada, Aboriginal Affairs and Northern Development Canada (BREA funding), the Inuvialuit Regional Corporation, and the Inuvialuit Land Administration, undertook a co-designed project to assess the risk of flooding and coastal erosion for subsistence infrastructure along the Beaufort Sea coast (NI Forbes with Whalen, Manson, Couture).
- Undertook study of coastal hazards at Simpson Point and Pauline Cove, Herschel Island (Qikiqtaruk Territorial Park) off the north coast of Yukon in the Beaufort Sea. This included historical aerial photographs, a DEM created from LiDAR and bathymetric surveys to assess historic shoreline movement and flood vulnerability (Lantuit with post-doctoral fellow Radosavljevic and NI Pollard).

Nunavut

- Analysis of Radarsat-2 synthetic aperture radar (SAR) imagery acquired from late winter and the breakup season for the Coppermine River delta at Kugluktuk NU confirmed that techniques to detect bottomfast ice in the outer Mackenzie Delta are transferable to smaller Arctic deltas and communities (Couture et al., 2014) (NI Forbes with Fraser and Manson).
- Results of reconnaissance studies and landscape instability in four communities of the Nunavut Climate Change Partnership were assembled and published in the Summary of Activities 2013 report of the Canada-Nunavut Geoscience Office (NIs Allard, Bell, Forbes, Smith).
- The study of coastal hazards and implications for planning policy in the City of Iqaluit was largely wrapped up with completion of an M.Sc. thesis (Hatcher, 2013). Further write-up of results and reporting back to the community are ongoing (NI Forbes with Hatcher and Manson).

Nunatsiavut sustainable communities partnership

- As part of the Nunatsiavut DISC (Digital Information for Sustainable Communities) project, research team conducted ground-penetrating radar and dGPS surveys, coastal shoreline classification, surficial sediment and surface drainage mapping and landscape hazard assessment in the communities of Hopedale and Postville (NI Bell with Hatcher, Riedlsperger, Belbin and Baikie).
- Used WorldView-2 satellite imagery pairs to construct digital elevation models, slope maps, watershed outlines and building footprints as base information for planning constraint mapping in each of the five Nunatsiavut communities.

Ground control points were established in communities prior to image acquisition. Mapped data are being incorporated into digital information layers to inform ongoing community planning process (NI Bell with Hatcher and Lee).

- Facilitated workshops with community members of Postville and Nain to identify valued spaces and places in their communities as part of the DISC project (NI Bell with Baikie and Riedlsperger). Coordinated with NI Furgal and students Knight and Kouril in complementary mapping workshop in Hopedale (link to Project 4.9).
- Co-investigators in an NRCan-funded review of climate hazard-related mapping and vulnerability assessments of the built environment in Canada's North to inform climate change adaptation (see Champelle et al. 2013; Ford et al. in press)(NI Bell and PhD student Riedlsperger)(link with Project 1.1 [Ford]). Project results were adapted to and specific recommendations made for future landscape hazard mapping in Nunatsiavut (see Riedlsperger et al. 2013).
- Conducted a review of available data for and relevance of climate scenarios for adaptation planning in the built environment of Nunatsiavut (NI Bell and Finnis; link to Project 4.6; see Bell et al. 2013).
- Former student Goldhar and NI Bell published her ArcticNet sponsored graduate research on water system vulnerabilities to climate change in Nunatsiavut (see Goldhar et al. 2013, in press). Former post-doctoral fellow Wolf published her ArcticNet sponsored research on community values and climate change adaptation in Labrador (see Wolf et al. 2013, in press).

Communications at national level

- Presented findings in northern radio and print media (CBC North and others) (NIs Bell and Forbes, Whalen).
- Contributed to IRIS regions 1 and 2 reports and workshops (NIs Bell, Forbes, Allard, Edinger, and others).
- Communicated findings at the Canadian Association of Geographers annual conference in St. John’s, NL, August 2013 (NIs Aitken, Bell, Edinger, Forbes and students).
- Presented results at ArcticNet Annual Scientific Meeting in Halifax, Nova Scotia, December 2013 (NIs Aitken, Allard, Bell, Edinger, Forbes and students).
- Presented in collaboration with the Inuvialuit Land Administration at the Inuvik Petroleum Show, June 2013 (NI Forbes with Whalen).
- Invited presentation at the Pan Territorial Permafrost Workshop in Yellowknife, November, 2013 (NIs Allard, Bell).

Communications at international level

- Shared results within the context of the LOICZ Arctic coasts initiative at the annual meeting of the LOICZ Scientific Steering Committee in Niteroi, Rio de Janeiro, Brazil, August 2013 (NI Forbes).
- Communicated results on community hazards and sustainability in Iqaluit as part of a C-Change session at the Caribbean Studies Association annual conference in Grenada, June 2013 (NI Forbes).
- Presented results at the American Geophysical Union Fall Meeting, San Francisco, December 2013 (NIs Atkinson, Pollard).
- Presentations at 8th International Conference on Geomorphology, Paris, and at European Geophysical Union General Assembly, Vienna (Collaborator Lantuit).

Results

Coastal geoscience and sea levels

The synthesis of coastal geoscience data along the Beaufort Sea coast undertaken as part of the BREA program was intended to identify major data gaps affecting capacity to assess the potential impacts of offshore oil and gas development in the region (Figure 4). Repeat shoreline surveys at numerous sites (18 in 2013) and historical shoreline vectors digitized from georectified aerial photography provide a rich data set on the spatial and temporal variability of coastal change over the past 50 years and more. Detailed studies have been undertaken at locations of cultural and archaeological significance, at sites identified as potentially important for support of offshore hydrocarbon development, and at seasonal and permanent settlements (Shingle Point on the Yukon coast and the Hamlet of Tuktoyaktuk east of the Mackenzie Delta in the NWT). Limited new surveys have been carried out as part of this project, addressing gaps identified early in the process. A student from Christian Albrechts University in Kiel, Germany, worked with NI Forbes and ArcticNet collaborators Manson and Couture on an analysis of coastal retreat on the western Yukon coast (area 1 in Figure 4) in Ivvavik National Park (Konopczak et al., in press). This study showed that the mean retreat rate was 1.2 ± 0.4 m/a (1951–2009) and was higher in the west than in the east, consistent with a general west-east decline in erosion rates on the North Slope from Alaska to the Yukon. In general, rates have decreased over time, contrary to expectation, but there is evidence for recent local acceleration at the international border (partially obscured site symbol at lefthand border of Figure 4).

Further east along the front of the Mackenzie Delta and adjacent coast, rates of shoreline retreat show high spatial variability, related to variable backshore morphology and elevation, ground ice content, lithology, regional exposure, inner-shelf bathymetry, and the complex breached thaw-lake morphology of the coast (Manson et al., 2005). Erosion rates for much of this coast (Solomon, 2005) have an overall mean rate 0.6 m/a (1972–2000) and again show a slight decline in rates over time. Mean retreat rates for various sectors of the coast ranged from 0.4 to 1.8 m/a, with local maximum rates ranging from 4.6 to 15.3 m/a (1972–2000) and up to 22.5 m/a on the outer islands (1985–2000). Work is currently underway to update this analysis to 2010. A recent synthesis of the transgressive process (sea-level rise and coastal retreat) in the Beaufort Sea and on a comparable mid-latitude cold-temperate coast (the North Shore of Prince Edward Island in the southern Gulf of St. Lawrence) revealed distinct differences related to the presence of excess ground ice in coastal sediments, the relative severity of sea-ice scour on the inner shelf, and the restricted wave fetch and energy along the Beaufort coast (Forbes et al., 2014b). Shoreline vectors for Tuktoyaktuk show long-term shore retreat along the western side of the hamlet (slowed by shore protection efforts with varying degrees of success over the years), dramatic trimming of Tuktoyaktuk Island protecting the mouth of the harbour, and rapid overstepping of thin sand and gravel beaches along the outer shore of the Pingo Canadian Landmark (Parks Canada) southwest of the community (Figure 5).

Small-boat multibeam, sidescan sonar, and shallow seismic surveys along the southeast coast of Herschel

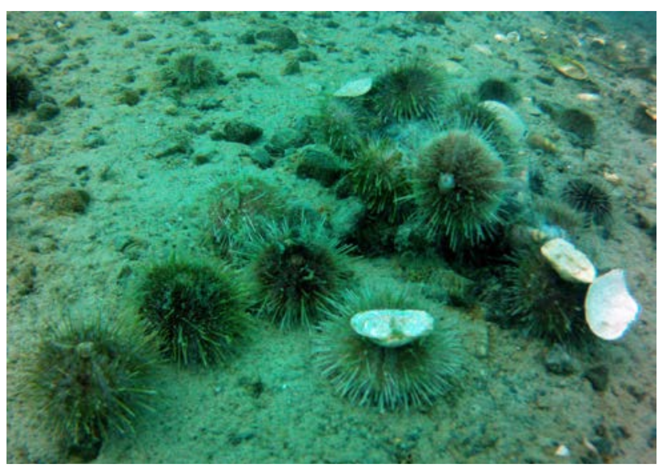

Figure 5. A seabed image acquired by the drift camera deployed from the boat in Figure 1 showing abundant sea urchins (Strongylocentrotus sp.) on a heterogeneous substrate along the southern shore of Broughton Island.

Island (Figure 6) provided detailed characterization of the inner shelf in this area, which is protected from the most severe storms from the northwest (Radosavljevic et al., 2013b). Sediments derived from retrogressive thaw flow failures, shoreline erosion, and the Mackenzie River plume can accumulate at shallower nearshore depths than on the more exposed northern coasts of the island.

The Mackenzie Delta front (area 3 in Figure 4) has some of the highest erosion rates and is retreating overall through a combination of delta-front erosion

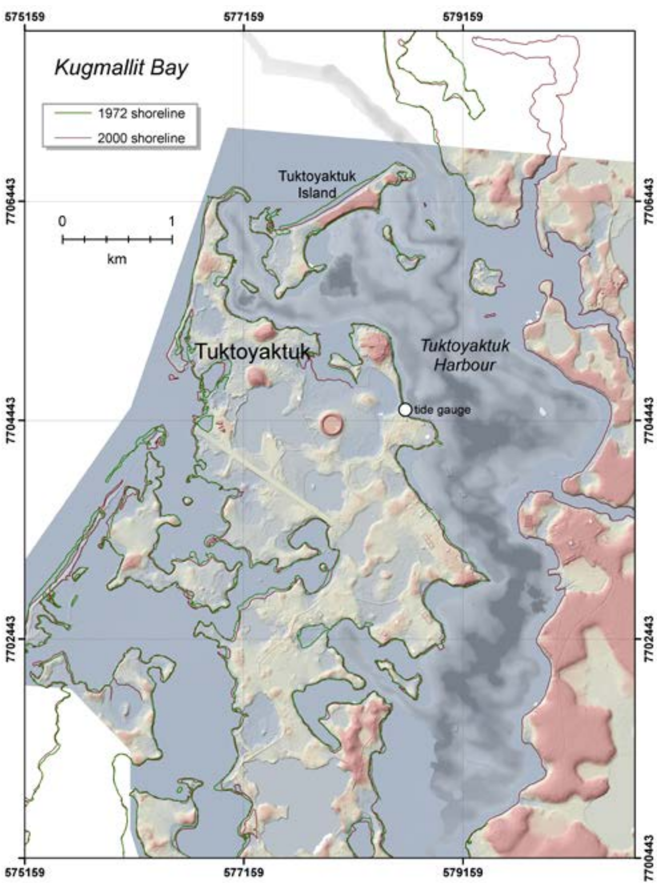

Figure 6. Colour-shaded relief topography (pink shades high), grey-scale multibeam bathymetry (in harbour), and sidescan sonar mosaic (seabed outside harbour) at Tuktoyaktuk, NWT (modified after Forbes et al., 2014b). Note 1972 and 2000 vector shorelines, showing rapid erosion along the outside of Tuktoyaktuk Island, extension of southwestern spit, and rapid overstepping along the coast to the southwest.

and subsidence combined with sea-level rise, resulting in gradual inundation on parts of the outer delta (Forbes et al., 2012). Additional data acquired in 2013 have updated measurements of deep subsidence obtained from GPS observations on fixed monuments and revealed rapid sedimentation (up to 64 mm/a) on levees but negligible elsewhere (marker horizons exposed after 3 years) and evidence for additional shallow subsidence of at least 10 mm/a assumed to result from active-layer deepening and loss of excess ice in the zone of deeper thaw (Morse et al., 2009). These results point to more severe projections of land loss in the outer delta, with negative consequences for conservation of critical waterfowl nesting habitat in the Kendall Island Bird Sanctuary.

Seabed mapping for sea-level lowstand indicators

Multibeam mapping using the GN vessel MV Nuliajuk was again very successful in 2013. The search for submerged shorelines and other lowstand sea-level indicators around the outer Cumberland Peninsula was extended into a number of fiords and inlets, which had

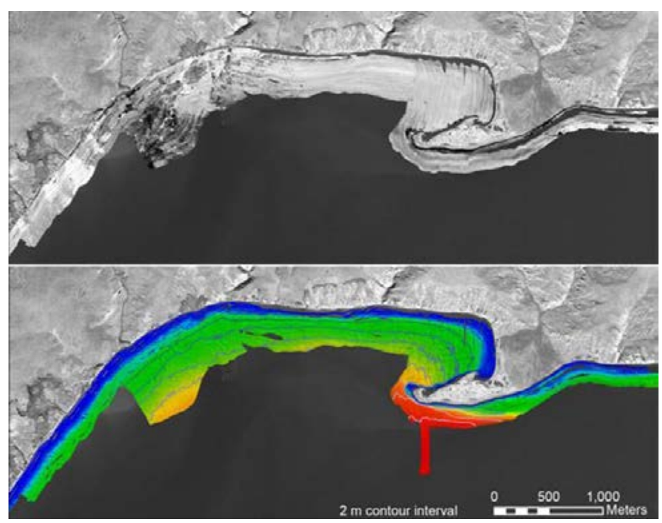

Figure 7. Bathymetry and sidescan backscatter image of Pauline Cove and Tethis Bay, Herschel Island, YT, acquired from small boat using interferometric sidescan sonar with real-time kinematic GPS positioning; onshore topography is grey-scale shaded-relief LiDAR image (Radosavljevic et al., 2013a, b).

to be bypassed with the time available in 2012 and a number of new features were discovered (Figure 2). New sites include a side-entry delta at -18 m in Kangert Fiord (Figure 7), another in the outer part of Clephane Fiord at about -45 m, and a complex sill terrace at about -50 m in the mouth of Akpait Fiord (Figure 8). This may be a wave-trimmed terrace on the fiord sill, suggesting a sea level no lower than about -47 m, but this is nonetheless another 4 m deeper than the deepest feature (-43 m) discovered in 2012 (Figure 2). However, a small side-entry feature in the inner part of Akpait Fiord appears to be a delta at -50 m, suggesting the possibility that sea level dropped

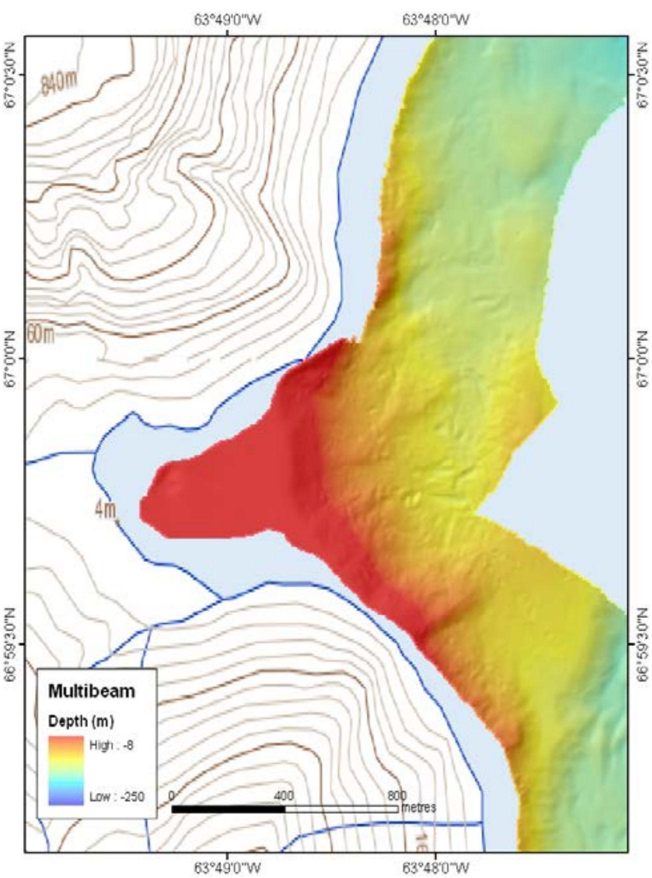

Figure 8. Colour shaded-relief bathymetry of submerged side-entry delta terrace at -18 m in Kangert Fiord, Cumberland Peninsula, south of Qikiqtarjuarq, NU (see Figure 2 for location), acquired using the EM3002 multibeam sounder on MV Nuliajuk, with assistance of UNB Ocean Mapping Group (project 2.6).

even lower, allowing the sill to impound a lake at this depth. These results are all very new and the depths and interpretation presented should be considered preliminary.

Sea-level change and vertical motion

During fieldwork west of Hudson Bay in the summers of 2009, 2010 and 2012, measurements of relative sea level position were collected, and GPS site ARVI was established and reoccupied near Arviat. Simon et al. (submitted) demonstrate that several of these new observations of relative sea-level change provide tight constraint on the late Holocene sea level history (from ~5000 cal yr BP onward). In addition, repeat GPS occupations at site ARVI yield a preliminary vertical land uplift rate of 9+ mm/yr, and thus provide an additional new observation that will help to constrain ongoing GIA in the region. The improved sea level curve for Arviat is compared to a GIA model

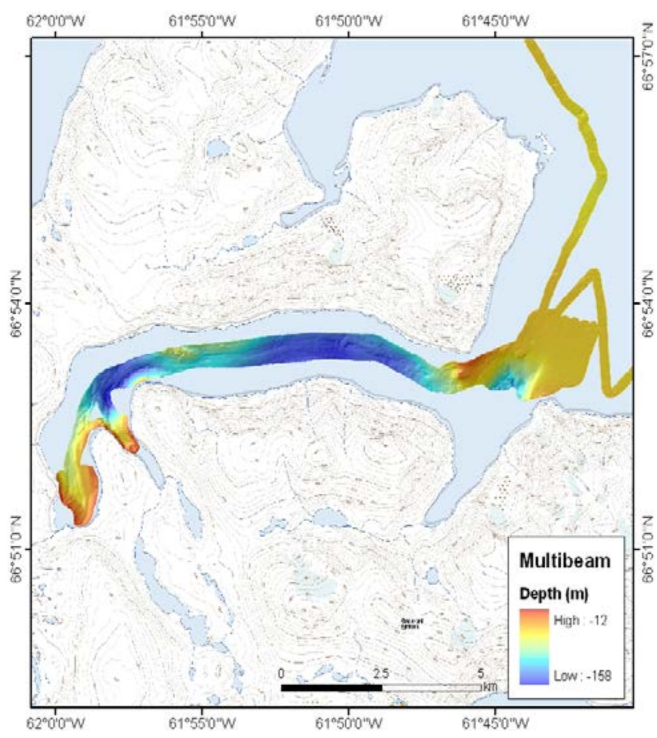

Figure 9. Colour shaded-relief bathymetry of -50 m terrace on sill of Akpait Fiord and small delta at same level in side entry valley near the head of the fiord (see Figure 2 for location). Data acquired as for Figure 8.

that examines ice sheet thickness variations to the frequently used ICE-5G ice sheet reconstruction of Peltier (2004). The modelling results suggest that the peak thickness of the central region of the Laurentide Ice Sheet was ~3.4 km, which represents a 30-35% ice thickness reduction west of Hudson Bay relative to the original ICE-5G model (Figure 9). An improved estimate of vertical motion at Arviat helps to constrain projections of local sea-level rise, which is likely to remain negative this century (James et al., 2011; Forbes et al., 2014a).

Sea ice, storms (waves and surges), and other weather

Processes of seabed scour and onshore ride-up and pile-up were evaluated and compared in the coastal zone of the Beaufort Sea (Forbes et al., 2014b) and in Baydaratskaya Bay in the southern Kara Sea (Ogorodov et al., 2013). There is evidence for limited landward transport of sediment by ice in both regions and for maximum scour depths and frequency in the 'stamukhi' zone along the margins of the landfast ice. Maximum scour depth in the Beaufort is 5 m but scour penetration in depths shallower than 10 m is 1.6 m or less; depth of scouring increases seaward out to a maximum at 30 m depth (Blasco et al., 2013). In the more restricted waters of Baydaratskaya Bay, the maximum scour penetration is <0.2 m in depths less than 12 m and scour depth increases to a maximum of about 1.5 m in 19 m water depth (Ogorodov et al., 2013). Maximum scour density in the Beaufort is in depths of 7–14 m; in Baydaratskaya Bay, it peaks in 15–19 m. Onshore ice push can threaten coastal infrastructure in both regions, but the prevalence of such events is poorly documented.

Work undertaken under the direction of NI Atkinson included modelling of storm frequency and assessment of the frequency of reduced visibility (primarily due to fog) in coastal communities. One of Atkinson's students, Khalilian, produced a 20-page overview document: A Review of Numerical/Statistical Models to Predict Fog and Low Visibility Events: the Climatological Approach. Another University of Victoria student, Shippee, has made significant progress in modelling storm frequency in the Gulf of Alaska (Shippee et al., 2013). This work will be incorporated into ArcticNet regions of interest after the method has been perfected for the Alaska region.

Benthic habitat mapping

Preliminary results from the 2013 field campaign on eastern Baffin Island reveal several distinct benthic habitats within the Broughton Harbour and southern Broughton Island study areas. At depths of 10−55 m, the seabed is characterized by heterogeneous substrates consisting of various proportions of sand, gravel, boulders and shell hash; the coarser clasts support an abundance of rockweed (*Fucus sp.*) and kelp (*Laminaria sp.*, *Agarum sp.*). Brittlestars, shrimp, fish (eelpout, sculpin), bivalves (Mya truncata) and whelks (*Buccinum sp.*) occur commonly on these substrates. Broughton Harbour habitats are distinguished by the presence of crinoids (*Heliometra sp.*), sea anemones and coralline algae, while southern Broughton Island habitats are distinguished by the abundance of sea urchins (*Strongylocentrotus sp.*) (Figure 10).

Studies of coralline algae in Arctic Bay (northern Baffin) and northern Labrador showed that because growth of these algae is light dependent, their growth rates are inversely related to sea ice cover. Arctic Bay coralline algae included several skeletons with up to 600 years of growth recorded, but unfortunately, the high-Mg calcite in many of these samples was too recrystallized to use for geochemical analyses. The best preserved colony from Arctic Bay had a growth record more than 200 years long. The combined growth and Mg/Ca ratio in the skeleton showed a strong inverse correlation with regional sea ice coverage as far back as observations were available. The rapid decline in sea ice in the past 150 years is unprecedented during the >600 year record of the algae from Arctic Bay and northern Labrador analyzed in this study (Halfar et al., 2013).

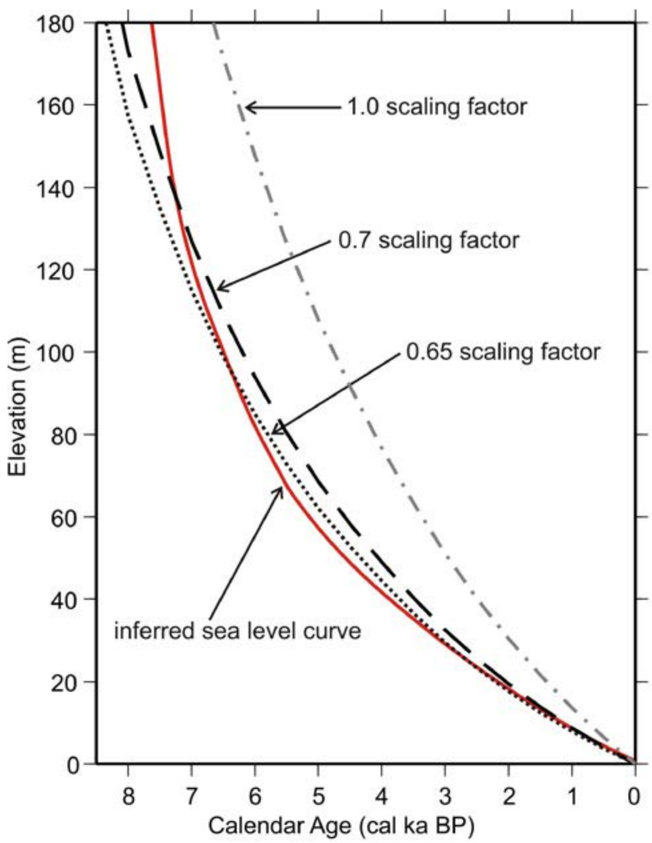

Figure 10. Model-predicted relative sea-level change at Arviat for ice sheet thickness scaling factors of 1, 0.7 ad 0.65, applied to ICE-5G. The reference model has the load thickness scaled by a 1.0 scaling factor (grey dash-dot line) and overpredicts the sea level curve inferred from the data (solid red line). GIA models with the ice sheet thickness scaled down uniformly west of Hudson Bay by scaling factors of 0.65 (black dotted line) and 0.7 (black dashed line) better fit the observations. The best-fit GIA model corresponds to a peak Laurentide Ice Sheet thickness of approximately 3.4 km west of Hudson Bay.

Coastal landscapes and terrestrial habitat

Volumetric erosion was highly variable over an 8-year period (2004-2012) for three retrogressive thaw slumps on Herschel Island, YT. The range of headwall retreat rates 5–18 m/a (Simpson, 2013). An estimated 13.4 million kg of soil organic carbon (SOC) has flowed into the Arctic Ocean from these three slumps over an eight-year period. A 3-dimensional model was developed to recreate the land surface 350 years ago before slump activity began on Herschel Island.

Science for sustainable Arctic communities

Inuvialuit Settlement Region

The vulnerability of the historic settlement at Simpson Point (Pauline Cove) onHerschel Island (Figure 7), was assessed through flood simulation on a LiDAR digital elevation model (DEM) by ArcticNet collaborator Hugues Lantuit and students from the Alfred Wegener Institute. The surface elevations on this spit deposit are generally less than 2 m. The analysis determined that local relative sea level is rising and storm-surge flooding of the historic structures is occurring more frequently. Raising these buildings and moving them back from the shore may be required, but preservation of the historic character of the site may be challenging. Combined with coastal realignment, the long-term stability of the spit on which the settlement is located is unclear (Radosavljevic et al., 2013a).

In collaboration with the Inuvialuit Land Administration (ILA), we have undertaken an analysis of the vulnerability to erosion and storm-surge flooding of subsistence infrastructure belonging to beneficiaries of the Inuvialuit Final Agreement (Forbes et al., 2013). These structures, most of which are located away from permanent settlements, are nevertheless integral to community well-being because they provide the means to maintain cultural traditions and provide country food, which represents an important component of food security. Using high-resolution satellite imagery, the locations of structures have been mapped and combined in a geographic information system with place-based traditional knowledge held by the ILA (Figure 11). Erosion and flooding risk were assessed by superimposing historical shoreline vectors to measure past rates of shoreline recession (e.g. Figure 5) and by flood simulation on a LiDAR DEM where that was available (in the vicinity of Tuktoyaktuk). The elevations of the highest driftwood, related to past major flood events in 1944, 1963, 1970, and 2000 were determined in the area of the DEM and assumed to be similar for driftwood deposits mapped in the satellite imagery along the nearby coast. In this way,

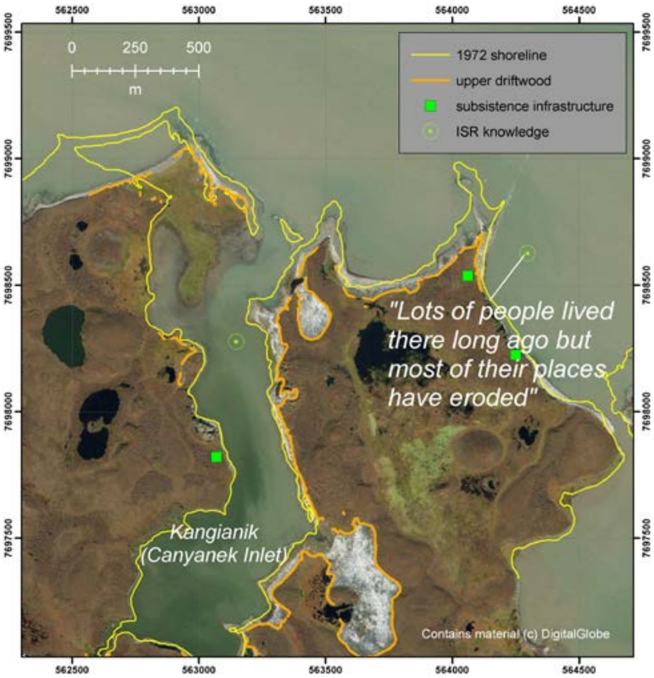

Figure 11. Subsistence infrastructure at Kangianik (Canyanek Inlet), south coast of Kugmallit Bay in the southern Beaufort Sea (see Figure 4 for location); shows 1972 shoreline vector superimposed on 2010 satellite image; also extreme water levels, as indicated by upper limits of driftwood; and example of georeferenced traditional knowledge from ILA records (source: Forbes et al., 2013).

the infrastructure close to or below past flood limits and sites vulnerable to shoreine retreat at historic rates could be identified. Traditional knowledge provided information on sites where subsistence infrastructure or archaeological sites had been lost in the past (Figure 11). These results are being compiled in pamphlet form, the locally preferred method of disseminating the information, for distribution in the community.

Nunavut

The project undertaken in partnership with C-Change and Natural Resources Canada on coastal hazards to development in the City of Iqaluit was successfully completed (Hatcher, 2013) and the results are being readied for publication. Storm-surge flooding was found to be of minor importance, but impacts from sea ice, waves, and extreme tides were recognized as concerns. Slow rates of ongoing crustal uplift and suppressed sea level rise related to fingerprinting from the Greenland Ice Sheet result in projections of limited sea level rise over coming decades at this location, except in the event of significant ice loss from Antarctica. Surveyed elevations of various types of infrastructure along the Iqaluit waterfront showed that the most critical municipal facilities such as pumping stations, sewage lagoon dam, and the museum are above the limits of historical flooding and wave runup, but roads and parts of the cemetery are vulnerable to flooding (Figure 12). On the other hand, subsistence infrastructure along the waterfront is highly exposed and vulnerable to flooding, wave impacts, and potentially ice, although the formation of a wide icefoot in winter usually prevents ice damage (Figure 13).

Results of rapid reconnaissance surveys in five communities of the Nunavut Climate Change Partnership were published this year (Allard et al., 2014; Forbes et al., 2014a; Smith, 2014; Smith and Forbes, 2014). These examined landscape hazards and potential impacts of climate change in Whale Cove and Arviat (Kivalliq) and Kugluktuk and Cambridge Bay (Kitikmeot). Undertaken to provide a scientific foundation for climate-change adaptation planning where little information was available, these provided a preliminary overview of constraints to development and natural hazards in the context of a warming climate. Communities such as Whale Cove and Cambridge Bay, located on gravel-rich deposits or with bedrock at shallow depth, appeared to have a lower prevalence and risk of foundation instability than Arviat and Kugluktuk, where ice-rich soils cover larger areas and may constrain development. Poor drainage resulting in standing water was noted as an issue in three of the four communities and erosion associated with heavy rainfall was a recognized hazard in two communities. In the communities located along the west coast of Hudson Bay, falling rather than rising sea level is the expected trend for the foreseeable future. The implications for sea-lift shipments of progressively shallower depths in the harbour approaches have not been assessed and require

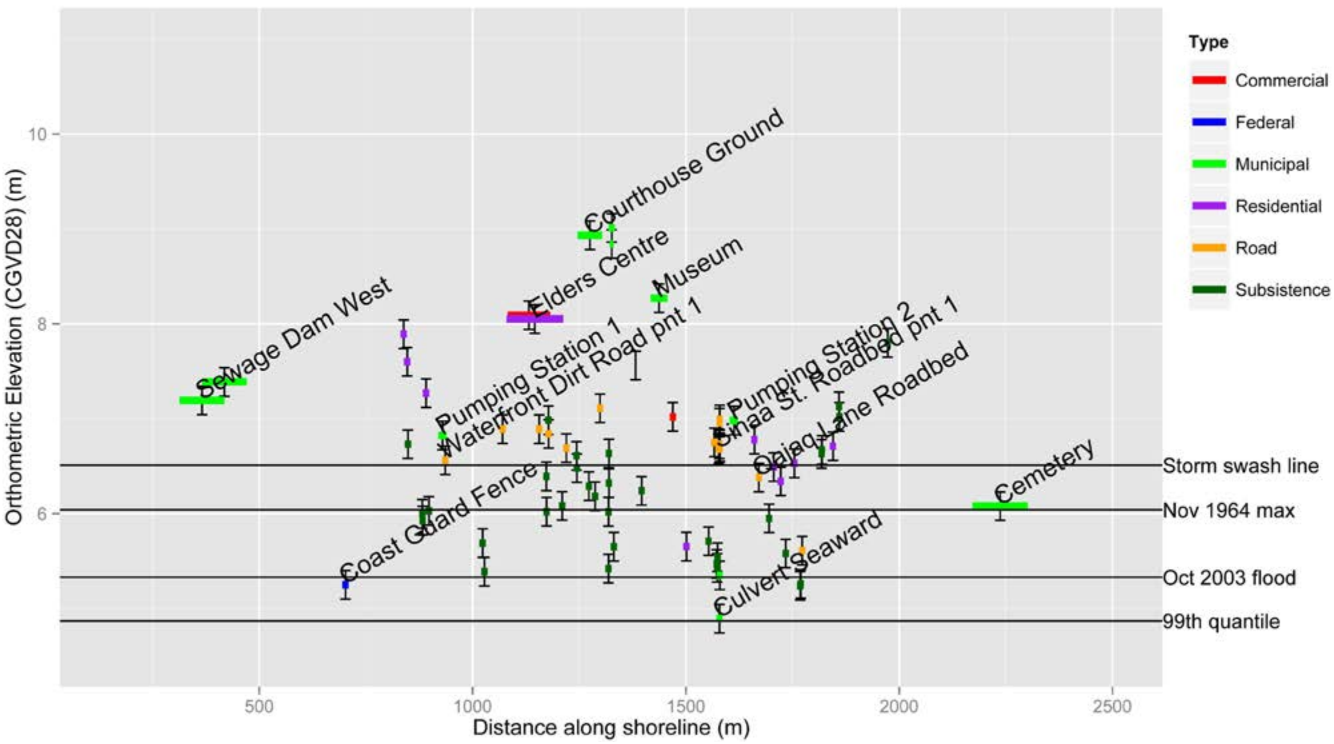

Figure 12. Elevations of infrastructure along the waterfront in Iqaluit, NU, surveyed using real-time kinematic GPS tied to geodetic monuments and tidal benchmark. Most municipal infrastructure (green), commercial property (red), and most roads lie above the highest recorded water level (November 1964) and above the highest storm swash line. A few residences and most subsistence infrastructure lie below the upper limit of storm runup and a substantial number are below the November 1964 flood level (source: Hatcher, 2013).

Figure 13. Subsistence infrastructure along the beach in Iqaluit during freeze-up in November 2011; developing icefoot protects the infrastructure from small ice pile-up at its outer edge; high spring tide has flooded the icefoot and reached almost to the base of several sheds; note larger institutional and commercial buildings in background (photo credit: Scott Hatcher).

consideration. Minor local coastal erosion was noted in a few locations, but appeared to be significant only on parts of the Kugluktuk waterfront, notably close to the harbour; elsewhere in Coronation Gulf, Bathurst Inlet, Dease Strait, and Cambridge Bay, coastal erosion is minimal (James et al., 2013; Couture et al., 2014). These results have provided an initial basis for adaptation planning and a starting point for more comprehensive hazard mapping in support of GN (Community and Government Services) planning and community needs.

Nunatsiavut

Our Digital Information System for Communities (DISC) project addresses the issue of building land in communities through the production of planning constraint maps that identify available, suitable areas for development across a range of land uses and under current and projected future climate states. These maps combine existing community information with Inuit Knowledge and new geoscientific data in a georeferenced information database to support community infrastructure planning and development decisions. Each community database compiles for the first time digital information on community infrastructure and resources, landscape characteristics and hazards, regulated land areas, protected and valued spaces and places, climate scenarios and environmental modeling. To aid in landscape and community visualization (e.g., shaded relief, variable solar illumination), terrain imagery is draped over a digital elevation model created from satellite image pairs and combined with selected information layers (Figure 14). The DISC project also provides each Nunatsiavut Inuit Community Government (ICG) with the infrastructure and training to access and update their digital database. The applicability of, and engagement with, the DISC database will be assessed during community planning revisions in Hopedale in 2013-2014, and appropriate modifications made for planning updates in the other four Nunatsiavut communities by 2015.

Climate change projections were reviewed for their applicability to regional and local scale climate change adaptation planning for the built environment in Nunatsiavut (Bell et al. 2013). While four studies were initially reviewed, two met the study criteria and were thus selected for analysis. One study was conducted by Ouranos as part of the Nunavik-Nunatsiavut ArcticNet IRIS report, published in 2012. The other study by Finnis employed Regional Climate Models nested within GCMs. Where climate variables generated by the two studies overlap, there is broad agreement in projections. Projections from both studies identify average winter temperature increases for Nunatsiavut of 3-4°C by 2050. These winter air temperature changes will drive changes in thawing degree-days (projected to increase by 25-50%), frost season duration (reductions up to 19 days per year), continuous snow cover (reduction of three weeks per year) and summer season (identified to increase duration by three-weeks per year). Projected trends in precipitation suggest an increase of up to 10-15%, with a larger fraction falling as rainfall, a resulting reduction in mean annual snowpack of up to 15%, and an increase in intensity of extreme rainfall events, particularly in spring and summer. While the trends provided by these studies are useful tools in regional-scale adaptation planning, finer resolution projections would be even more valuable for the development of community-scale climate change adaptation plans and strategies.

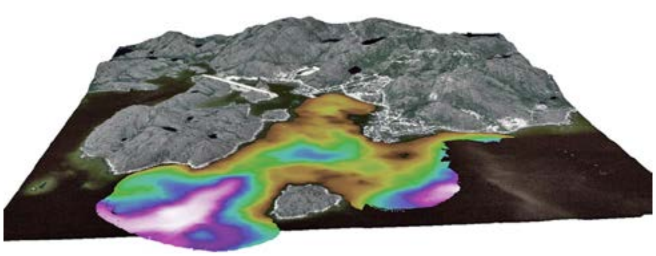

Figure 14. Oblique view of Hopedale in Nunatsiavut (NL), showing local topography, infrastructure and bathymetry, using WorldView satellite imagery draped over a digital elevation model.

Discussion

In last year's report, we reviewed progress against some of the key information gaps identified in the State of the Arctic Coast 2010 report (www.arcticcoasts.org). The workplan for this year was similarly linked to some of the key issues identified in that report, as follows:

- More robust projections of sea-level rise for residents and decision makers (Milestone 1 – NI James) and related activities to bolster understanding of vertical motion (Milestone 2 – NIs James, Forbes, Bell).
- Limited understanding of the impacts of a changing sea-ice regime and wave climate on coastal stability (Milestone 1 – NIs Atkinson, Pollard, Bell, Forbes).

- More detailed investigation of Arctic storms and how they might change in the future (Milestone 1 – NI Atkinson and student).
- Circumpolar systematic coastal observing and change detection (Milestones 1 and 3 – NIs Forbes, Bell, Atkinson and collaborators Nymand Larsen, Couture, Overduin).
- New integrated monitoring approaches to document the nature of environmental change and human interactions (Milestones 2 and 3 – NIs Aitken, Bell, Edinger, Atkinson, Forbes.
- Adaptive management in the face of change, building adaptive capacity in northern communities and regional governments, and recognition that change to both human and physical systems in the Arctic has become the norm (Milestone 3 – NIs Bell, Forbes, Atkinson).

Milestone 1: Coastal hazards and change – forcing and response

Prior to this study, there were only 8 observations of relative sea-level change for the Arviat region, and the regional sea-level curve was restricted to the early Holocene (Dyke and Dredge 1989). Simon et al. (in revision) present 28 new radiocarbon ages that record relative sea-level change in the region. Several of the new sea-level measurements are interpreted to originate from nearshore environments, and place tight constraint on the late Holocene sea-level history. These new sea-level data are best fit by a GIA model that features a 30-35% reduction in the maximum ice thickness west of Hudson Bay relative to ICE-5G. These results use a Holocene sea-level dataset to support similar conclusions obtained from present-day rates of gravity change and vertical land motion that also indicate the need for a thinner central Laurentide Ice Sheet reconstruction (Lambert et al., 2006; Argus and Peltier, 2010). Ongoing GIA modelling work is currently using a combination of relative sea-level data and GPS measurements to constrain the ice sheet history of the Ungava Peninsula in the Nunavik region of northern Quebec.

The vertical land motion rate of 9+ mm/yr obtained at Arviat is in accordance with the large rate of postglacial isostatic uplift expected in the central region of the former Laurentide Ice Sheet. This preliminary uplift rate, and ongoing collection of campaign data at site ARVI, will help to supplement sparse continuous GPS coverage in the Kivalliq region. Community-specific rates of present-day vertical land motion measured by GPS are a critical component in the estimation of rates of future sea-level change in the North (e.g. James et al., 2011). Work is currently underway in connection with the NRCan-led assessment of climate change impacts and adaptation on Canada’s marine coasts, to produce updated projections of sea-level change for the 2010-2100 interval at a large number of sites throughout the Canadian Arctic. These will incorporate the fingerprinting associated with ice-melt sources of water to the ocean (a very signifiicant effect in the Canadian North) and projections from the latest report of the Intergovernmental Panel on Climate Change (5th Assessment Report) based on the new Representative Concentration Pathway (RCP) scenarios. Remaining uncertainty about the potential for ice loss from the West Antarctic Ice Sheet, the effect of which would be amplified in northern Canada, results in an ongoing wide envelope of potential sea-level change and, with the exception of northern Ellesmere Island, the possibility (albeit unlikely) of a reversal in the trend from falling to rising sea levels even in communities with the most rapid uplift (report in preparation).

In work initiated this year on conditions leading to limited visibility in Arctic coastal communities, it has become clear that the quality of data on atmospheric visibility in the Canadian North is limited. Work on this topic will have to focus on specific stations possessing sufficient data. In general, there is strong local and non-dynamic process control on fog occurrence. This suggests avoiding numerical modelling approaches and moving directly to computerizing forecaster "rules of thumb" based on physical principles and empirical analyses. In the work focused on storm conditions, it has emerged that results based on linear methods linking storm activity to climate forcing modes show greater seasonal predicitive skill if multiple climatic prediction modes and smaller sub-domains are specified (Shippee et al., 2013).

Milestone 2: Landscape and seabed mapping – hazards and change detection

The organisms most commonly recovered in grab and dredge samples from the seabed off Qikiqtarjuaq included brittlestars (*ophiuroid echinoderms*), sea urchins (*echinoid echinoderms*; *Strongylocentrotus sp.*), feather stars (*crinoid echinoderms*; *Heliometra sp.*), sea anemones (*actinian anemones*), and coralline algae (e.g. *Clathomorphum sp.*). The completion of the taxonomic identification of benthic organisms recovered in grab and dredge samples and/or recorded from drift camera imagery will facilitate the analysis of benthic community structure and its relation to mollusc abundance, seabed physical characteristics (sediment texture, organic carbon content, seabed topography), and water depth. The methodology employed in this study was also applied to the study of nearshore macrobenthos in the vicinity of the communities of Sach's Harbour, NWT, and Gjoa Haven, NU (Brown et al., 2011) and Arctic Bay, NU (Edinger et al., 2013). A comparison of benthic habitat structure at these four locations will be undertaken to better comprehend the physical environmental factors that influence nearshore benthic community structure across the Canadian Arctic Archipelago.

Within this project, the primary objective of the multibeam surveys with the GN vessel MV Nuliajuk was to identify lowstand shoreline indicators and thus contribute to improved understanding and projections of vertical motion and sea-level change. At the same time, the data acquired are valuable for a number of other reasons. Many of the embayments surveyed were previously uncharted, so this work contributes significantly to improved knowledge of the Canadian landmass and coastal waters (thus contributing to Project 2.6). In addition, the surveys support the ongoing interest of GN in the potential for a commercial clam fishery in the region. Finally, the multibeam imagery of the seafloor shows many examples of submarine slope failure. With a growing appreciation of the seismic risk in this region, there is emerging interest in the sedimentary archive of past earthquakes, which may be decipherable in some of the inlets we have explored.

Surface displacement in permafrost soils is a major hazard for the stability of foundations for homes and other buildings, and therefore highly relevant to this project. Detailed studies of ground thermal conditions and associated vegetation have been undertaken at a number of sites. Much effort has also been devoted to the study of retrogressive thaw flow (RTF) failures, particularly on Herschel Island with partners from the Alfred Wegener Institute. With over 13.4 million kg of soil organic carbon flowing into the Arctic Ocean from three large RTF features over an eight-year period, these processes are shown to be large contributors to the Arctic marine carbon budget. Rising concentrations of carbon within the Arctic Ocean can have various effects, including the reduction of sea-ice extent creating a positive feedback and further increase in coastal erosional processes, and a destabilizing of the local and global ecosystems (Barber et al., 2008).

Saline permafrost on Herschel Island and in the Eureka area (Ellesmere Island) indicates a marine origin for the sediments and the importance of sea level and glacial history in the analysis of coastal permafrost. This is recognized as an issue for foundation stability in numerous communities across the Canadian Arctic (Forbes et al., 2014a). Many communities in Nunavut and Nunavik are located on surfaces that have emerged from the sea as a result of postgacial isostatic uplift and therefore may have high soil salinity, which depresses the freezing point and reduces the strength of ice-bonding.

Milestone 3: Safe and sustainable communities

This has always been the primary focus of the project and the most compelling reason for investing in the study of landscape and shore-zone hazards on Arctic coasts. The project has made significant contributions to this issue across the north from the Yukon coast and the Beaufort Sea to various parts of Nunavut and communities in northern Labrador (Nunatsiavut). In the Yukon, where there are no permanent settlements on the North Slope, the project has addressed the vulnerability of archeaological sites in Ivvavik National Park, of the historic trading centre at Pauline Cove on Herschel Island, erosion of contaminated soils associated with military sites, and coastal hazards for the seasonal fishing and whaling settlement at Shingle Point. A major focus of recent and ongoing work is the community and port of Tuktoyaktuk, where construction of a new all-weather road and offshore oil and gas development may bring unprecedented change in the coming few years. In Nunavut, the project has provided greater certainty on the nature and severity of coastal hazards in the City of Iqaluit and has compiled preliminary results from rapid reconnaissance surveys in a number of communities in two regions of the territory. Similar work in Nunatsiavut is informing government policy and adaption initiatives which aim to make a real difference in the quality of life for northern residents.

We have built collaborative relationships with northern residents and organizations to further the relevance and applicability of the science undertaken in this project. These include our work with the Inuvialuit Land Administration in the Inuvialuit Settlement Region, a partnership with the Government of Nunavut for detailed landscape hazard studies in key communities, and a strong collaboration with the Nunatsiavut Government in Labrador. Work over the past year has sought to link these initiatives into a larger whole and to explore opportunities for international collaboration on these issues. A recent proposal from members of this project team and partners to initiate a circum-Arctic network of integrated coastal community observatories has received seed funding from both LOICZ (Land-Ocean Interactions in the Coastal Zone) and IASC (International Arctic Science Committee). This initiative will be a primary focus of work in the project over the coming transition year.

Conclusion

The project continues to have significant impact in jurisdictions across the Arctic and internationally. In several key regions, it is closely connected to decision makers and is making a difference in the planning process. Being part of the winning team for the Arctic Inspiration Prize, which recognized innovation in the development of sustainable housing for Nunatsiavut, was a signal achievement and an acknowledgement of the impact the project has had.

The project has also enabled new insight on a number of relevant issues.

- It has led to new discoveries in previously uncharted waters, demonstrating that post-glacial sea levels were lower than previously suspected off the east coast of Baffin Island.
- It has provided new knowledge on rates of vertical motion and sea-level change at many sites across the north, providing the basis for new and more robust projections of future sea levels based on the latest IPCC report.
- It has yielded new understanding of the potential for important habitat loss on the outer Mackenzie Delta, the second largest delta on the Arctic Ocean.
- It has promoted the exchange of knowledge on coastal ice processes between Northern Canada and the Russian Arctic.
- It has build new partnerships that allow for the merging of quantitative geomatics data and traditional knowledge to support decisions on where subsistence infrastructure required for food security can be safely located to avoid the risk of storm-surge flooding and coastal erosion.

These are just a selection of the project's achievements over the past year. Others are highlighted in the Key Messages.

Priorities over the coming transition year will be focused on building relationships to support enhanced adaptive capacity in Arctic coastal communities. One promising initiative we will be exploring in partnership with IASC, LOICZ, and a number of international colleagues and community representatives is the concept of networked communities capturing and exchanging knowledge on physical, ecological, and socio-cultural change – an Arctic Coastal Communities Observatory Network. Our expectation is that better and more integrated awareness of change that is widely shared within and between communities is an important foundation for building resilience in the face of accelerating social and environmental challenges.

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