CHAPTER 5: PERSPECTIVES ON CANADA'S NORTH COAST REGION

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KEY FINDINGS

The environment and socio-economic characteristics of the northern coast are unique. Inhabited primarily by Indigenous populations living in small remote communities, Canada's northern coastline is vast, representing more than 70% of all Canadian coasts. The presence of sea ice is a defining feature of this coast, affecting transportation access, shaping geomorphological processes and providing a platform for culturally valued and economically important harvesting activities. Social, economic and demographic characteristics of northern coastal communities differ considerably from the Canadian average, with resource development and public administration being mainstays of northern economies.

The northern coast is a hotspot for global climate change. The region has experienced some of the most rapid climate change anywhere on the globe, and projected future climate changes for the northern coastline will continue to be significant. Impacts on the physical environment include declining sea-ice concentration, earlier ice break-up and later freeze-up, a lengthening of the ice-free open-water season, permafrost warming and thaw, coastal erosion, sea-level rise and changing weather patterns, including wind and waves.

Northern coastal communities, ecosystems and economic activities are being affected by climate change impacts. Many communities have a high sensitivity to climate change impacts, as they are situated on low-lying coasts and have infrastructure built on permafrost, economies strongly linked to natural resources and dependence on land-based harvesting activities. Negative impacts of climate change on a variety of sectors have been widely documented across the northern coast. New opportunities associated with a longer ice-free shipping season are also recognized, but increased marine traffic also brings risks.

Climate change will exacerbate existing vulnerabilities. Vulnerability differs significantly by region and community and, within communities, as a function of geographic location, nature of climate change impacts and human factors. Capacity to manage climate change is high in some sectors, such as subsistence harvesting and health, but is being undermined by long-term societal changes. In other sectors, such as infrastructure, limitations in climate risk-management capacity (e.g., institutional, financial, regulatory) result in continuing high vulnerabilities.

Northern coastal communities and industries are adapting. Adaptation actions are already taking place in the North, with examples of adaptation planning documented across all levels of government. The effectiveness and sufficiency of the existing responses have not been evaluated, although barriers to adaptation, including limited resources, institutional capacity and a lack of 'usable' research, have been identified. Publicly available information on how the private sector is approaching adaptation is limited.

Opportunities for additional adaptation are diverse. Mainstreaming adaptation into ongoing policy initiatives and priorities to address underlying socio-cultural determinants of vulnerability can help address the risks posed by climate change to harvesting activities, culture and health. Adaptation actions targeted at specific climatic risks are also required, particularly to manage the impacts of climate change on community and industrial infrastructure.

1 INTRODUCTION

Canada's northern coasts are experiencing dramatic changes in climate. Climate models project that they will experience some of the most pronounced climate changes of any region in the world (*see* Chapter 2; Anisimov et al., 2007; Prowse and Furgal, 2009; Larsen et al., 2014). Changes in temperature and precipitation trends, sea-ice conditions and shifts in seasonality are widely documented, as are implications for traditional lifestyles, health, sovereignty, security, resource development and infrastructure (Furgal and Prowse, 2008; Prowse and Furgal, 2009; Ford et al., 2012b).

A rapid increase in research focusing on the biophysical and human dimensions of climate change on northern coasts has taken place during the last decade, and a number of assessments, literature reviews and gap analyses have been conducted to examine current understanding. These reports can be grouped as follows:

- **Arctic-wide assessments:** These reviews focus on the Arctic as a whole, with information on northern Canadian coasts contained within specific chapters. They include the *Arctic Climate Impact Assessment* (Arctic Climate Impact Assessment, 2005), reports from the International Polar Year (Kulkarni et al., 2012), the 'Polar Regions' chapter of the Intergovernmental Panel on Climate Change assessment reports (Anisimov et al., 2007; Larsen et al., 2014), the *Human Health in the Arctic* report (AMAP, 2009), the *State of the Arctic Coast 2010* report (Forbes, 2011), the *Arctic Marine Shipping Assessment 2009 Report* (Arctic Council, 2009), the *Arctic Human Development Report I* (Arctic Human Development Report, 2004) and *Arctic Human Development Report II* (Larsen et al., 2015), and the *Arctic Resilience Interim Report 2013* (Arctic Council, 2013).
- **Canada-wide assessments:** These reviews focus on documenting the state of knowledge on climate change in Canada as whole, with specific chapters targeted at the North. They include the northern chapters of *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008; Prowse and Furgal, 2009) and *Human Health in a Changing Climate: A Canadian Assessment of Vulnerabilities and Adaptive Capacity* (Seguin, 2008).
- **Northern focused reviews:** These reviews and synthesis documents focusing on the state of knowledge on climate change in northern Canada include *Putting the Human Face on Climate Change* (Nickels et al., 2006), the Canadian Arctic Shelf Exchange Study (Fortier et al., 2008), work using systematic literature reviews focusing on the Inuvialuit Settlement Region and the eastern Arctic (Ford and Pearce, 2010; Bolton et al., 2011; Ford et al., 2012a, b, 2014a) and the ArcticNet Integrated Regional Impact Study reports (Allard and Lemay, 2012).
- **Sector-specific studies focused on northern Canada:** These studies provide in-depth focus on specific subsectors in northern regions, characterizing current understanding of impacts, adaptation and vulnerability, and identifying future research priorities, including assessments of health (Furgal and Seguin, 2006) and built infrastructure (Ford et al., 2014c).

These comprehensive reviews provide a broad understanding of climate change impacts, vulnerability and adaptation in northern Canada. This chapter complements and updates these earlier assessments, focusing specifically on coastal areas of Canada's north and with a strong emphasis on communities and economies. It addresses the physical setting and processes that make communities and environments of the North Coast region particularly sensitive to changing climate, emphasising sea-ice reduction, permafrost thaw and rising sea level as key drivers of change. Discussion of current and potential vulnerabilities of socio-economic sectors reflects the focus of available literature on the built environment (particularly in isolated communities and related to transportation); subsistence and emerging resource economies; community health, well-being and culture; and traditional livelihoods. The chapter concludes with reviews of adaptation planning in the North Coast region and knowledge gaps that may constrain adaptation actions. Although Canada's northern coast is home to diverse cultural heritages, including First Nations, Inuit, Métis and non-Indigenous, the North Coast chapter has a strong focus on Inuit, again reflecting the available literature.

2 CANADA'S NORTHERN COAST

Canada's northern coastline is vast, extending more than 176 000 km from the Yukon in the west to Labrador in the east, and encompasses more than 70% of all Canadian coasts. Three territories (Yukon, Northwest Territories, Nunavut) and four provinces (Manitoba, Ontario, Quebec, Newfoundland and Labrador) have northern coastlines (Figure 1), as do regions with land-claims agreements that have been settled with Indigenous populations (Inuvialuit Settlement Region, Nunavik, Nunavut, Nunatsiavut, James Bay and Northern Quebec Agreement). Canada's North Coast region is home to 58 communities and more than 70 000 people, the majority of whom are Inuit, First Nations or Métis. All of Canada's Inuit communities, except for Baker Lake, NU and Kuujjuaq in Nunavik (QC), are located on the northern coast.

The size and climate of the northern coast differentiates it from Canada's western and eastern coasts, as does the presence of sea ice for much of the year. The communities along Canada's northern coastline have distinctive social-

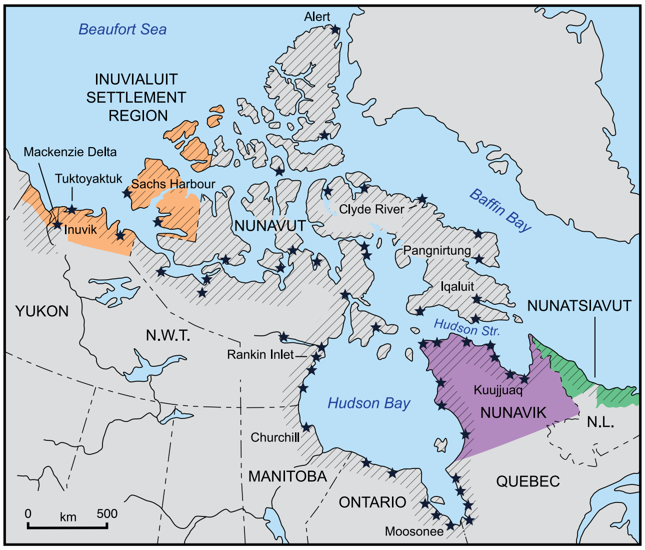

FIGURE 1: Location of the North Coast region. Communities are depicted with small stars. Abbreviation: N.W.T., Northwest Territories and N.L., Newfoundland and Labrador.

cultural characteristics, demographics and economies, including use of the coastal region for culturally valued and economically important harvesting activities. Accordingly, the 'coast' in this chapter is defined to extend both inland and seaward of the shoreline (the interface between land and water) to include the sea ice and open water, which are essential for travel and harvesting activities, and therefore the sustainability and well-being of coastal communities and ecosystems (*see* Chapter 1). Some communities mentioned in the chapter are farther inland of the marine coast (e.g., Inuvik, NT; Kuujjuaq, QC) but have been included because of their strong cultural, livelihood and transportation links to the marine environment.

This section provides background information on the communities and environment of Canada's North Coast region, focusing on their distinctive characteristics. Particular attention is given to the key physical attributes of the cold-climate coastal zone. Discussion of coastal ecosystems is in the context of ecosystem services and how they are integral to the sustainability of northern subsistence economies and cultural well-being. The section concludes with a focus on how the changing climate is causing physical changes along the northern coast, highlighting regional variability in the magnitude of changes and in environmental sensitivity.

2.1 COMMUNITIES AND ECONOMY

Canada's northern coastal population mostly lives in small, remote communities that range in size from 112 in Sachs Harbour, NT to 6699 in Iqaluit, NU (Statistics Canada, 2011). Most communities are accessible by air year-round and ship in the ice-free season, with only a few communities (e.g., Inuvik, NT and Chisasibi, QC) accessible year-round by road. Churchill, MB and Moosonee, ON are the only communities on the northern coast with rail access. The Port of Churchill exports primarily grain during the ice-free season from July to November, and is the largest port facility on the northern coast (Bristow and Gill, 2011). Other ports and harbours serve local and regional needs associated with supplying communities and northern industries.

The economies of communities in the North Coast region encompass a combination of waged employment and subsistence hunting, fishing and trapping, characteristic of what some have termed a 'mixed' economy (Gombay, 2005; Wenzel, 2013). Both components are interdependent in contemporary life in northern coastal communities, with Gombay (2005, 2007) arguing that the distinction between the two economies is increasingly blurred. For example, the ability to engage in harvesting depends on access to financial resources to purchase necessary equipment and gasoline to hunt and fish. Similarly, the ability of those in waged employment to access culturally valued traditional foods is determined by access to sharing networks. Complex sharing networks involving reciprocal exchange of food (e.g., from hunting and fishing) and other resources (e.g., financial) have evolved in contemporary coastal communities, influenced by historical sharing practices, although they have been documented to be coming under increasing strain (e.g., Gombay, 2005, 2007; Collings, 2011; Harder and Wenzel, 2012; Wenzel, 2013).

The wage economy of Canada's northern coastal communities is based largely on public administration, resource extraction, and arts and crafts, with tourism also being important in some regions. Waged employment is proportionally more important and well developed in the larger communities, such as Inuvik, Iqaluit, Kuujjuaq and Rankin Inlet, which serve as gateway communities and centres for the regions in which they are located (Furgal and Prowse, 2008; Inuit Tapiriit Kanatami, no date; Poppel et al., 2015).

Resource development, in the form of mining and oil-and-gas exploration, makes up approximately one-quarter of the GDP for the three northern territories, compared to 8% for Canada as a whole (Canadian Northern Economic Development Agency, 2014). Mining activities have expanded significantly during the last decade in the eastern coastal Arctic, with new mines of various sizes and types being developed, including gold, nickel, lead, zinc, iron, uranium, copper, silver, platinum, palladium and cobalt. Nunavut currently has two operating mines, with more in the development stage and significant exploration in progress (Aboriginal Affairs and Northern Development Canada, 2015a, b). In the western coastal Arctic, potential offshore reserves of up to 150 trillion cubic feet of natural gas and more than 15 billion barrels of oil exist (Government of the Northwest Territories, 2015). A number of infrastructure projects associated with resource development have been announced for the northern coast in recent years, including construction of the all-season 140 km long Inuvik to Tuktoyaktuk highway, due to be completed in 2018, along with investment in northern port infrastructure.

Public administration is a major employer in the three northern territories, accounting for 18% of GDP (compared to 7% Canada-wide; Canadian Northern Economic Development Agency, 2014) and 23% (12 300 positions) of the total labour force (Employment and Social Development Canada, 2014a, b). In 2011, wages and salaries related to the public sector totalled more than $800 million in Northwest Territories and $500 million in Nunavut (Statistics Canada, 2011). Together, resource development and public administration account for more than 40% of GDP in the Canadian north (Canadian Northern Economic Development Agency, 2014).

Many northern coastal communities retain a strong connection with the environment, with traditional foods derived from hunting, fishing and trapping having important social, economic and dietary importance. The Survey of Living Conditions in the Arctic, for example, documented that the majority (74%) of respondents from northern Canada obtain half or more of their meat and fish from traditional sources (Poppel et al., 2015). Traditional foods are widely shared within and between communities, and underpin Indigenous cultures across the North (Kuhnlein et al., 2001; Chan et al., 2006; Kuhnlein and Receveur, 2007), with the ability to engage in these activities influenced by factors such as ice and weather conditions, and animal health and migration behaviour. Along with the dependence of northern regions on climate-sensitive transportation routes, traditional food cultures make northern coastal communities more sensitive to changing environmental conditions (Furgal and Seguin, 2006; Ford et al., 2010c) than would be the case in the south.

Social and demographic characteristics of northern coastal communities also differ considerably from the Canadian average. Unemployment is a chronic problem in many regions, exceeding 50% in some communities, with labour-force participation also lower than in the rest of Canada (Inuit Tapiriit Kanatami, 2008; Nunavut Tunngavik Incorporated, 2014). Although median household income in some regions is greater than the Canadian average, costs of living are considerably higher. For example, food in Inuit communities typically costs at least double the Canadian average (Egeland et al., 2010; Huet et al., 2012). Nunavut has the highest fertility rate in Canada, with nearly 3 children per woman, compared to a national average of 1.6, and higher-than-average rates are generally documented elsewhere in the North (Nunavut Tunngavik Incorporated, 2010, 2012; Larsen et al., 2015). Reflecting this, the northern population is younger than in Canada as whole, with the median age of Inuit being 21 years in Nunavut and Nunavik, and 26 years in the Inuvialuit Settlement Region (Statistics Canada, 2013). Northern coastal communities are challenged by limited access to health services, crowded and poor-quality housing, concerns regarding drinking-water quality and sanitation, high levels of food insecurity and low educational achievement (Chatwood and Young, 2010; Knotsch and Kinnon, 2011; Young and Chatwood, 2011; Chatwood et al., 2012). Many of these challenges reflect the sweeping socio-cultural changes that took place in the North in the second half of the 20th century, including the relocation of formerly seminomadic peoples into fixed communities, residential schooling, development of the waged economy and migration from southern Canada (Damas, 2002; Cameron, 2012; Wenzel, 2013).

2.2 PHYSICAL SETTING

2.2.1 CLIMATE

An ice-covered Arctic Ocean is the keystone of the Arctic climate system (Melling et al., 2012). Canada's North Coast region is characterized by long, cold winters interrupted by short, cool summers. Precipitation is light and occurs predominantly in the summer. The presence of sea ice for much of the year greatly reduces the moderating influence of the ocean. This results in extremely cold temperatures in winter and local cooling along the coast in summer.

The annual variability in temperature is much greater for the North Coast region than for Canada's other coasts. For much of the year, the jet stream tends to be positioned south of most northern coasts and the region is generally dominated by cold air masses in winter. Episodic warm-air advection events in winter can bring freezing rain, fog and melt conditions, causing problems for transportation and communities. These warm-air advection events have been more frequent in recent years (Wang, 2006), associated with greater variability in the jet stream (Francis and Vavrus, 2012). The western and northern parts of the Canadian Arctic receive limited precipitation (<300 mm annually) and experience relatively few storms. In contrast, the eastern Arctic, especially Labrador, Nunavik and Baffin Island, experience much higher annual precipitation (up to 1000 mm) arising from more frequent storm events moving in along the Baffin Bay storm track (*see* Chapter 2).

2.2.2 GEOLOGY AND GEOMORPHOLOGY

The northern coast is characterized by a wide diversity of environments, described in regional-scale studies (e.g., Owens, 1994; Shaw et al., 1998; Forbes and Hansom, 2012) and in studies focused on coastal conditions in specific communities (e.g., Hatcher et al., 2011; Forbes et al., 2014; Smith and Forbes, 2014; Hatcher and Forbes, in press). One important control on coastal processes is geology, with approximately 62% of the northern coasts consisting of unlithified materials that are more sensitive to erosion and deposition processes associated with coastal dynamics than coasts made up of more resistant bedrock (Figure 2). Another important control, discussed in detail in Chapter 2, is relative sea-level change. Glacial isostatic adjustment have resulted in many regions experiencing a fall in relative sea level during the past several thousand years. Hudson Bay and portions of the central Canadian Arctic Archipelago (CAA) have experienced the largest postglacial crustal uplift in Canada. Raised beach terraces, perched deltas and marine terraces indicative of past sea levels are found at elevations up to about 200 m. Where relief is low, they may be located tens or even hundreds of kilometres inland.

In the eastern coastal Arctic, fiords with steep cliffs carved out of resistant bedrock dominate the coastal morphology (Syvitski et al., 1987). Boulder-strewn tidal flats are found in some macrotidal areas on southern Baffin Island, such as Iqaluit and Pangnirtung, and around Ungava Bay (e.g., Lauriol and Gray, 1980; McCann et al., 1981; Forbes and Hansom, 2012). Glaciers extend down to the coastline on a number of islands, whereas ice shelves are found only on northern Ellesmere Island (Box 1). Bedrock coasts are highly resistant and erosion rates tend to be on the order of millimetres per year (e.g., Allard and Tremblay, 1983). In regions of unlithified sedimentary forelands, erosion can be on the order of 0.3–0.5 m/year, with rates of up to 0.3–0.5 m/day recorded on Bylot Island, NU during one extreme storm event (Taylor, 1980).

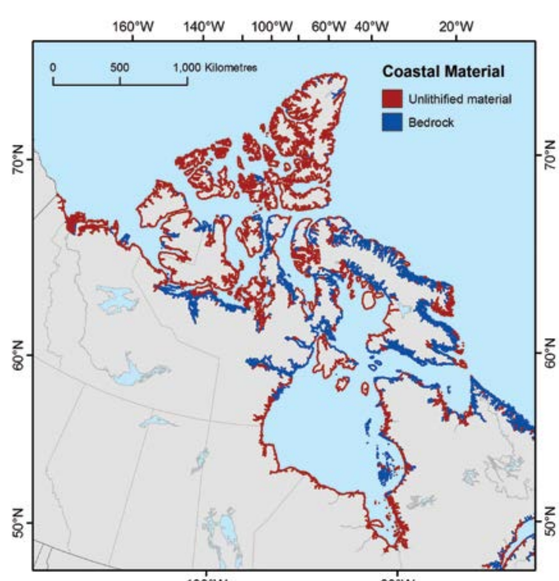

FIGURE 2: Variability of coastal material in the North Coast region (*from* Couture and Manson, 2016).

The northwestern coasts of the Queen Elizabeth Islands (QEI) that border on the Arctic Ocean are generally lower lying and developed in poorly lithified sedimentary rocks (Figure 2). The region is microtidal and open water is minimal, limiting coastal dynamics, and most shoreline reworking is due to the action of sea ice (e.g., Forbes and Taylor, 1994). The inner coasts of the QEI are variable in terms of geology and topography, but they share a low–wave-energy environment as a result of prolonged ice cover. Farther south, around Melville and Bathurst Islands, the open-water season tends to be of longer duration, increasing the influence of wave action on the gravel and sandy beaches, but ice-push features are also evident. Gravel beaches around Jones and Lancaster Sounds are reworked during storms, but long-term changes are minimal (Shaw et al., 1998; St-Hilaire-Gravel et al., 2012). The mainland and the southern portion of the CAA are experiencing relative sea-level fall. Overall relief is generally low and bedrock coasts are widespread, although eastern Banks Island has numerous unconsolidated bluffs. Gravel and sand beaches and spits are also common.

Along the Beaufort Sea in the western Canadian Arctic, the shoreline consists of unlithified materials (Figure 2) that are typically rich in ground ice. Much of the coast consists of low bluffs with low barrier beaches, barrier islands and spits. The Mackenzie Delta, the second largest delta in the world, is approximately 120 km wide at the delta front. More than 40 000 lakes dot the low-lying surface of the delta (Emmerton et al., 2007) and it is an important bird breeding and staging ground. The outer delta plain is flooded by the river in the spring and by storm surges in the summer and fall (Marsh and Schmidt, 1993). The extremely high content of ground ice leads to high rates of erosion along the Beaufort Sea coast, averaging 0.5–1.5 m/year (Harper, 1990; Konopczak et al., 2014) and ranging as high as 22.5 m/year (Solomon, 2005). Erosion also occurs along some parts of the delta front, despite the fact that the Mackenzie River is the single largest source of sediment to the Arctic Ocean (Rachold et al., 2000). Spring melt begins in the southern portion of the Mackenzie River drainage basin earlier than at the river mouth, so sea ice is still present when the freshet arrives at the coast. Meltwater overflows onto the ice, then drains through cracks and holes in the ice, generating scours on the sea bed that can be tens of metres in diameter and more than 4 m deep (Solomon et al., 2008). This scouring presents a major hazard for nearshore infrastructure due to its potential to disturb the seabed and subsurface sediments.

BOX 1
TIDEWATER GLACIERS AND ICE SHELVES

Glaciers that terminate in the ocean (tidewater glaciers) are common in some fiords of the eastern and northern Canadian Arctic where high topography and high snowfall rates support ice caps that drain to the sea (Figure 3). Glacier-ice discharge to the ocean from the Queen Elizabeth Islands is currently ~2.6 billion tonnes/year, which equates to 7.5% of pan-Arctic discharge for all glaciers and ice caps outside of Greenland (Van Wychen et al., 2014). In comparison, glaciers on Baffin and Bylot Islands only discharge ~0.25 billion tonnes/year of ice to the oceans (Gardner et al., 2011).

Tidewater glaciers, through iceberg calving, can be responsible for a significant component of loss in glacial-ice volume for some ice caps in the Canadian High Arctic, such as the Devon Ice Cap, where they account for 30–40% of total losses (Burgess et al., 2005; Williamson et al., 2008). Recent work has also indicated that approximately half of the total iceberg discharge from the Canadian Arctic is currently funneled through the Trinity-Wykeham Glacier complex, which flows from the Prince of Wales Icefield on eastern Ellesmere Island (Van Wychen et al., 2014). This means that changes in the discharge of just a few glaciers can have a dramatic impact on total iceberg discharge from this region. Understanding how tidewater glaciers are, and will be, responding to a warming climate, and the implications for iceberg production rates, are therefore key in projecting both changes in the cryosphere and in iceberg risk for marine transportation. Recent studies in the Canadian Arctic indicate that there is a strong relationship between increased iceberg production and removal of buttressing sea ice from the tidewater glacier terminus, whereas influences from tides and air temperature are minor (Herdes et al., 2012).

Another distinctive feature of the Canadian Arctic coast is the ice shelves of northern Ellesmere Island (Figure 3). These ice masses range in thickness from ~30 to 100 m, and are formed from a combination of very old landfast sea ice, glacier inflow and local snow accumulation. At the start of the 20th century, they totalled >9000 km^2 in area and stretched in a continuous body across northern Ellesmere Island, but today they are restricted to a few protected fiords and total ~500 km^2 in area (Copland et al., in press). Although they constitute only a very small component of the Arctic coastline, they are unique in the northern hemisphere and are quickly vanishing, due to rapidly warming air temperatures and increased open-water conditions that make them vulnerable to break-up (Figure 3; Copland et al., 2007; White et al., 2015). Since 2005, three of six ice shelves have completely broken up and the total area of the ice shelves has been reduced to almost half (Copland et al., 2007; Mueller et al., 2008; White et al., 2015).

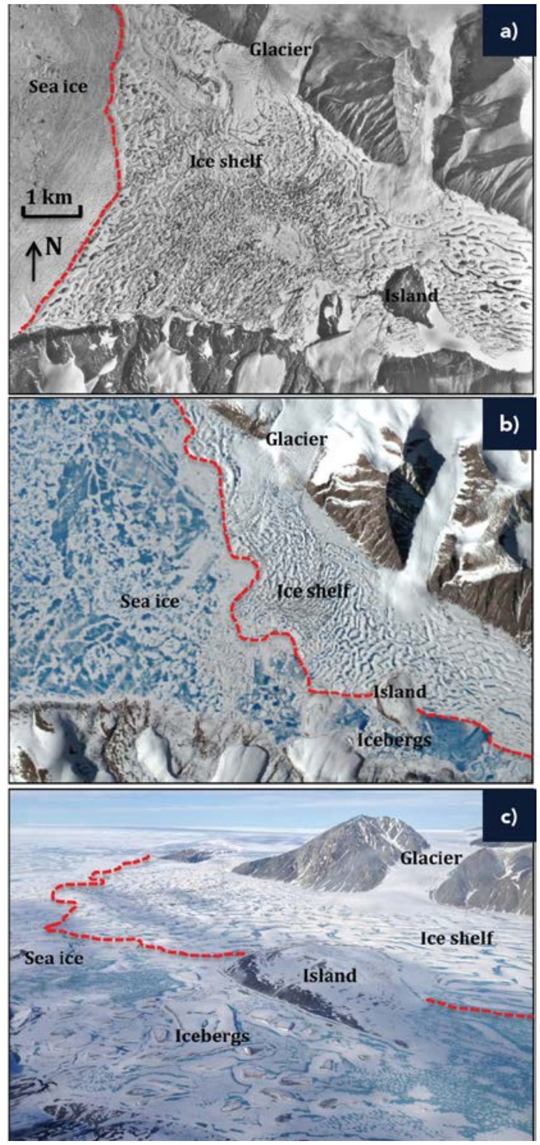

FIGURE 3: Changes in the extent of the Petersen Ice Shelf, Ellesmere Island, between **a)** an aerial photograph from August 13, 1959 (photo A16724-63); **b)** ASTER satellite imagery from July 7 and 11, 2014; and **c)** an oblique photograph from July 13, 2014. Dashed red line marks the boundary between the ice shelf and sea ice. The area of the ice shelf was 48.40 km^2 in 1959 and 19.32 km^2 in 2012 (White et al., 2015; little area change has occurred since 2012). The images also show an example of a tidewater glacier (labelled glacier) that flows into the ice shelf along its northern margin. *Figure courtesy of L. Copland.*

Hudson Bay and James Bay are regions with mostly low-lying but variable coastlines, all of which are experiencing rapid fall in relative sea level. Along western Hudson Bay, the coast is rocky (Figure 2) with wide tidal flats, whereas the eastern coast has narrow beaches and tidal flats (Shaw et al., 1998). Around southwestern Hudson Bay and western James Bay, flat and poorly drained estuarine coasts with wide marshes are important sites for wildlife (Martini et al., 1980). Hudson Bay has a fairly energetic wave environment, whereas James Bay is more sheltered. The coastlines around Ungava Bay are mostly low and rocky, whereas high-relief rocky coasts predominate along Hudson Strait.

2.2.3 PERMAFROST AND GROUND ICE

Permafrost, which is permanently frozen ground, underlies virtually all of Canada's northern coasts. It can be continuous or discontinuous, or occur only in patches. Permafrost can be up to several hundred metres thick, or it may be only tens of metres thick in the more southerly parts of the permafrost zone. Above the permafrost, a thin surface layer (active layer) thaws in summer and refreezes in winter. The active layer can range from tens of centimetres to several metres in thickness, depending on factors such as temperature at the ground surface, soil type, soil moisture, vegetation and snow cover. The distribution and thickness of permafrost are a reflection of a region's long-term climate and glacial history. In parts of the western Arctic, permafrost that formed during the last glaciation when sea level was much lower (Mackay, 1972) still persists as subsea permafrost in the nearshore and shelf of the Beaufort Sea (Taylor et al., 1996). Subsea permafrost helps to generate an environment conducive to the formation of shallow deposits of methane gas hydrate, a potential source of energy (O'Connor et al., 2010). This subsea permafrost also acts to cap the methane in seabed sediments, preventing its release to the water column and subsequently the atmosphere, where it acts as a potent greenhouse gas (Ruppel, 2011).

Permafrost usually contains some ice, either within the soil pores, as thin layers or as large discrete bodies of massive ice that can be up to 30 m thick and extend for hundreds of metres (e.g., Rampton, 1982; Harry et al., 1988; Pollard, 2000). Ground ice is more often found in fine-grained soils and organic soils that are rich in silt and clay, and is less common in coarser grained material consisting of sand and gravel. Massive ice beds are commonly found at the interface where fine-grained sediments overlie coarse-grained ones (Mackay, 1972). Coastal materials contain varying amounts of ground ice, ranging from almost none in bedrock to more than 20% by volume in some unlithified materials (Figure 4). In extreme cases, up to 70% of a coastal section may consist of ground ice (French et al., 1986). Ground ice binds permafrost soil and gives it strength, but the soil becomes less stable upon thawing and

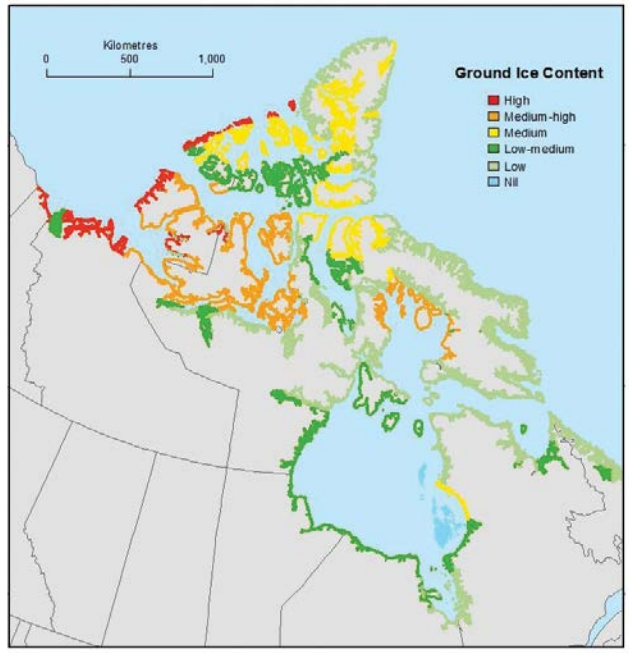

FIGURE 4: Ground-ice volumes in the North Coast region (Couture and Manson, 2016), based on data from Natural Resources Canada (1995). High ground-ice content is >20% by volume, medium is 10–20% and low is <10%.

slope failures are more likely. If there is an excess of ground ice, thawing reduces the volume of the soil, leading to subsidence and compaction. These responses to thawing exacerbate local coastal hazards and erosion response by enhancing the ease with which wave action can remove sediments and by increasing susceptibility to inundation.

In permafrost regions, coastal erosion is both a mechanical process and a thermal process (Aré, 1988; Wolfe et al., 1998). Thermal erosion occurs above the normal waterline when higher water levels associated with storm surge and waves thaw the permafrost. It also occurs below the waterline when thawed material at the water-sediment interface is removed mechanically by waves, currents or sea-ice scour, and the underlying frozen sediment is then subject to degradation.

Coastal erosion in permafrost regions results from several mechanisms. Retrogressive thaw slumping is commonly seen along unlithified coastal slopes and occurs when massive ground ice is exposed by wave action (Figure 5). The ice body thaws quickly and the headwall retreats backward. Sediment contained within the massive ice or in the overburden accumulates at the base of the slump or forms a mud slurry that flows downslope to the beach and is easily washed away. The back-wasting of the slump headwall continues until the ice body melts completely or enough sediment accumulates at the base that the ice face becomes insulated and protected from further thaw. Continued wave action may later expose the ice once again, initiating a new cycle of retrogressive thaw-slump activity.

FIGURE 5: Aerial photograph of retrogressive thaw slump along the Beaufort Sea coast, YK, generated by the thawing of ice-rich sediment. *Photo courtesy of N.J. Couture.*

FIGURE 6: Aerial photograph of erosion by block failure along the Beaufort Sea coast, YK. Note that failure occurs along ice wedges, which outline the tundra polygons. *Photo courtesy of N.J. Couture.*

Another common mechanism of shoreline retreat is block failure. This occurs because of the presence of ice wedges that form when the soil contracts and cracks during especially cold winters. The following spring, surface water trickles into the crack in the permafrost; it then freezes and expands, forming a thin vein of ice. This vein becomes a plane of weakness in the soil, so that any additional cracking tends to occur at the same location. Over time, these veins build up to form wedges of ice that can be several metres wide and high (Figure 6). When waves attack a bluff during storms, they erode a horizontal niche at the base. Once the niche becomes deep enough, the weight of the overlying block of sediment causes it to collapse, generally along the plane of an ice wedge (Walker, 1988). The occurrence of block failure is episodic, being a function of storminess, water level and other physical factors (Hoque and Pollard, 2009; Barnhart et al., 2014).

Erosion along permafrost coasts may be intensified by the thaw of ice-rich, subsea permafrost. The volume loss of the degrading ground ice causes the seabed to subside, resulting in a steepening in the nearshore zone and enabling larger waves to reach the shore, particularly during storms (e.g., Nairn et al., 1998; Wolfe et al., 1998).

2.2.4 SEA ICE

Sea ice is one of the most defining features of Canada's northern coasts (*see* Chapter 2; Forbes and Taylor, 1994; Forbes and Hansom, 2012). In winter, when the sea-ice cover is essentially complete, ice acts to protect the coast by suppressing wave action (Wadhams et al., 1988; Squire, 2007). It also provides a transportation route between communities and a means of accessing hunting and fishing areas (Aporta, 2002, 2009; Aporta et al., 2011). During the open-water season, the absence of sea ice results in the shoreline and coastal infrastructure being vulnerable to erosion and inundation from waves and storm surges (e.g., Forbes and Taylor, 1994; Kobayashi et al., 1999). When sea ice is in motion, particularly during break-up and freeze-up when ice concentrations are lower, wind and currents can cause ice floes to collide and form pressure ridges that, in turn, can gouge the sea floor (Rearic et al., 1990; Shapiro and Barnes, 1991). Sea ice can also enhance hydrodynamic scour of the seabed (Forbes and Taylor, 1994), pile up or ride up on shore (Kovacs, 1983), thrust sediments landward or entrain and transport them seaward (e.g., Reimnitz et al., 1990; Eicken et al., 2005).

The duration and extent of sea-ice cover vary across Canada's north and are largely dependent on regional climate and latitude. For the period 1981–2010, break-up began in earnest in early June (Figure 7a) and continued through late August in parts of Foxe Basin and the CAA. Sea ice is perennial in some channels of the archipelago and off the Beaufort Sea coast, reaching its minimum extent in early September. Fall freeze-up begins anywhere from late September to early December (Figure 7b). These are long-term averages, however, and break-up now occurs earlier and freeze-up is delayed (Section 2.4.2), resulting in a longer melt season (Howell et al., 2009; Stroeve et al., 2014).

2.2.5 WAVES AND STORM SURGES

Much of the coastal retreat in the Arctic occurs as a result of high waves and storm surges (Solomon et al., 1994). The rates of erosion are determined by wave energy, the composition and morphology of coastal features and the presence of sea ice (e.g., Héquette and Barnes, 1990; Dallimore et al., 1996; Barnhart et al., 2014), and they can be up to eight times higher than in more temperate regions (Reimnitz et al., 1988).

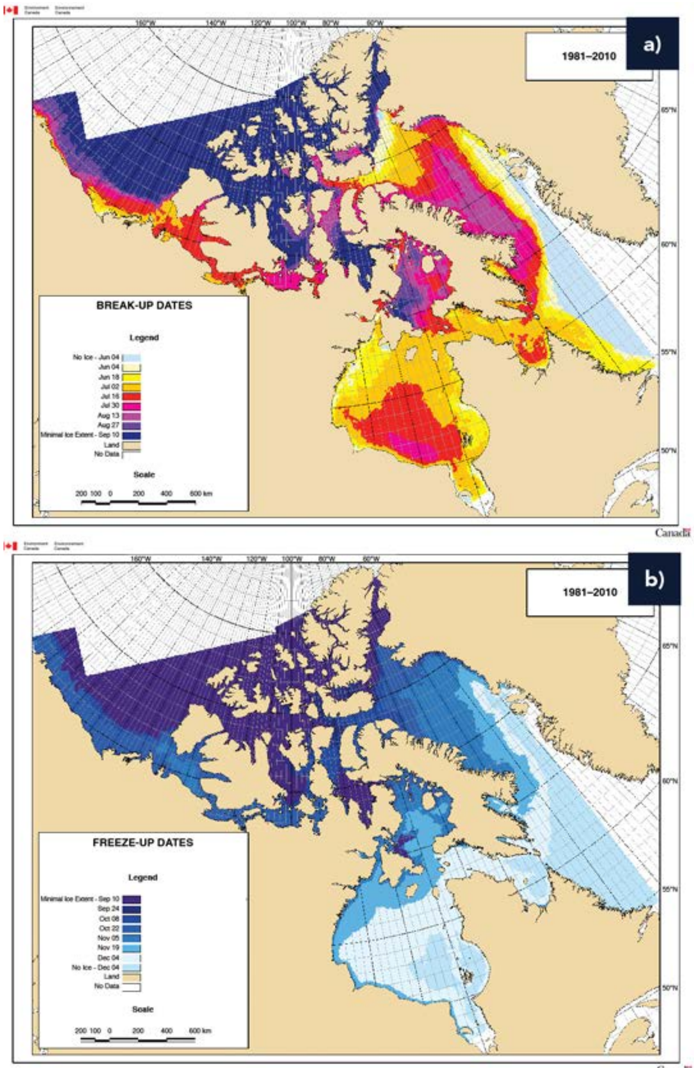

FIGURE 7: Climatic ice atlas 1981–2010 (*from* Environment Canada, no date), showing the extent of sea ice during **a)** the break-up and **b)** freeze periods.

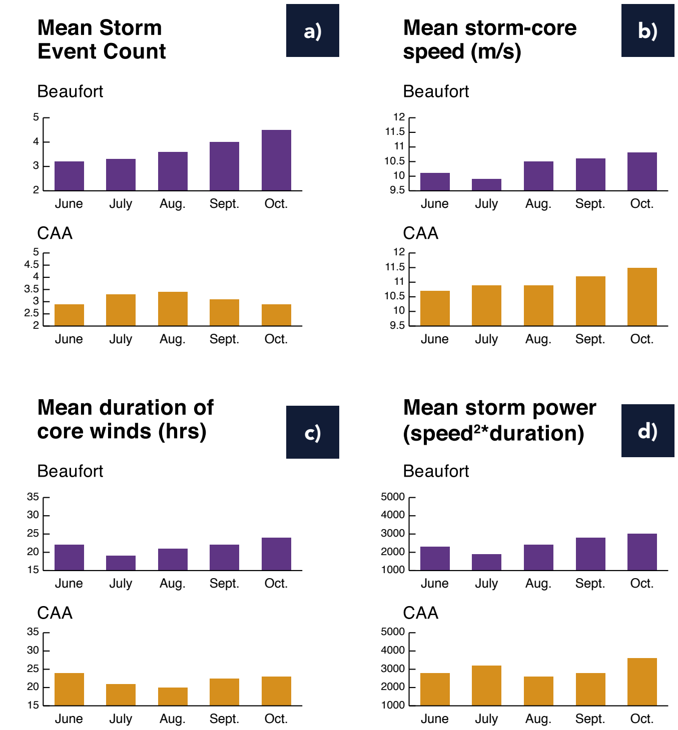

FIGURE 8: Storm statistics for 1950–2000 (*from* Atkinson, 2005), based on data from ground-based stations on the Beaufort Sea coast and the outer margins of the CAA, including **a)** mean storm count per month per sector; **b)** mean core wind speed (upper 50th percentile of all wind speeds); **c)** mean duration of the core-speed wind; and **d)** mean storm power, which is a derived parameter designed to provide a rough indication of the total power potentially available from a storm event. Abbreviation: CAA, Canadian Arctic Archipelago.

Wave behaviour is strongly controlled by the extent and duration of sea ice. This is a primary distinguishing feature that sets apart the coastal dynamics regime in Canada's North Coast region from those in the West and East Coast regions. Wave energy and wave height in the Beaufort Sea increase as a direct function of fetch (open-water distance; Thomson and Rogers, 2014). Baffin Bay has the largest potential fetch in the eastern Arctic but has an open-water season of fewer than 130 days (Shaw et al., 1998). Some regions, such as parts of the northern CAA, are fetch limited throughout the year and therefore have only restricted wave activity (Forbes and Taylor, 1994; Shaw et al., 1998). Along the Beaufort Sea coast, fetch reaches up to several hundred kilometres in September when ice cover is at its minimum.

Storm climatologies for the period 1950–2000 for the Beaufort Sea and CAA are shown in Figure 8 (Atkinson, 2005). In the Beaufort region, the increasing number of storms coincides with increasing duration and fetch of open water, and storm power is at a maximum in the fall when sea-ice extent is lowest. In the CAA, the total number of storms is lower and August is the most active month for storms, when the highest wind speeds and power tend to occur. Counts drop off in the fall and sea ice returns. A storm climatology analysis covering 2003–2009 for Resolute, NU in the central CAA found that only 35% of the storms had the potential to generate wave activity at the coast (St-Hilaire-Gravel et al., 2012). For the period 1962–1993, storms over the Beaufort Sea had significant wave heights ranging from 2.4 to 4.3 m, and were almost always associated with winds from the north and northwest (Manson and Solomon, 2007). The nearshore wave energy generated by storms depends not just on fetch length but also on shoreline orientation, wind direction and shore-face bathymetry, such that the same storm may have different impacts on parts of the coast that are as close as a few kilometres (Hoque et al., 2009).

The shallow shelf bathymetry along the Beaufort Sea coast (Figure 9) contributes to the occurrence of large storm surges (Figure 10), with several sites recording surges in excess of 2 m (Forbes and Frobel, 1985; Harper et al., 1988). In the low-lying Mackenzie Delta, the impact of surges can extend far inland (Case Study 1). Storm surges that occur during full ice cover (documented in 1974 and 2005) may not contribute immediately to onshore erosion but can alter the underwater nearshore morphology through pressure-ridge development, ice scour or ice push, which later translates into coastal retreat.

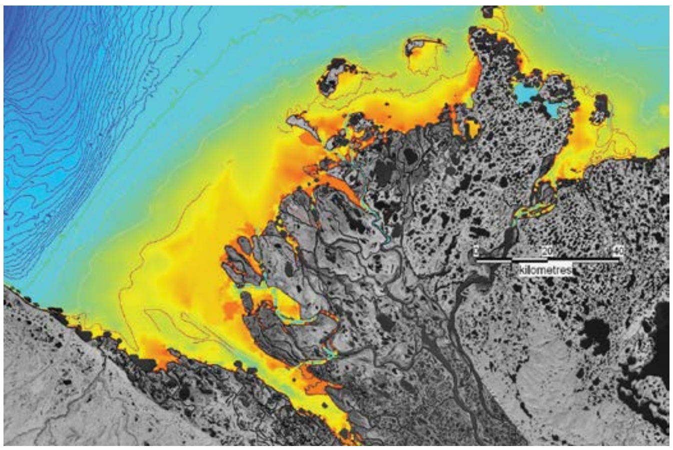

FIGURE 9: Low coastal gradient on the Beaufort Sea shelf along the Mackenzie Delta. The 2 m isobath is indicated in red (*from* Geological Survey of Canada, 2016).

FIGURE 10: Flooding at Simpson Point, Herschel Island, YK following a storm surge in August 2010. *Photo courtesy of W. Pollard.*

CASE STUDY 1

IMPACTS OF THE 1999 STORM SURGE IN THE MACKENZIE DELTA

Along northern coasts, rapid declines in sea-ice cover make low-lying terrestrial ecosystems particularly susceptible to coastal inundation that will alter vegetation composition and structure, and terrestrial productivity. Insight into the consequences of widespread coastal inundation is provided by examining the impacts in the Mackenzie Delta region of a major storm-surge event that occurred in September 1999. Gale force winds sustained for a period of 36 hours propagated a surge that completely inundated most terrestrial surfaces in the outer Mackenzie Delta for several days (Kokelj et al., 2012). The storm surge drove marine waters up to 30 km inland from the coast, increasing soil chloride levels and leading to the die-back of more than 30 000 ha of tall and dwarf shrub tundra and sedge wetland (Kokelj et al., 2012; Lantz et al., 2015). Sediment cores collected from lakes affected by the surge showed diatom assemblages dominated by brackish taxa for the first time in 1000 years (Pisaric et al., 2011). Independent lines of evidence, including interviews with knowledgeable hunters, suggest that this was likely the largest storm-surge event in the past millennium (Kokelj et al., 2012).

Ongoing monitoring in the outer delta shows that soils and vegetation are recovering, with the rate of recovery dependent on terrain type. Low-lying areas that are more regularly flooded in the spring have shown significant recovery after a decade, but elevated surfaces that are only infrequently affected by the spring freshet have exhibited little to no recovery (Lantz et al., 2015).

Storm impacts are also influenced by tidal range, which varies widely in the North Coast region, from <0.5 m to >13 m (Figure 11). If a storm surge coincides with a high tide, flooding and erosion will be increased regardless of the tidal range. In a microtidal regime, it does not matter when a storm surge strikes—it will always cause inundation. Hence microtidal environments are more sensitive to storm surge than are macrotidal environments (*see* Chapters 2 and 4). Northern storms can also be slower moving than those in southern Canada, which prolongs exposure to damaging waves and surge conditions.

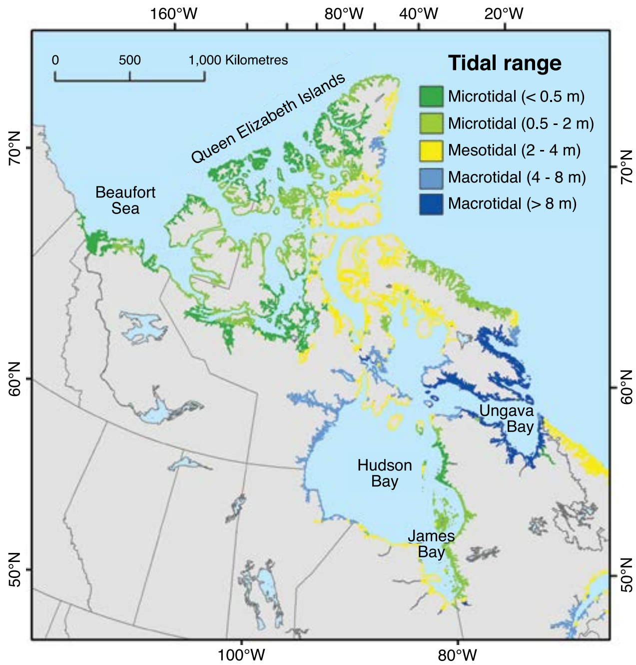

FIGURE 11: Variability in tidal range across the North Coast region (*from* Couture and Manson, 2016). Tides range from <0.5 m along the Beaufort Sea to >13 m in Ungava Bay.

2.3 ECOSYSTEM SERVICES

Canada's northern coastal environments provide a diversity of ecosystem services, representing all four categories (Box 2) identified by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005).

Provisioning services are extremely important to Indigenous populations of the North Coast region, as they sustain subsistence, economic and recreational activities (Huntington, 2013). Perhaps most important is the food obtained from harvesting activities performed along the shore, from boats or directly on the sea ice (Berkes, 1990; Arctic Climate Impact Assessment, 2005). Indigenous communities on the northern coast harvest a diverse range of Arctic species, including coastal breeding birds, fish and marine mammals. For instance, Inuit, Dene/Métis and Cree people harvest coastal birds, such as snow goose, Canada goose, eider duck and ptarmigan; fish species, such as Arctic char, whitefish, cod and turbot; benthic organisms, such as clams and mussels; and marine mammals, such as ringed seal, harp seal, beluga whale, bowhead whale, walrus, narwhal and polar bear (Berkes and Farkas, 1978; Receveur et al., 1997; Delormier and Kuhnlein, 1999; Priest and Usher, 2004). The species harvested vary seasonally and by community with respect to wildlife migration, species range, health of wildlife populations and accessibility.

BOX 2
CATEGORIES OF ECOSYSTEM SERVICES

Provisioning services: direct goods that humans get from nature, such as food and water

Cultural services: nonmaterial benefits that maintain ways of life, including recreation and spiritual experience

Regulating services: benefits associated with the regulation capacities of ecosystems, such as climate and hydrological regulation

Supporting services: ecosystem processes such as photosynthesis and nutrient cycling that underlie the supply of other categories of ecosystem services

The cultural services provided by northern coastal ecosystems are the cornerstone of Indigenous well-being and cultural survival (Nuttall, 1998; Millennium Ecosystem Assessment, 2005; Parlee et al., 2005; Huntington, 2013; Cunsolo Willox et al., 2013a, 2015). For instance, Cree people consider that their own physical, spiritual and mental health depends on that of 'the land' (Adelson, 2000). Cultural services can be both intangible, such as spiritual experience, and tangible, such as recreation and tourism. Tourism as a cultural service is becoming increasingly important in northern Canada and includes five markets: mass tourism (e.g., cruise ships); sport fishing and hunting; nature tourism; adventure tourism; and culture and heritage experiences (Snyder, 2007; Huntington, 2013). Some northern coastal destinations are gaining national and international reputations, such as Nunavut and Nunavik for sport fishing and hunting (Twynam and Johnston, 2002; Lemelin et al., 2012) and Churchill, MB for polar bear (Stirling, 2012) and beluga whale viewing. The Northwest Passage has also become a popular destination for cruise vessels, with a 70% increase in the number of passages in recent years (Stewart et al., 2011). For Indigenous communities, tourism represents an additional source of income and a way to promote their land and culture (Robbins, 2007).

Regulating and supporting services provided by Canada's northern ecosystems benefit people over a wide range of spatial scales. At the global scale, the Arctic Ocean, including marginal seas and northern terrestrial biomes, acts as a climate regulator through diverse biophysical mechanisms (Millennium Ecosystem Assessment, 2005). For instance, the production of dense, cold ocean water in the Arctic is an important regulator of global thermohaline circulation, as demonstrated by recent weakening of the Atlantic meridional overturning circulation (Rahmstorf et al., 2015). Reduced sea-ice cover along with increased air and surface-water temperatures could also enhance carbon sequestration due to increased primary production (Schneider von Deimling et al., 2012). Coastal areas of the Canadian Arctic are already showing increasing rates of primary production due to sea-ice retreat (Tremblay et al., 2012). Regionally, coastal areas are critical habitats for a number of Arctic species because terrestrial carbon inputs from coastal and riverine sources are an important part of the restricted Arctic food web (Dunton et al., 2006).

Sea ice, by itself, is a structural component of Arctic marine ecosystems that provides important regulating and supporting services (Eicken et al., 2009; Euskirchen et al., 2013). At the global scale, the high albedo of sea ice has a cooling effect on Earth's climate. Regionally, sea ice can reduce coastal erosion by attenuating wave action (Section 2.2.4; Jones et al., 2009). The reduction in this service could have dramatic consequences for coastal communities of the Canadian Arctic. High erosion rates due to loss of Arctic sea ice have already led to the relocation of some communities along Alaska's northernmost coast, with substantial socio-economic impacts (Lovecraft and Eicken, 2011). In addition, sea ice acts as a supporting service by providing crucial habitats to key and emblematic Arctic marine species that are central to traditional ways of life in Indigenous communities in Canada's North Coast region (Gradinger and Bluhm, 2004; Blix, 2005; Darnis et al., 2012).

2.4 CHANGES IN COASTAL CONDITIONS AND PROCESSES

2.4.1 TEMPERATURE AND PRECIPITATION

There is no regional analysis of temperature and precipitation trends limited to coastal sites available for northern Canada. However, the Mackenzie District in the western Arctic has warmed by 2.6°C during the period 1948–2014 (Table 1). This rate of warming is more than 50% greater than the warming observed for Canada as a whole during the same period (Environment Canada, 2015) and represents one of the greatest rates of warming anywhere in the world. All of Canada's northern coasts lie in climate regions that have warmed more than the Canadian average. There has been an increase in annual precipitation for the period 1950–2010 at virtually all northern coastal sites (one site on James Bay shows a decrease that is not statistically significant), and an increase in the ratio of snow to rain (Mekis and Vincent, 2011a, b).

Warming in the North Coast region is projected to continue under all climate change scenarios, with the magnitude of warming strongly dependent on the emission scenario considered (*see* Chapter 2). At virtually all sites, warming is projected to be greatest in winter and least in summer. Under the high-emissions scenario (RCP8.5), a temperature increase in excess of 8°C is projected during winter for the period 2070–2100 (relative to average values between 1961 and 1990; Bush et al., 2014). Similarly, precipitation is projected to increase under all scenarios, with greatest increases in autumn and winter. Winter precipitation increases in excess of 25% are projected for parts of the eastern and central Arctic by the year 2050 (Bush et al., 2014).

TABLE 1: Annual temperature trends and temperature and precipitation extremes during the period 1948–2014 for climate regions that cover the majority of Canada's North Coast region. Note that the data are for entire regions, not coastal sites. Temperature trend is warming (C°) during the 67-year period. Source: Environment Canada (2015). Abbreviations: mtns., mountains; temp., temperature.

Region	Temp. trend	Coldest year	Departure (°C)	Warmest year	Departure (°C)	Driest year	Departure (%)	Wettest year	Departure (%)
Northern BC mtns. and Yukon	2.3	1972	–2	1981	2.4	1950	–27.2	1991	20.2
Mackenzie District	2.6	1972	–1.6	1998	3.3	1954	–23.7	1974	21.7
Arctic tundra	2.0	1972	–2.5	2010	4.4	1954	–32	2005	28.7
Arctic mtns. and fiords	1.6	1972	–2.4	2010	4.5	1948	–38.5	2013	59
Canada	1.6	1972	–2	2010	3	1956	–12.2	2005	15.6

2.4.2 SEA ICE

The September monthly average extent of Arctic sea ice is decreasing at a rate of 13.3% per decade, while March extent is decreasing at a rate of 2.6% per decade (Figure 12; Perovich et al., 2014). Decreases are seen in every month of the year but are most pronounced in September (Serreze et al., 2007). In the Canadian Arctic, the rate of loss ranges from 2.9% per decade in the CAA (although areas within the CAA have much higher rates) to 10.4% per decade in Hudson Bay (Table 2). These trends are expected to continue or accelerate (Dumas et al., 2006; Holland et al., 2006; IPCC, 2013), with some models projecting almost complete loss of summer ice cover before mid-century (e.g., Wang and Overland, 2012). The occurrence of multiyear ice is also declining (Table 2; Maslanik et al., 2007, 2011). Overall, Arctic sea ice is thinning; average spring ice thickness was 2.4 m in 2008 (Kwok et al., 2009) but is projected to be only 1.4 m by 2050 (Stroeve et al., 2012).

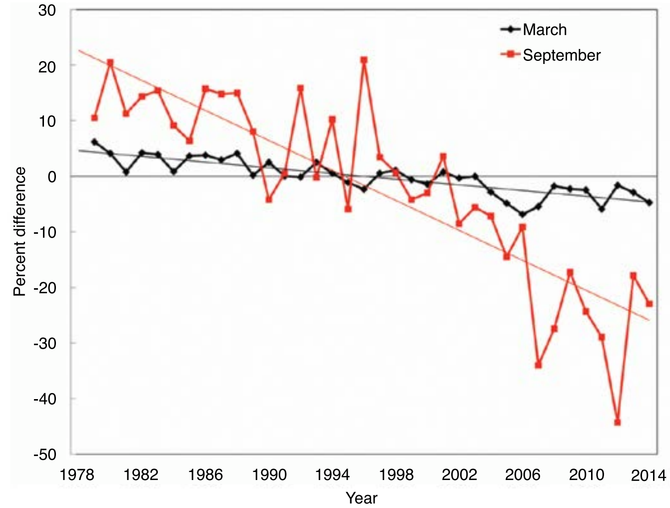

FIGURE 12: Anomalies in Arctic sea-ice extent (relative to the mean values for the period 1981–2010) for the month of maximum ice extent (March, indicated by black line) and the month of minimum ice extent (September, indicated by red line). Source: Perovich et al. (2014).

TABLE 2: Trends in total sea ice and multiyear ice (MYI), expressed in percentage per decade. Values with † are statistically significant at the 95% confidence level or higher. Abbreviations: CAA, Canadian Arctic Archipelago; N/A, not available; Sept., September.

Region	Region within*	Subregion*	Period of record	Parameter reported	Sea-ice trend	MYI trend	Source
Arctic	–	–	1979–2010	Sept. sea-ice extent	–12.4	N/A	Stroeve et al. (2012)
Arctic	–	–	1979–2014	Sept. sea-ice extent	–13.3	N/A	Perovich et al. (2014)
Canada	Hudson Bay	–	1968–2008	Average summer sea-ice cover	–10.4†	N/A	Tivy et al. (2011)
Canada	Baffin Bay	–	1968–2008	Average summer sea-ice cover	–8.9†	10.7	Tivy et al. (2011)
Canada	Beaufort	–	1968–2008	Average summer sea-ice cover	–5.2†	–4.6	Tivy et al. (2011)
Canada	CAA	–	1968–2008	Average summer sea-ice cover	–2.9†	–4.1	Tivy et al. (2011)
Canada	CAA	–	1979–2008	Sept. sea ice area	–8.7†	–6.4	Howell et al. (2009)
Canada	–	Queen Elizabeth Islands	1979–2008	Sept. sea-ice area	–2.5	–2.4	Howell et al. (2009)
Canada	–	West Parry Channel	1979–2008	Sept. sea-ice area	–8.2	–0.8	Howell et al. (2009)
Canada	–	East Parry Channel	1979–2008	Sept. sea-ice area	–15.4	–7.0	Howell et al. (2009)
Canada	–	M'Clintock Channel	1979–2008	Sept. sea-ice area	–10.0	–11.0	Howell et al. (2009)
Canada	–	Franklin	1979–2008	Sept. sea-ice area	–17.5	–24.4†	Howell et al. (2009)
Canada	–	Baffin Inlets	1979–2008	Sept. sea-ice area	–20.5†	–25.8†	Howell et al. (2009)
Canada	–	West Arctic Waterway	1979–2008	Sept. sea-ice area	–24.9	–7.9	Howell et al. (2009)

* Ice-regime regions and subregions (Canadian Ice Service, 2007).

As a result of this decline in sea-ice cover, the open-water season has grown at an average rate of 5 days per decade Arctic wide since 1979 (Stroeve et al., 2014). In Canada's north, the open-water period is increasing by 3.2–12 days per decade (Table 3), in some cases resulting in melt seasons that are more than a month longer than they were previously. In some areas, the change is greatest during fall freeze-up (Figure 13). In Resolute Bay, NU, the melt season increased by close to 30 days over a 30-year period, driven primarily by a delay in freeze-up (St-Hilaire-Gravel et al., 2012). The decrease in the extent of sea ice means that fetch is increasing in many coastal regions, resulting in larger waves and increased wave power at the coast (Overeem et al., 2011; Lintern et al., 2013). This, in turn, leads to increased erosion and flooding (e.g., Solomon et al., 1994; Manson and Solomon, 2007;

TABLE 3: Trends in the onset of melt and freeze-up, and duration of the melt season, expressed in days per decade. Values with † are statistically significant at the 95% confidence level or higher. Abbreviation: CAA, Canadian Arctic Archipelago.

Region	Region within*	Subregion*	Period of record	Melt trend	Freeze trend	Melt duration	Source
Arctic	–	–	1979–2013	–2.1†	3.0†	5†	Stroeve et al. (2014)
Canada	Hudson Bay	–	1979–2013	–3.1†	3.4†	6.5†	Stroeve et al. (2014)
Canada	Baffin Bay	–	1979–2013	–4.6†	1.3	5.9†	Stroeve et al. (2014)
Canada	Beaufort	–	1979–2013	–2.7†	6.5†	9.2†	Stroeve et al. (2014)
Canada	CAA	–	1979–2013	–1.0	2.2†	3.2†	Stroeve et al. (2014)
Canada	CAA	–	1979–2008	–3.1†	3.9†	7†	Howell et al. (2009)
Canada	–	Queen Elizabeth Islands	1979–2008	–3.7†	2.9	5.6†	Howell et al. (2009)
Canada	–	West Parry Channel	1979–2008	–3.6†	3.0	6.5†	Howell et al. (2009)
Canada	–	East Parry Channel	1979–2008	–5.1	5.5	10.6†	Howell et al. (2009)
Canada	–	M'Clintock Channel	1979–2008	–3.4	4.4†	7.7†	Howell et al. (2009)
Canada	–	Franklin	1979–2008	–3.2	6.3†	9.5†	Howell et al. (2009)
Canada	–	Baffin Inlets	1979–2008	–4.7†	7.3†	12.0†	Howell et al. (2009)
Canada	–	West Arctic waterway	1979–2008	–1.2	2.6	3.8	Howell et al. (2009)

* Ice-regime regions and subregions (Canadian Ice Service, 2007).

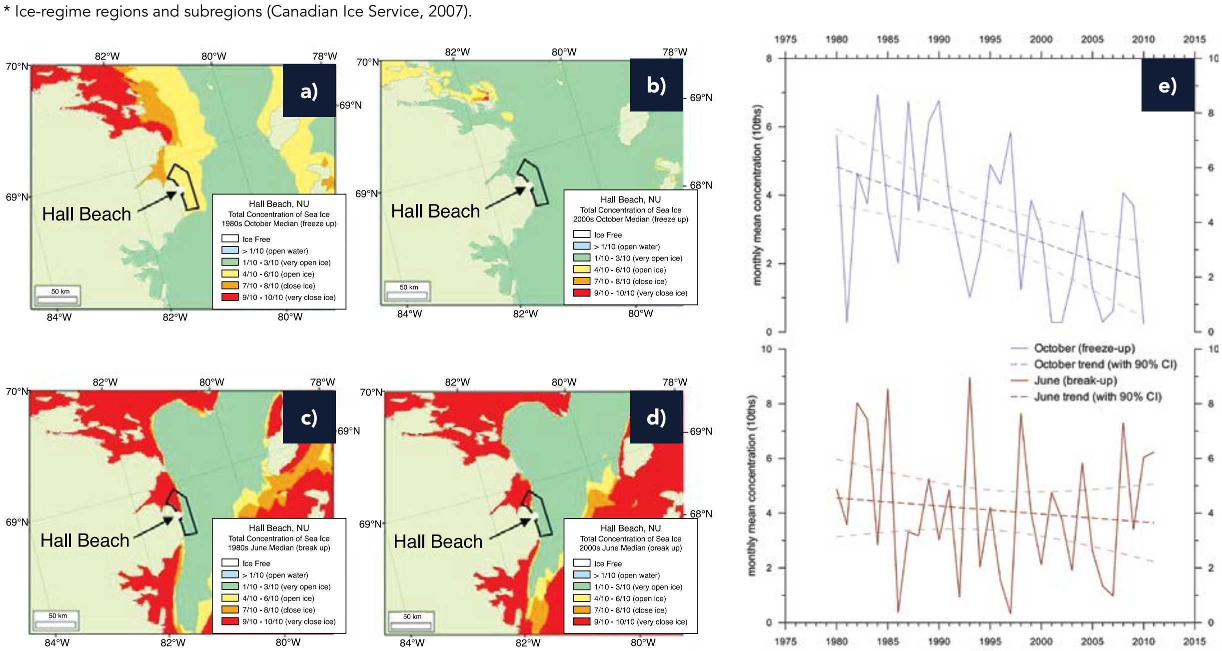

FIGURE 13: Changes in sea-ice concentrations at Hall Beach, NU during freeze-up (October) and break-up (June): **a)** decadal median ice concentrations for October during the 1980s, **b)** decadal median ice concentrations for October during the 2000s, **c)** decadal median ice concentrations for June during the 1980s, **d)** decadal median ice concentrations for June in 2000, **e)** change in concentration during the period of record for October (in blue) and June (in red).

Barnhart et al., 2014). It is also important to note that the greatest increase in fetch generally occurs in September, which is often also the stormiest period of the year (Section 2.2.5; Atkinson, 2005; Manson et al., 2005).

2.4.3 STORM INTENSITY

There is strong evidence that the frequency and intensity of storms in the Arctic are increasing (Arctic Climate Impact Assessment, 2005; Manson and Solomon, 2007; IPCC, 2013; Akperov et al., 2014). The positive correlation between the amount of open water and cyclone intensity in the Arctic suggests that storms will likely be larger and stronger as sea-ice extent continues to decrease (Simmonds and Keay, 2009; Perrie et al., 2012). The consequence of more intense storms on coasts will be greatest in areas of significant fetch, such as the Beaufort Sea (Lintern et al., 2013), and less in areas of more limited fetch, such as the channels of the Queen Elizabeth Islands. The frequency and intensity of storm surges are also likely to continue to increase along susceptible, shallow coastal areas. Lake-sediment records from the outer Mackenzie Delta show 1) a significant correlation between increased air temperature and the occurrence and severity of storm surges, and 2) that surge activity closely matches trends in sea-ice extent (Vermaire et al., 2013).

2.4.4 SEA LEVEL AND EXTREME WATER LEVELS

Observed changes in sea level vary greatly across the North Coast region. Tide-gauge observations over a period of about 50 years indicate that sea level has risen 2.4 mm/year at Tuktoyaktuk, NT and fallen by 1.5 mm/year at Alert, NU (*see* Chapter 2, Figure 19). In contrast, sea level at Churchill, MB has fallen at a much faster rate of 9.3 mm/year during the past 75 years. The differences in observed sea-level change are largely due to differences in vertical land motion and are primarily generated by glacial isostatic adjustment (*see* Chapter 2).

As with observed relative sea-level changes during past decades, projected relative sea-level changes in the North Coast region (Figure 14) differ from location to location, and differ from projections of global sea-level rise (*see* Chapter 2). Factors that affect projected changes in relative sea level, in addition to glacial isostatic adjustment, include dynamic oceanographic changes and gravitational and crustal responses to present-day changes in ice mass that act to reduce projected sea-level change across the Arctic (*see* Chapter 2; James et al., 2014). On the Mackenzie Delta, sediment compaction also contributes to land subsidence (Forbes, 2011).

Where the land is rising rapidly, sea level is projected to continue to fall, even under a high-emissions scenario (Figure 14), with some locations projected to experience

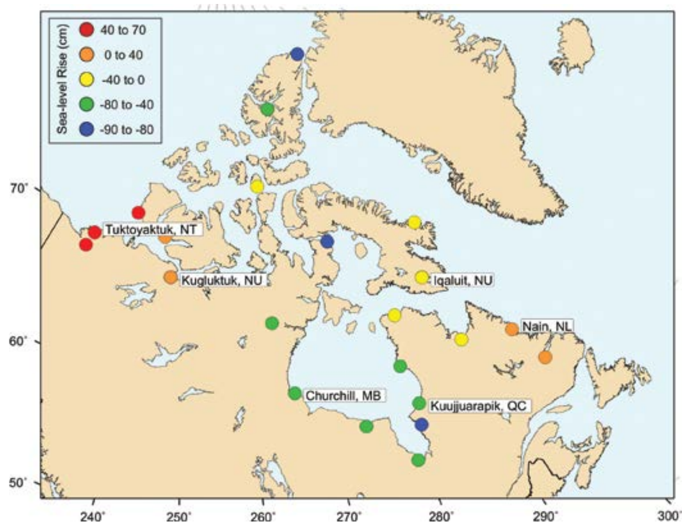

FIGURE 14: Projected median relative sea-level change in 2100 for the high-emissions scenario (RCP8.5; *after* James et al., 2014, 2015). Six labeled locations correspond to those in Figure 15, and projected changes for all sites are presented in Appendix A. See Chapter 2 for a description of scenarios and methods.

more than 80 cm of sea-level fall by 2100. On the other hand, where the land is sinking slowly, sea level is projected to rise more than 40 cm by 2100. Figure 15 presents projected relative sea-level changes through the 21st century at six communities in the North Coast region. Current uplift rates in these communities range from 14 mm/year at Kuujjuarapik, QC to –1 mm/year at Tuktoyaktuk, NT. The uplift rate at Kuujjuarapik is so high that the site is not projected to experience sea-level rise for even the largest sea-level–change scenario considered (high emissions plus Antarctic ice-sheet reduction, which incorporates an additional sea-level contribution from West Antarctica). In contrast, Tuktoyaktuk, which is subsiding, could experience 140 cm of sea-level rise for the same scenario by 2100 (Figure 15).

An important consequence of sea-level rise is the associated increase in extreme-water-level events (*see* Chapters 2 and 3). At Tuktoyaktuk, sea-level rise is projected to increase the frequency of an extreme-water-level event (2.2 m above chart datum) from once every 25 years to about once every 4 years by 2100. Put another way, the height of a 10-year event is expected to increase from 1.1 m to 2.1 m (Lamoureux et al., 2015), signifying substantially increased frequency of extreme-water-level events and concomitant flooding. These values do not take into account the effects of reduced sea ice (Section 2.4.2) and increases in storm intensity (Section 2.4.3), which will increase wave heights across much of the Arctic, including the Beaufort Sea coastline (Khon et al., 2014). These factors will further increase the frequency and magnitude of extreme-water-level events in this region.

In the long term, where sea level is projected to continue to fall (which applies to much of the North Coast region;

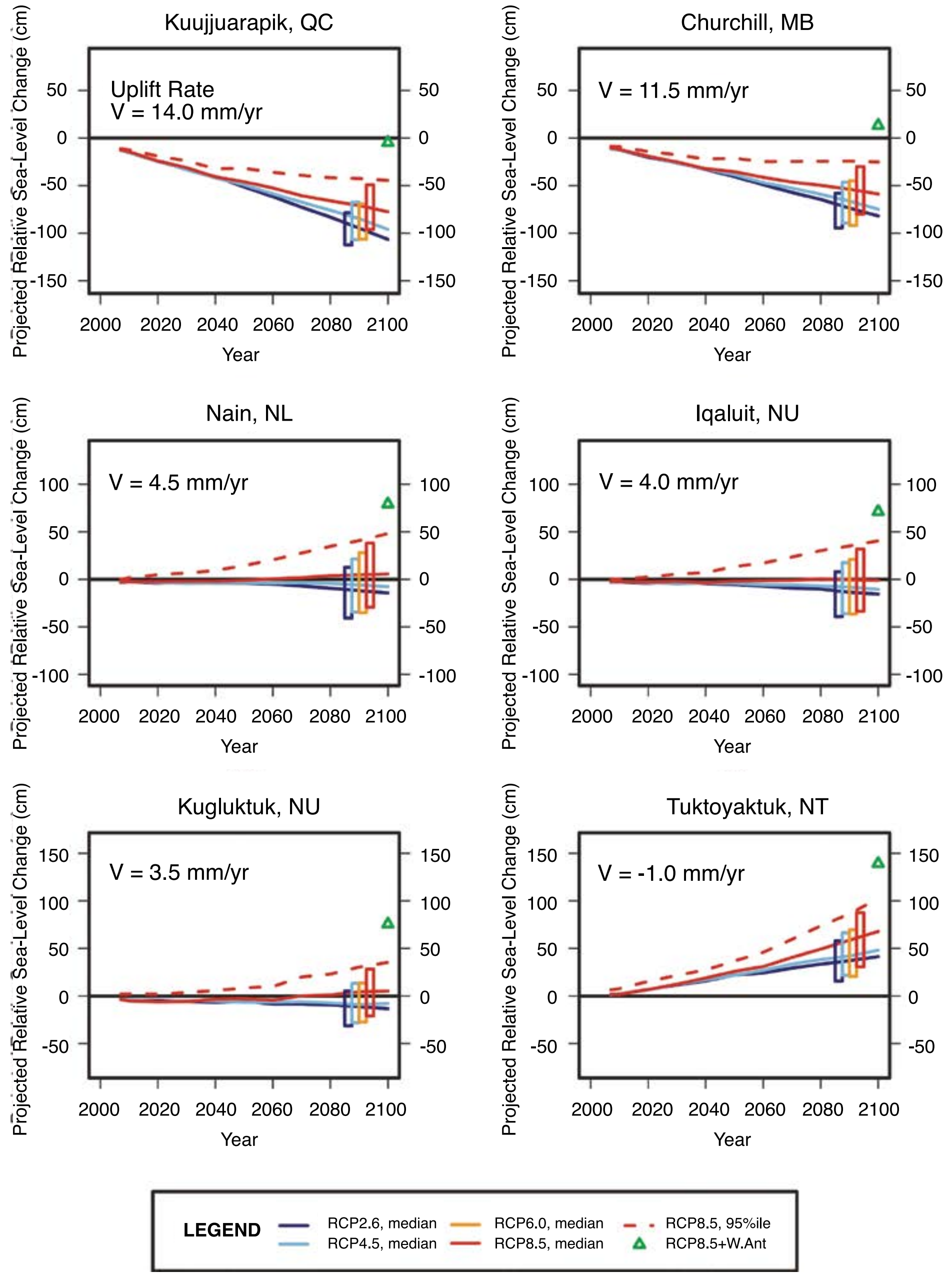

FIGURE 15: Projected relative sea-level change, based on the IPCC Fifth Assessment Report (Church et al., 2013 a, b) and using the vertical (V) crustal motion (uplift rate, given to the nearest 0.5 mm/year, derived from GPS observations) indicated in each panel (James et al., 2014, 2015). Projections are given through the current century for the low-emissions (RCP2.6), intermediate-emissions (RCP4.5) and high-emissions (RCP8.5) scenarios. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario (RCP8.5+W.Ant; green triangle). Rectangles show the 90% confidence level (5–95%) of the average projection during the period 2081–2100 and also include the RCP6.0 scenario; the dashed red line shows the 95th percentile value for the high-emissions scenario. *See* Chapter 2 for further explanation of scenarios. Projections for all sites indicated in Figure 14 are given in Appendix A.

Figure 14), the reduced elevation of mean sea level will contribute to reduced occurrence of extreme-water-level events over the course of this century. In the short term, however, changes to sea-ice extent and duration and to storm intensity in many areas are expected to lead to increased frequency and magnitude of extreme-water-level events and coastal erosion, even in locations where sea level is falling. In particular, with later freeze-up extending the open-water season into the fall storm season when higher waves may occur, the overall probability of a wave event increases. This is also when the seasonal depth of thaw in the beach face is close to maximum and hence the period when the coast is most vulnerable to erosion (Hansom et al., 2014).

2.4.5 PERMAFROST

Comprehensive overviews of the state of permafrost in Canada and how it has been changing in recent decades (e.g., Burn and Kokelj, 2009; Smith et al., 2013; Ednie and Smith, 2015) indicate that, with few exceptions, permafrost temperatures are increasing (Figure 16). These trends are projected to continue as the climate continues to warm (e.g., Woo et al., 2007; IPCC, 2013). Regions that experience the greatest thermal responses, however, are not necessarily the ones that exhibit the greatest physical impacts (Smith and Burgess, 2004). For example, if there is a large increase in ground temperature but the ground has a very low ground ice content, the physical impacts of permafrost warming will be minimal.

Higher permafrost temperatures can intensify coastal processes, such as thawing of the shore face (Aré et al., 2008), block failure (Hoque and Pollard, 2009) and retrogressive thaw slumping (Section 2.2.3; Lantuit and Pollard, 2008). Increased temperature of permafrost is generally associated with an increase in the thickness of the active layer, which can, in turn, destabilize coastal infrastructure. Several northern communities have incorporated research on changing permafrost conditions into their coastal adaptation planning (e.g., Couture et al., 2002; Forbes et al., 2014).

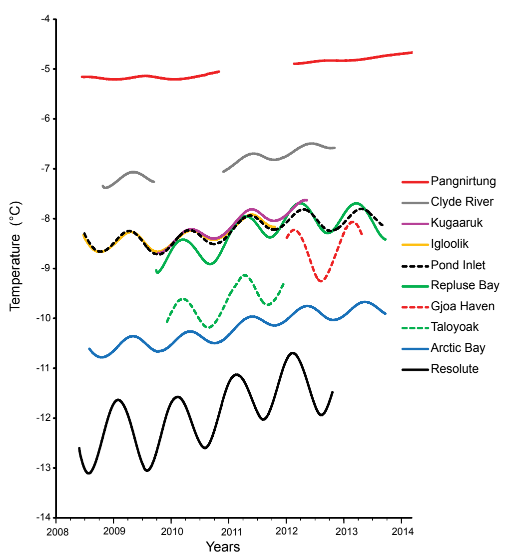

FIGURE 16: Permafrost temperatures at 15 m depth for 10 communities in Nunavut (*from* Ednie and Smith, 2015). Steady increases are seen at all sites during the period of observation, ranging from 0.04°C/year in Igloolik to 0.29°C/year in Resolute. The average increase is 0.15°C/year for all sites.

2.5 INDIGENOUS OBSERVATIONS OF CLIMATE CHANGE

Traditional knowledge refers to "a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission" (Berkes, 1999, p. 8). Traditional knowledge (TK) is widely recognized to hold valuable insights for understanding how the climate of the northern coastline is changing and documenting associated impacts (Riedlinger, 1999, 2001; Riedlinger and Berkes, 2001; Fox, 2002; Furgal et al., 2002; Nickels et al., 2002; Thorpe et al., 2002; Ford and Smit, 2004; Gearheard et al., 2006; Tremblay et al., 2006; Smith and Sharp, 2012).

Riedlinger and Berkes (2001) identified five ways that TK complements scientific approaches to understanding climate change and adaptation including:

- **TK as local-scale expertise:** Complex global-climate models have limited ability to describe change at a local or regional scale. TK can help bring in an additional understanding of environmental and social change, and can highlight complex feedback loops and connections between climate and biophysical environments (Riedlinger and Berkes, 2001; Gearheard et al., 2006).
- **TK as a source of climate history and baseline data:** TK can complement other data sources in creating a past climate history by providing specific perceptions based on past cumulative experience. Storytelling and oral histories, for instance, have been widely used to help elucidate climatic conditions throughout the 20th century and beyond (MacDonald, 1998; Cruikshank, 2001; Aporta, 2002, 2011; Berkes and Jolly, 2002; Duerden, 2004; Ford et al., 2006a; Aporta and MacDonald, 2011). For example, elders from Sachs Harbour, NT talk about extreme ice years, such as the 'cold ice year' of 1933, in their stories about travelling between hunting and trapping locations (Riedlinger and Berkes, 2001).
- **Insights into impacts and community adaptation:** Adapting to change is an inherent part of livelihood systems and culture for northern coastal Indigenous communities. TK provides insight both into the ways climate change is manifest (Table 4) and into how local community members see, understand and experience these impacts and cope with changes. One example from Igloolik, NU relates to nigajutait/putlaujaraq (small pockets of open water that remain as the ice is freezing/air pockets underneath ice). When these phenomena occur during autumn freeze-up, hunters use harpoons to test ice thickness and determine whether it is safe for walking, dog sledding or snowmobiling (Laidler and Ikummaq, 2008; Laidler et al., 2009). This technique is an adaptive strategy for coping with sea-ice change based on a long tradition of understanding the fine details of local sea-ice processes and formation (Laidler et al., 2009).

TABLE 4: Community observations of environmental change in the northern coastal region, compiled from the various sources cited in Section 2.5.

WEATHER

Observations based on traditional knowledge (TK)	Northwest Territories (Inuvialuit Settlement Region)	Nunavut	Quebec (Nunavik)	Labrador (Nunat-siavut)	Quebec (southern Hudson Bay [Cree])	Implications (generalized across communities)
Increasing variability and decreased ability to predict weather	Yes	Yes	Yes	Yes	Yes	Increased danger when travelling on land or ice
Changes in wind velocity, direction and frequency	Yes	Yes	Yes	Yes	Yes	Increased danger when travelling on land or ice; decreased reliability of TK
Increased frequency of thunderstorms and extreme weather events	Yes	Yes	Yes	Yes	No	Increased danger when travelling on land or ice; increased damage to infrastructure; constrained access to resource harvesting; accelerated coastal erosion
Differences in snow: less snow in winter, but more snow in some cases; arriving later in the fall/ winter; lighter and wetter in texture	Yes	Yes	Yes	Yes	Yes	Increased danger/difficulty when travelling on land or ice; constrained access to hunting grounds; changes in hunting routes; decreased reliability of TK; implications for sea-ice freeze-up and break-up, and ice consistency and reliability
Increased storm surges and coastal erosion	Yes	Yes	No	No	No	Increased danger when travelling on land or ice; increased damage to infrastructure; constrained access to resource harvesting; accelerated coastal erosion
Increased rain (usually in fall and/ or spring, summer)	Yes	Yes	No	No	No	Implications for infrastructure; implications for sea-ice freeze-up and break-up, and ice consistency and reliability

TEMPERATURE

Observations based on traditional knowledge (TK)	Northwest Territories (Inuvialuit Settlement Region)	Nunavut	Quebec (Nunavik)	Labrador (Nunat-siavut)	Quebec (southern Hudson Bay [Cree])	Implications (generalized across communities)
Warmer summer (in some communities)	Yes	Yes	Yes	Yes	No	Implications for aging processes of traditional foods; changing flora/fauna; implications for sea ice
Cooler summer (in some communities)	Yes	Yes	No	Yes	No	Implications for aging processes of traditional foods
Warmer winter; fewer cold days; winter starting later	Yes	Yes	Yes	Yes	Yes	Implications for aging processes of traditional foods; changing flora/fauna; implications for sea ice and travel on ice

ICE DYNAMICS

Observations based on traditional knowledge (TK)	Northwest Territories (Inuvialuit Settlement Region)	Nunavut	Quebec (Nunavik)	Labrador (Nunat-siavut)	Quebec (southern Hudson Bay [Cree])	Implications (generalized across communities)
Earlier sea-ice break-up	Yes	Yes	Yes	Yes	No	Constrained access to hunting grounds; increased danger when travelling on ice; lengthening of shipping season
Thinning of ice	Yes	Yes	Yes	Yes	No	Increased danger when travelling on ice and risk of breakoff; more difficulty predicting thickness
Slower sea-ice freeze-up	Yes	Yes	Yes	Yes	No	Constrained access to hunting grounds; increased danger when travelling on ice
Changes in colour and texture/ consistency of ice	Yes	Yes	No	Yes	Yes	Increased danger when travelling in ice; more difficulty predicting thickness and safety; increased break-off events (especially at the floe edge)
Less or no multiyear ice in the summer; more open water and rougher water in some areas; changes in floe-edge location	Yes	Yes	No	No	No	Increased length of shipping season; floe edge closer to town; constrained and increased access to different hunting grounds; wildlife changes
Changes in river and lake ice: thinning ice, earlier break-up, later and slower freeze-up	Yes	No	Yes	No	Yes	Increased danger when travelling on ice; more difficulty predicting thickness and safety; constrained access to hunting grounds and trails

GEOMORPHOLOGICAL PROCESSES AND VEGETATION

Observations based on traditional knowledge (TK)	Northwest Territories (Inuvialuit Settlement Region)	Nunavut	Quebec (Nunavik)	Labrador (Nunat-siavut)	Quebec (southern Hudson Bay [Cree])	Implications (generalized across communities)
Permafrost thaw	Yes	Yes	Yes	Yes	No	Infrastructure damage; decrease in available land for development
Increases in coastal erosion	Yes	Yes	Yes	No	No	Damage and loss of cultural sites and infrastructure; relocation of buildings in some communities
Land subsiding in some areas	Yes	Yes	No	No	No	Infrastructure damage; decreased availability of land for development
More mud on the land and drainage issues	Yes	Yes	Yes	No	No	Damage to infrastructure; changes to hunting routes; decreased availability of land for development
Changes in flora	Yes	Yes	Yes	Yes	Yes	Species switching; changes in fauna
Changes in water levels of lakes and rivers	No	No	Yes	No	Yes	Flooding; implications for infrastructure; coastal erosion; implications for fauna

WILDLIFE

Observations based on traditional knowledge (TK)	Northwest Territories (Inuvialuit Settlement Region)	Nunavut	Quebec (Nunavik)	Labrador (Nunat-siavut)	Quebec (southern Hudson Bay [Cree])	Implications (generalized across communities)
Changing migration behaviour	Yes	Yes	Yes	Yes	Yes	Changes in hunting practices and routes; changes in availability of country food for consumption
Decline in animal health in some species or changes in species body composition (i.e., thinner fur, skin or hides)	Yes	Yes	No	No	No	Changes in availability of country food for consumption
Changes in population numbers	Yes	Yes	No	No	Yes	Changes in hunting practices and routes; changes in availability of country food for consumption; imposition of import ban by the United States on polar bear skins
Changes in species	No	Yes	Yes	No	Yes	Species switching; changes in hunting practices and routes; changes in availability of country food for consumption

3 VULNERABILITY

Canada's northern coasts are already experiencing rapid environmental changes. The inherent biophysical sensitivity of coasts, as well as the magnitude of projected future climate changes in the Arctic, suggest that northern coastal communities are likely to be highly susceptible to future climate impacts. This section reviews knowledge on the potential vulnerability of northern communities and economies by sector: infrastructure and transportation, health and well-being, business and economy, culture and education, and subsistence harvesting (Ford and Pearce, 2010; Ford et al., 2012a, b). The majority of published work in this area focuses on Inuit communities. Case studies are included to provide more in-depth discussion of sector-wide issues or highlight examples of specific issues.

3.1 INFRASTRUCTURE AND TRANSPORTATION

Transportation networks and infrastructure along northern coasts are uniquely sensitive to climate change impacts due to the importance of permafrost and sea ice. Research in this sector focuses on two key areas: the built environment (including port infrastructure) and semiperma-nent trails between communities. Shipping is addressed in Section 3.3.

3.1.1 BUILT ENVIRONMENT

The built environment along northern coasts is defined here to include roads, buildings, airstrips, port facilities, water and waste-water treatment facilities, drainage infrastructure, communication (transmission lines), pipelines and industrial facilities (e.g., mine sites and mine-access roads). The built environment is a key determinant of both community well-being and future sustainable growth. While new infrastructure investment has the opportunity to incorporate consideration of a changing climate, existing infrastructure faces a range of risks and opportunities, as well as options for adaptation (Case Study 2).

CASE STUDY 2

PORT OF CHURCHILL, MB

The Port of Churchill is Canada's largest and only deep-water port on the northern coast (Figure 17), making it a strategic location for freight transportation for the Arctic and Atlantic oceans. It has four berths, including a tanker berth that can accommodate Panamax-size vessels. Constructed in the 1930s, the port and rail link to The Pas, MB, were purchased by OmniTRAX in 1997 and continue to operate under the Hudson Bay Port Company and Hudson Bay Railway (HBR; Port of Churchill, no date). Together, the rail line and the port provide a key trade connection, with the port's primary uses being international shipping (e.g., exporting grain from Western Canada to North African, Europe, Middle Eastern, South American and Mexican markets) and shipping resupply of dry goods, fuel and industrial cargo for Nunavut's Kivalliq region. The Churchill Gateway Development Corporation was created in 2003 to

FIGURE 17: The Port of Churchill is the only deep-water port in Canada's North Coast region. *Photo courtesy of the Hudson Bay Route Association.*

advocate for expansion and diversification of Churchill as a gateway to northern Canada.

Challenges currently facing the port include 1) a short shipping season (marine access for 14–16 weeks); 2) a heavy reliance on grain shipping; 3) reliability and efficiency of the rail supply chain; 4) difficulties with marine insurance extensions and low Coast Guard support for navigation in challenging waters; 5) an aging port infrastructure that requires significant financial investment to update and expand; and 6) competition from ports in Thunder Bay and Québec. Many of these challenges relate to climate risks, which climate change may exacerbate while also providing new opportunities for growth. For example, the increasing length of the open-water season is creating potential for port expansion and growth, with projections that the shipping season could increase by as much as two weeks at both ends of the summer and fall window (Section 3.3). Application of the Public Infrastructure Engineering and Vulnerability Committee protocol (Public Infrastructure Engineering Vulnerability Committee, 2007) to the port infrastructure identified factors such as increased freeze-thaw cycles, high-intensity rainfall and increased storminess as key climate impacts. More than 450 potential climate interactions were examined, with 21 identified as medium risk and requiring additional analysis (Stantec, 2015).

Greater risks relate to the single-track HBR railbed that supplies the port. Substantial usage and maintenance problems are being caused by 1) thawing of the discontinuous permafrost; 2) the poor geotechnical properties of the muskeg soil that underlies the railbed; and 3) heavy precipitation events that lead to landslides, flooding and washouts on the tracks (Bristow and Gill, 2011; Addison et al., 2015). These adverse effects are projected to worsen as climate change continues, posing increased risk for land-based transportation infrastructure connecting the port (Bristow and Gill, 2011). Adaptation measures proposed to address these risks include new engineering technologies that can help stabilize permafrost terrain, using gravel instead of pavement for road construction (e.g., Manitoba–Nunavut highway proposal) and building bridges to the highest ratings (Bristow and Gill, 2011).

In 2013, a federal and provincial task force on the future of Churchill was commissioned to examine future opportunities. The 5-year Churchill Port Utilisation Program, started in 2012, provides economic incentives for the shipment of eligible grain through the port and diversification of resource exports to include, for example, potash, liquid natural gas and crude oil. The goals include opening the North's undeveloped markets to greater competition, strengthening business ties between Manitoba and Nunavut, and developing new grain-industry players.

There are three distinct approaches to assessing vulnerability of the built environment evident in the literature (Champalle et al., 2013): community-, engineering- and sectoral-based assessments.

Community-based vulnerability assessments integrate science and local/traditional knowledge with a strong emphasis on understanding the decision-making processes that govern how climate risks to the built environment are managed. Barriers to adaptation at the community level include 1) difficulties accessing information about climate change (Box 3), 2) a lack of clear jurisdiction or protocols for addressing the impacts of climate change on the built environment, 3) the cost of climate-proofing infrastructure, and 4) understaffing within municipalities (Andrachuk and Pearce, 2010; Ford et al., 2010a; Hovelsrud and Smit, 2010;

BOX 3

ARCTIC ADAPTATION EXCHANGE PORTAL

The Arctic Council identified access to information resources as a barrier that many northerners face with respect to understanding and responding to climate change impacts (Arctic Council, 2015). To address the issue, an adaptation information portal was developed through the Council's Sustainable Development Working Group. Entry to the portal is through the Adaptation Exchange website that was launched in 2015 (www.arcticadaptationexchange.com). The portal facilitates knowledge exchange on climate change adaptation in the circumpolar North and serves as a central information hub for communities, researchers and decision makers in the public and private sectors. Pearce et al., 2010a;

Boyle and Dowlatabadi, 2011). Some communities have developed adaptation plans targeted at the built environment that identify recommended activities, the entity responsible for implementation and priority actions (Case Study 3; Callihoo and Ohlson, 2008; Callihoo and Romaine, 2010; Hayhurst and Zeeg, 2010; Johnson and Anold, 2010).

CASE STUDY 3

PLANNING FOR PERMAFROST THAW IN NUNAVUT

Permafrost temperatures have increased during the last 20–30 years across almost all of the Arctic. Although collecting *in situ* permafrost data helps quantify changes and informs planning for future impacts, it is time consuming and challenging (Vaughan et al., 2013). As a result, other techniques are required to identify permafrost degradation, including the use of satellite data (Vaughan, et al., 2013). The Terrain Analysis in Nunavut project, managed by the Government of Nunavut's Department of Community and Government Services, involves seven communities: Arviat, Baker Lake, Kimmirut, Gjoa Haven, Cape Dorset, Pangnirtung and Kugluktuk (Government of Nunavut, 2013). The objective is to identify ground that is susceptible to climate change impacts using radar satellite images, digital elevation models, optical images, site visits and local knowledge. This information is converted into hazard maps that rank the suitability of land for future development. Decision makers, such as planners and engineers, will use these maps in developing municipal community plans (Mate et al., 2012).

Community engagement is a key aspect of the project. Mechanisms used include information nights, radio interviews, school information sessions and open discussions. During summer 2013, such events were held in the Hamlet of Arviat to engage community leaders, local businesses, the housing sector, elders and youth. Preliminary results of the land-suitability map for Arviat were displayed, along with presentations and a short documentary by a local Arviat Youth Media team. Discussions were held regarding the decision-making process in planning and construction, impacts of permafrost on local buildings and the consideration of different foundation types or building designs. Community elders shared their knowledge on landscape changes and their experience with walls cracking and shifting foundations (Nunavut Climate Change Centre, no date). The project is expected to give communities the tools and policies for better land management to minimize infrastructure failure due to permafrost degradation.

Engineering-based vulnerability assessments in the North Coast region examine mainly the risks posed by permafrost thaw on specific infrastructure assets, based on geotechnical profiles, field inspections by engineers, stakeholder consultations and/or permafrost modelling. The Ministère des Transports du Québec (MTQ) identified permafrost thaw to be affecting nine of thirteen MTQ airport-infrastructure facilities in Nunavik, causing significant settling (Boucher and Guimond, 2012). Assessment of the vulnerability of building foundations in Inuvik, NT documented poor functioning of thermosyphon foundations due to poor design/construction of the granular pads on which the thermosyphon evaporator pipes are founded and inadequate insulation design (Holubec Consulting Inc., 2008). Assessment of the vulnerability of buildings to permafrost degradation in three NWT coastal settlements identified opportunities for building design to minimize potential risk, indicating that 'informed adaptation' could reduce the cost of impacts by one-third relative to costs when no actions are taken (Zhou et al., 2007). Engineering studies also inform the development and monitoring of specific measures to address coastal erosion.

Sectoral-based vulnerability assessments focus on infrastructure within specific sectors. In northern Canada, there has been a particular focus on what climate change means for mining (Box 4; Ford et al., 2010d; Pearce et al., 2010a). Climate change sensitivities relate to the potential impacts of permafrost thaw, frost heave and freeze/thaw on infrastructure and tailings stability, and the impacts of extreme weather events on mine operations. Efforts to design mine infrastructure to incorporate climate change considerations have been limited to date, creating potentially significant vulnerabilities, particularly in the post-operational phase of mines (Pearce et al., 2010a).

Other studies have examined the vulnerability of energy-transmission infrastructure within northern coastal communities. Changing storm tracks, with stronger temperature advection, stronger updrafts and more moisture, could increase the probability of freezing precipitation and stronger storms (Roberts and Stewart, 2008; Roberts et al., 2008), with implications for energy-transmission infrastructure. These include electrical wires, where there is concern about the thickness of wires compared to those in the south, and potential susceptibility to ice storms (Roberts and Stewart, 2008). The energy sector is also affected by increased variability in streamflow throughout northern regions (Barber et al., 2008), which will impact hydroelectricity production (Dery et al., 2009).

BOX 4
CLIMATE CHANGE AND MINING INFRASTRUCTURE IN NORTHERN CANADA

Ongoing climate change has implications for resource-extraction activities in northern coastal regions. Some changes, particularly reduced sea-ice cover, could provide benefits for mining in the region as a result of shorter shipping routes and longer shipping seasons (Lemmen et al., 2014). Most research on mining infrastructure is focused on climate risks. Depending on the nature and location of a mine, different components, including containment facilities, buildings, energy sources, transportation networks and mine-site drainage, may be affected by permafrost thaw, rising average temperatures and extreme precipitation events (Ford et al., 2010b, 2011b; Pearce et al., 2011a). Historical changes in these parameters have, in some cases, weakened the structural integrity and safety of ice roads, bridges, pipelines and airstrips, and the walls of open-pit mines and containment structures. The risk of structural failure due to projected climatic changes is a concern at several operating and abandoned or orphaned mines across northern Canada.

3.1.2 SEMIPERMANENT TRAILS

Small Indigenous communities are heavily reliant on semipermanent trails on sea ice, and on terrestrial environments and river/lake ice, for harvesting and recreational travel. Changing snow and ice regimes, less predictable weather and changing wind patterns are making travel more dangerous and less dependable, compromising the ability of residents to engage in harvesting activities (Case Study 4; Tremblay et al., 2008; Laidler et al., 2009; Peloquin and Berkes, 2009; Lemelin et al., 2010; Gearheard et al., 2011; Ford et al., 2013b). A survey of residents in Nain, NL revealed that, during the anomalously warm winter of 2009–2010, about half couldn't use their typical travel routes and took more sea-ice travel risks, and about three-quarters reported being unable to predict ice conditions and were afraid to use the ice. Close to one in twelve sea-ice users surveyed had fallen through the ice that winter (Furgal et al., 2012).

CASE STUDY 4
ADAPTING WINTER TRAVEL

More variable and less predictable sea-ice and snow conditions are compromising the use of winter trails, affecting safety, access to country food and firewood, and intergenerational transmission of land skills (Riedlsperger et al., in press). Local sea-ice users around Makkovik and Postville, Nunatsiavut, NL have reported that recent mild winters have increased the occurrence of travel hazards, noting that their confidence in travelling in these areas has decreased during their lifetime. Residents have identified dangerous travel areas and abandoned some sea-ice travel routes that are less sheltered from open-sea conditions (Figure 18). Inland trails are less affected by climate variability and change, and many Inuit community governments have adapted to changing conditions by establishing or upgrading inland groomed trails that provide dependable and safer access to harvesting and hunting sites.

For situations where inland trails are not a viable option, a new integrated, community-based, sea-ice information gathering and dissemination system is being developed and piloted with communities in Nunatsiavut and Nunavut (Bell et al., 2014). SmartICE (Sea-Ice Monitoring And Real-Time Information for Coastal Environments; http://nainresearchcentre.com/research-projects/smartice/) complements existing regional-scale sea-ice charts (e.g., Laidler et al., 2011) by providing observations and local knowledge of sea-ice thickness and surface features

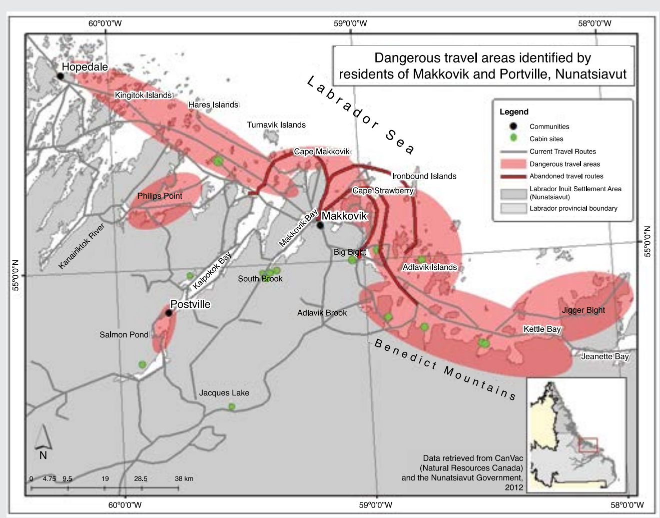

FIGURE 18: Dangerous travel areas (red) identified by residents of Makkovik and Postville, Nunatsiavut, NL (*from* Riedlsperger, 2013). Abandoned sea-ice travel routes are depicted as dark red lines. Inland trails (grey lines) now provide safer and more dependable travel routes.

relevant to local travel safety (Figure 19). The main technology elements of the system are 1) a network of automated *in situ* sensors that measure sea-ice thickness and other characteristics, and transmit the data via Iridium satellite; 2) an adapted ground-conductivity meter for use as a sled-based autonomous ice-thickness sensor (Haas et al., 2011); 3) repeat satellite imagery from which sea-ice surface conditions (e.g., concentration, roughness, water content) are mapped following user-defined classification systems; and 4) information technology that integrates the *in situ* and remotely sensed sea-ice data to generate raw and processed digital products that match the needs of user groups, from ice-navigation managers to Inuit ice experts to recreational ice users. SmartICE strives to augment Inuit *Qaujimajatuqangit* (traditional knowledge) about local sea-ice conditions, not replace it.

Other adaptation responses include upgrading equipment and improving trail maintenance, using more powerful snowmobiles, adopting more flexible subsistence activities, strengthening traditional-knowledge and skill-learning programs, and enhancing collaboration and formal sharing networks (Riedlsperger, 2013). Barriers to adaptation include financial and human-resource constraints, which can prevent access to the most suitable equipment for travel safely, as well as regulations that reduce flexibility in where and when to travel, such as mandatory hunting and trapping permits (Riedlsperger, 2013).

FIGURE 19: Community ice-monitoring station in Nain, NL, with a prototype SmartICE sensor frozen into the ice (right foreground). The sensor sends daily measurements of sea-ice thickness via satellite to the SmartICE data portal. *Photo courtesy of R. Briggs.*

Fall freeze-up is a time of the year characterized by acute danger and constrained access, and climate warming and more variable temperatures will act to prolong the period of ice instability (Laidler et al., 2009). For communities that engage in late spring–early summer floe-edge hunting, such as along eastern Baffin Island, NU, or that use floating pack ice as a hunting platform, more dynamic ice conditions have been particularly problematic. Various adaptations have been documented in response to these changes, including changing the timing and location of harvesting activities, switching species harvested and hunted, developing new travel routes and avoiding travel at certain times and locations (Gearheard et al., 2006; Ford et al., 2008; Tremblay et al., 2008; Aporta, 2011; Ford et al., 2013b). Traditional knowledge, social networks and technology such as satellite phones, SPOT devices and GPS have all been identified as foundations for this adaptive action, although many studies document concerns over a weakening of land skills and traditional knowledge among younger generations (Peloquin and Berkes, 2009; Pearce et al., 2011b; Pearce et al., 2015).

3.2 HEALTH AND WELL-BEING

The health impacts of climate change on northern coastal communities will be multifaceted (Table 5). They may be direct, resulting from changes in temperatures and/or extreme climate events (Furgal et al., 2008; Parkinson and Berner, 2009), or they may be indirect, resulting from how climate change affects livelihoods, infrastructure, wildlife and infective agents (Furgal et al., 2002; Furgal and Seguin, 2006; Healey et al., 2011). Studies have focused mainly on Indigenous populations, primarily small Inuit communities, with a strong emphasis on food security and travel danger. Water security, mental health and the implications of climate change for contaminants are emerging areas of study (Constant et al., 2007; McKinney et al., 2009). Key determinants of how climate change will affect health include the following:

Socio-Economic Conditions: those living in the North, particularly Indigenous people, are at higher risk of living in poverty, experiencing housing and food insecurity, and experiencing higher rates of acute gastrointestinal illness (Raphael et al., 2008; Young and Chatwood, 2011; Chatwood et al., 2012; Young, 2013; Harper et al., 2015a, b). Poverty has been documented to influence vulnerability to the health effects of climate change in a number of ways in northern coastal communities.

At the individual and household level, poverty increases sensitivity to climate risks by forcing people to live in suboptimal conditions and increasing the risk of engaging in unhealthy behaviours (Ford et al., 2010c). Overcrowding in inadequate housing, and food and water insecurity, for example, have been identified as chronic poverty-related problems facing northern coastal communities, and have been identified to increase the risk of spread of infectious diseases, favour transmission of respiratory and gastrointestinal diseases, and increase susceptibly to heat stress. These climate-related health outcomes are expected to become more prevalent with climate change (Furgal and Seguin, 2006; Parkinson et al., 2008; Harper, 2014). Studies indicate that people who are nutritionally challenged will be particularly vulnerable to changing access to, and availability and quality of, traditional foods, and more susceptible to increasing incidence of climate-sensitive infectious diseases (Furgal and Seguin, 2006; Ford, 2009b; Hueffer et al., 2013). Ability to manage the impacts of climate change on health at an individual and household level is negatively affected by poverty, as poverty reduces options to adapt to changes in access to traditional foods, with widely documented implications for food security (Furgal and Seguin, 2006; Wolfe et al., 2007; Furgal et al., 2008; Turner and Clifton, 2009; Pearce et al., 2010b).

A number of studies document the pathways through which historical processes, such as relocation into centralized communities and the transforming of livelihoods, education and culture within a generation (Pearce, 2006; Ford et al., 2010c; Cameron, 2012; Ford et al., 2013a; Wolf et al., 2013), affect present-day vulnerability of northern Indigenous societies to the health effects of climate change. For example, mental-health issues documented among Inuit hunters in response to an increasing inability to hunt due to changing ice conditions have been shown to reflect not only the decreased ability to provide food for family but also a loss of cultural identity and livelihood practices (Case Study 5; Pearce et al., 2010b; Cunsolo Willox et al., 2012; Cunsolo Willox et al., 2013b).

CASE STUDY 5

CLIMATE CHANGE AND HEALTH IN NUNATSIAVUT

Studies in Nunatsiavut, NL provide insights on the impacts of climate change on mental health and water-borne disease. Climate change is already having effects on mental health and well-being (Cunsolo Willox et al., 2012, 2013a, c, 2015). Rapid changes in weather patterns, sea-ice formation and extent, snowfall amounts and surface temperature are combining to disrupt the ability to safely go on the land for hunting, trapping, harvesting and travelling to cabins. Since the land is essential and foundational to mental health and well-being, these disruptions are leading to mental-health impacts through several interconnected pathways, including:

- strong emotional responses, such as anxiety, depression, grief, anger and sadness;
- increased family stress, due to being confined in often-overcrowded houses and being unable to enjoy land time as a family;

TABLE 5: Potential direct and indirect health impacts of climate change in the Canadian north (based on Furgal and Seguin, 2006).

Identified climate-related change	Examples of potential health impacts
Increased magnitude and frequency of temperature extremes (Direct)	▪ Increased heat- and cold-related morbidity and mortality ▪ Respiratory stress in summer among high-risk populations (e.g., elderly, those with decreased respiratory health)
Increase in frequency and intensity of extreme weather events (e.g., storms) (Direct)	▪ Increased frequency and severity of accidents while hunting and travelling, resulting in injuries, death, psychological stress
Increased magnitude and frequency of temperature extremes (Indirect)	▪ Increase in incidence and transmission of infectious disease, psychosocial disruption ▪ Changing animal travel/migration routes
Decrease in ice distribution, stability and duration of coverage (Indirect)	▪ Increased frequency and severity of accidents while hunting and travelling, resulting in injuries, death, psychosocial stress ▪ Decreased access to country foods; decreased food security, erosion of social and cultural values associated with preparation, sharing and consumption of country foods
Change in snow composition (Indirect)	▪ Challenges to building shelters (igloo) for safety while on the land
Increase in range and activity of existing and new infective agents (e.g., biting flies) (Indirect)	▪ Increased exposure to existing and new vector-borne diseases
Change in local ecology of water-borne and foodborne infective agents (introduction of new parasites) (Indirect)	▪ Increase in incidence of diarrheal and other infectious diseases ▪ Emergence of new diseases
Increased permafrost melting, decreased structural stability (Indirect)	▪ Decreased stability of public health, housing and transportation infrastructure
Sea-level rise (Indirect)	▪ Physical impacts and psychosocial disruption associated with infrastructure damage and community relocation (partial or complete)

- potential increases in drug and alcohol usage and thoughts about suicide, due to disruptions to livelihoods, impacts to sense of identity, loss of self-worth, and deep sadness and depression from no longer being able to go out on the land and being forced to spend more time in the community without meaningful activities or employment opportunities; and
- magnification or amplification of previous or ongoing sources of stress and distress, including intergenerational trauma from residential schools and forced relocation, loss of traditional knowledge and activities, and impacts to sense of identity.

Other studies are examining how a changing climate may increase the risk of water-borne disease in northern coastal communities. In many small communities, some residents prefer to drink untreated brook water while out on the land, at their cabins or in the community. A collaborative community-based project examined the relationship between weather patterns (especially rainfall and snowmelt), water quality, and diarrhea and vomiting in Nain and Rigolet, NL (Harper et al., 2011a, b). The communities co-designed environmental monitoring plans (2005–2008), which included microbial testing of brook water at locations where community members commonly collect untreated water to drink. Results indicated that increased rainfall and snowmelt were significantly associated with increased *Escherichia coli* (*E. coli*) and total coliform concentrations in untreated brook water; and, 2–4 weeks after heavy rainfalls or rapid snowmelts, there was a significant increase in clinic visits for diarrhea and vomiting.

Dependence On The Environment: many northern coastal communities maintain a close relationship with the land, sea, ice and local environmental resources for livelihoods, culture, diet and well-being, which increases sensitivity to climate-related risks. Climate change–related impacts on hunting trails (Section 3.1.2) and wildlife-migration patterns constrain access to, and the availability of, traditional land-based foods (Krupnik and Jolly, 2002; Wesche and Chan, 2010; Kunuk and Mauro, 2011; Ford et al., 2012a). Since traditional foods are often transported and stored outdoors using traditional practices, rising temperatures may also increase the risk of foodborne disease (Furgal et al., 2008; Parkinson and Berner, 2009; Parkinson and Evengard, 2009). The collection and drinking of untreated ice and surface water, a traditional practice in many regions, can increase exposure to water-borne pathogens that could be magnified by climate change (Martin et al., 2007; Harper et al., 2011a, b). Heavy rainfall and rapid snowmelt have been linked with higher levels of *E. coli* and associated illness due to consumption of untreated drinking water (Case Study 5; Harper et al., 2010, 2011a, b).

Residents of northern coastal communities are also exposed to a variety of zoonoses (infectious diseases transmitted to humans from animal hosts by direct contact) through contaminated food or water and by insect and tick vectors. Northern Canadians are particularly at risk through consumption and preparation of traditional foods (Proulx et al., 2002; Gajadhar et al., 2004; Simon et al., 2011). Eating sea-mammal meat raw (e.g., seal, walrus), for example, increases the risk of parasitic diseases such as trichinellosis and toxoplasmosis. The proportion of animals infected is believed to be low, but the practice of community-wide sharing of meat from hunted sea mammals increases the impact of individually infected animals. Proximity to hunting and sled dogs increases risks from dog-borne zoonoses, including rabies and a range of endoparasites (Jenkins et al., 2011). Zoonoses are sensitive to climate change, which affects the abundance, migration and behaviour of animal hosts, the survival and abundance of vectors, the survival of pathogens outside the host and the seasonal phenology of lifecycle events. Potential effects of climate change on zoonosis transmission in the North remain unclear, as the ecology of zoonoses and human interactions with them has not been widely studied.

Traditional Knowledge and Culture: the 'traditional knowledge' (TK) of northern Indigenous populations has been identified as a protective factor to the health impacts of climate change (Furgal and Seguin, 2006; Ford et al., 2010c) and plays an essential role in managing climate-related health risks (Ford et al., 2014b). Land skills and knowledge embodied in TK assist northern coastal communities to manage the dangers of hunting, travelling and extreme weather in a rapidly changing climate (Ford et al., 2006a; Pearce et al., 2010a; Aporta, 2011; Gearheard et al., 2011; Heyes, 2011). New vulnerabilities are emerging that are associated with a weakening of traditional knowledge systems due to long-term processes of cultural change (Furgal and Seguin, 2006; Ford et al., 2008; Ford et al., 2010b). For example, reduced transmission of cultural knowledge and related land skills from older to younger generations, documented in work with Inuit communities, has reduced environmental 'apprenticeship' opportunities and may contribute to increased accidental injuries of youth engaged in land activities, exacerbating the impacts of climate change (Pearce et al., 2010a).

3.3 BUSINESS AND ECONOMY

The characteristics of northern economies and the nature of economic development will influence the impacts of future climate change. New opportunities for economic development may provide access to cash resources and assist in reducing the poverty that lies at the heart of vulnerability to many climate-related risks. Economic development could also erode the characteristics that have historically underpinned adaptive capacity in northern coastal communities, including sharing networks, social capital, resource-use flexibility and traditional-knowledge systems. It could also further stress wildlife resources that are already impacted by climate change (Wenzel, 1995a, 2005; Ford et al., 2006a, b; Wenzel, 2009). External factors, including market price, transportation access, government policy and international regulations, will also influence the impact of climate change on northern business and economy (Keskitalo, 2008a, b). Few studies examine how these broader influences affect vulnerability and adaptation in the North Coast region (Cameron, 2012; Ford et al., 2012b). This section examines opportunities and risks that changing climate presents for formal economic activities, including tourism, mining, oil and gas, and fisheries, as well as for community sustainability.

Opportunities are associated mainly with increased viability of marine transportation associated with reduced sea-ice cover. Some models project that non–ice-strengthened ships should be able to cross the middle of the Arctic Ocean by 2040 (Smith and Stephenson, 2013). This increases the opportunities for cruise-boat tourism, with associated potential opportunities for employment and income generation (Box 5; Stewart et al., 2007, 2010). Nunavik's Makivik Corporation is exploring partnering with Nunavut and Nunatsiavut in promoting the emerging cruise industry (Fugmann, 2009), although not all communities are expected to benefit. Cruise activity in Hudson Bay is predicted to eventually decline as species such as the polar bear shift northward (Stewart et al., 2010). The lack of a central authority for governing the northern cruise ship industry, and the lack of guidelines for operations and management as the industry expands into largely uncharted regions could increase the potential for accidents (Stewart and Dawson, 2011; Dawson et al., 2014). Similar concerns apply to the anticipated increase in marine transportation of cargo in the Canadian Arctic. With decreasing sea ice, cargo ships may transit the Northwest Passage and interisland channels to provision northern resource activities (minerals and oil-and-gas exploration and/or extraction) and communities, and to move extracted resources south. This would increase the number of ships at risk from ice and other marine hazards in a region with limited charts.

The increased length of the navigable season as a result of changing climate increases the viability of northern ports (Case Study 2) and is expected to be beneficial for future mine development (Nuttall, 2008; Pearce et al., 2010a; Ford et al., 2011b; Stephenson et al., 2011). Oil companies are interested in developing new offshore oil platforms, such as in the Beaufort Sea (Callow, 2013). Potential opportunities for new commercial fisheries may arise as a result of a northward shift in the distribution of cod and other species, and because of improved and longer boat access (Barber et al., 2008; Fortier et al., 2008). Across the North, a number of logistical, regulatory and financial barriers may result in opportunities not being realized without targeted adaptation action, although this has not been widely examined in completed studies.

BOX 5

MARINE TOURISM

Changes in seasonal climate patterns and decreasing sea-ice cover have increased navigable waters throughout Arctic Canada, which has, in turn, influenced rapid growth in the marine-tourism sector (Stewart et al., 2010; Dawson et al., 2014; Pizzolato et al., 2014). Private yacht and commercial cruise-ship traffic increased by 110% and 400%, respectively, between 2005 and 2015. The Northwest Passage has emerged as the most popular area to visit, with transits increasing by 70% since 2006. It is generally believed that the tourism industry is well positioned to be a beneficiary of climate change over the short term. A changing climate brings about new Arctic cruise corridors and a longer cruising season, which could also benefit local residents via increased seasonal employment. Increased tourism could also provide access to, and education about, Inuit culture and traditions, and promote historical and contemporary arts.

Despite potential opportunities, there are significant risks related to the lack of supporting infrastructure, including comprehensive charts, search-and-rescue capabilities and other tourism services. Some believe "it is only a matter of time before we witness a major ship based accident in Arctic Canada" (*interview quote taken from* Dawson et al., 2014, p. 93–94). Changing sea-ice conditions, including calving of ice islands (from ice shelves) and more abundant small icebergs, actually makes the region increasingly hazardous to navigate (Box 1; e.g., Stewart et al., 2007; Pizzolato et al., 2014) despite widespread perceptions that the region is open for business. Realization of opportunities and mitigation of risks will require investments that support marine tourism (e.g., improved bathymetric charts and land-based infrastructure) and strengthen management of this rapidly growing sector.

The risks for business and the economy of the North Coast region relate largely to environmental impacts and associated impacts on the subsistence economy. For example, the listing of polar bears as a 'vulnerable species' due to climate change under the United States Endangered Species Act in 2008, and the subsequent ban on the importation of polar bear hides to the United States had economic implications for the Canadian north (McLoughlin et al., 2008; Dowsley, 2009b; Schmidt and Dowsley, 2010). Between 1995 and 2008, trophy hunters from the United States represented 70% of all sport hunters in Nunavut (Dowsley, 2009b), providing important income for resident hunters. This income was used, in turn, to capitalize harvesting activities, illustrating the coupling between formal economic and subsistence activities in many small northern coastal communities (Wenzel, 2009).

Industrial activities may also impact the provision of ecosystem services along the northern coast (Clarke and Harris, 2003; Burek et al., 2008; AMAP, 2009). Exploration and development of natural resources in marine environments and shipping generate underwater noise that can disturb migrations of marine mammals and increase their levels of stress (Burek et al., 2008). Industrial activities can also release contaminants like mercury and persistent organic pollutants into northern environments (Clarke and Harris, 2003). These are of great concern, as they biomagnify along the food web and can reach potentially harmful concentrations for ecosystem and human health (e.g., concentrated in harvested foods; Jenssen, 2006; Courtland, 2008; Tartu et al., 2013). Poorly planned industrial development can directly conflict with harvesting activities, as happened in Tuktoyaktuk, NT when an oil company installed its dock at the preferred fishing spot of the community and prohibited access to local residents (Carmack and Macdonald, 2008).

3.4 CULTURE AND EDUCATION

For northern coastal communities, culture is closely linked to the coastal environment and the activities it sustains (Leduc, 2006; Cunsolo Willox et al., 2013b, c). The 'land' is deeply tied to the cultural identity of northern Indigenous people in particular, and is understood to be a source of health and wellness. Even subtle alterations to the land and environment can impact individuals, communities and cultures by affecting the ability to engage in land-based activities and access traditional sites, and through impacts on the health of culturally valued wildlife species. Cultural impacts may also arise when permafrost thaw, sea-level rise and coastal erosion occur at sites of historical value (e.g., graveyards, outpost camps; Case Study 6). Education will also be affected by climate change, as traditional learning and the preservation and promotion of traditional values are both closely connected to land-based activities, which are becoming more challenging with climate change (MacDonald et al., 2013).

CASE STUDY 6

THREATS TO HISTORICAL RESOURCES AND INFRASTRUCTURE ON HERSCHEL ISLAND, YK

Herschel Island lies off the Yukon coast in the Beaufort Sea. It was designated as the site of a National Historic Event by Parks Canada in 1972 due to its significance as a former base for the whaling industry, its role in asserting Canadian sovereignty in the western Arctic and as a site of intercultural contact. The historical settlement on Simpson Point, which dates from the whaling period (1890–1908) and includes the oldest frame buildings in the Yukon and several archeological sites, is threatened by sea-level rise and coastal erosion. Elevation of the spit does not exceed 1.2 m, so even a modest increase in sea level would flood most of the spit during extreme water-level events.

In 1954, coastal erosion prompted an archeological race against the sea, with archeologists documenting excavations at the 'Washout' site. At least nine Inuvialuit winter dwellings were lost to the sea in the course of the excavations. The site demonstrates continuous occupation of Herschel Island since 1200 CE (Friesen, 2012). In 2007, Herschel Island was placed on the World Monuments Fund list of the 100 Most Endangered Sites.

To inform hazard-reduction efforts and prioritize archeological investigations, digitized shorelines from historical aerial photographs were used to determine rates of shoreline movement and to project the position of the shoreline 20 and 50 years into the future (Figure 20; B. Radosavljevic et al., 2015). In addition, very high resolution elevation data (<1 m) from an aerial Light Detection and Ranging (LiDAR) survey was used to generate a map depicting flooding susceptibility for any location on Simpson Point. On the southern part of Simpson Point, the shoreline has both retreated and advanced, with annual rates of change for the period 1952–2011 ranging from 0.4 m/year of erosion to 1.1 m/year of accumulation. The northern part of Simpson Point is largely erosional and continued shoreline retreat threatens historical buildings. Coastal flooding represents a growing and more persistent threat because sea-level rise and more frequent storms will increase flooding frequency.

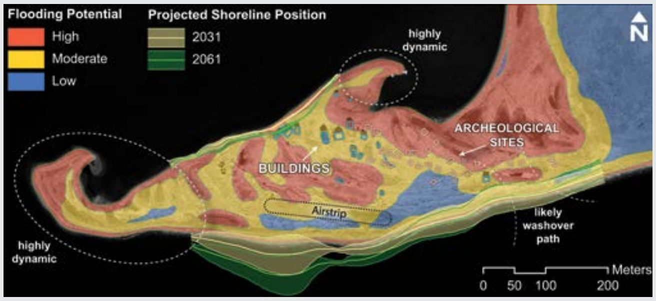

FIGURE 20: Coastal geohazard map of the historical settlement on Herschel Island (*from* B. Radosavljevic et al., 2015). The projected shorelines and potential flooding zones are superimposed on a 2011 satellite image showing the locations of buildings and archeological sites on the spit.

Given the remoteness and associated construction costs in the study area, standard hazard-reduction measures, such as seawalls or beach nourishment, are not viable. To date, several buildings have been moved away from the shoreline. Future adaptation strategies could include a combination of relocating and elevating the whaling-era buildings that are acutely at risk and prioritizing archeological investigations, based on Inuvialuit attitudes toward land use, burial and spiritual sites, and historical and cultural sites.

Specific components of northern Indigenous culture, primarily traditional knowledge, have been used to document and characterize changes in climate occurring along coasts, which can then be incorporated into impacts, adaptation and vulnerability assessments (Section 2.5; Riedlinger and Berkes, 2001; Fox, 2003; Kushwaha, 2007; Laidler and Elee, 2008; Laidler and Ikummaq, 2008; Laidler et al., 2009). Changing ice and weather conditions are already affecting the ability of northerners to take part in land-based activities, with implications for health and well-being (Section 3.2). Northern coastal communities are responding in numerous ways to these changes, indicating significant adaptability (Box 6; e.g., Ford et al., 2010a; Gearheard et al., 2010; Pearce et al., 2010b; Sayles and Mulrennan, 2010; Lemelin et al., 2012; Tam and Gough, 2012; Tam et al., 2013). The link between climate and culture is affected by longer term societal trends. In Sachs Harbour, NT, for instance, imposition of hunting regulations and quotas, changing location of hunting linked to resettlement, and new technology have undermined traditional adaptive strategies and created new risks, increasing vulnerability to changes in climate (Berkes and Jolly, 2002). Subsequent studies throughout northern coastal settlements have reinforced these conclusions, identifying youth to be at particular risk due to a weakening in the transmission of land skills and knowledge (Ford et al., 2010b).

BOX 6

RESPONSE TO CLIMATE CHANGE BY CREE HUNTERS IN WEMINDJI

For generations, the Wemindji Cree of James Bay have modified their landscape to deal with rapid environmental changes (Sayles, 2008; Sayles and Mulrennan, 2010). Among other practices, they construct dikes in wetlands and cut forest corridors over hillsides to harvest geese. These dikes and corridors are tens to hundreds of metres long and serve to slow habitat changes from uplifting land resulting from glacial isostatic adjustments (*see* Chapter 2), as well as from climate change. Cree try to slow changes but do so within a larger ethos of adaptability that balances resistance and flexibility to changes. Using dikes and corridors, they maintain known and productive hunting locations. Maintenance increases resource predictability and allows intergenerational use, which strengthens cultural identity and enables the learning of place-based history. Cree also stay attuned to larger landscape changes that overwhelm maintenance attempts and relocate hunting sites when this happens. Faced with novel environmental changes, they experiment with new techniques to attract geese, such as prescribed burnings. Some hunters are also building small roads into remote territories to monitor resources so they can balance hunting's cultural and economic importance with engagement in the global economy.

Sharing networks, which involve the distribution to relatives and those in need, have been affected by reduced availability of, and access to, animals. These effects are compounded by broader changes in northern Indigenous society associated with the development of waged economy and modernization (Wenzel, 1995b, 2009). Other cultural impacts on practices may stem from the potential for increased risk of contaminants in traditional foods due to climate change (Donaldson et al., 2010). A perception that foods are less safe and desirable may impact consumption practices and/or create anxiety around consumption. Climate change is also affecting sense of place in northern coastal communities, challenging traditional ways of knowing and changing features of the land and ice important to Inuit toponymy (Laidler and Elee, 2008; Laidler and Ikummaq, 2008; Bravo, 2009; Forbes, 2011).

3.5 SUBSISTENCE HARVESTING

Subsistence harvesting activities, including fishing, trapping and berry picking, have strong economic, dietary and cultural importance for northern coastal communities. This close association with the natural environment creates unique sensitivities to the rapidly changing climate. Indigenous observations of climate change include later freeze-up and earlier break-up of ice, more dynamic ice conditions, changing wind and weather patterns, larger storm surges, changes to berries, warming temperatures and changing animal-migration patterns (Gearheard et al., 2006; Tremblay et al., 2006; Laidler and Ikummaq, 2008; Laidler et al., 2009; Cunsolo Willox et al., 2012; Hori et al., 2012; Kokelj et al., 2012; MacDonald et al., 2013; Royer and Herrmann, 2013; Royer et al., 2013; Tam et al., 2013). Studies have sought to integrate Indigenous observations and instrumental data on changing conditions (Meier et al., 2006; Gearheard et al., 2010; Weatherhead et al., 2010; Ford et al., 2013b; Royer et al., 2013) and have made Indigenous observations available to a wider audience (Section 2.5; e.g., Kunuk and Mauro, 2011; Cunsolo Willox and the communities of Nunatsiavut, 2014).

Adaptive management of wildlife resources is an important issue facing the harvesting sector. Impacts linked to climate change have already been documented (Hovelsrud et al., 2008; Post et al., 2013), with particular focus on polar bears and ringed seals, where there is concern about population stability in light of changing sea-ice regimes (Castro de la Guardia et al., 2013; Hamilton et al., 2014). Some existing management frameworks may be unprepared to cope with rapidly changing environmental conditions, reducing the flexibility with which communities historically managed fluctuations in wildlife access and availability (Berkes, 1999; Berkes et al., 2003; Berkes and Armitage, 2010; Armitage et al., 2011; Dale and Armitage, 2011). Co-management structures have come under increasing pressure from northern communities, which have voiced dissatisfaction with quota allocations that are viewed as inconsistent with traditional knowledge on wildlife stocks, and from international nongovernment organizations concerned about the long-term viability of animal populations in light of climate change and hunting pressures. Recent work has begun to examine opportunities to improve management regimes and bridge the current polarization in viewpoints, with particular focus on polar bears and narwhals (Clark et al., 2008; Dowsley and Wenzel, 2008; Dowsley, 2009a). There are also opportunities for policies and measures at different scales to facilitate adaptation for subsistence harvesting (Table 6; e.g., Ford et al., 2010b; Wesche and Chan, 2010; Boyle and Dowlatabadi, 2011).

TABLE 6: Synthesis of key opportunities proposed in the literature for adaptation in the subsistence-harvesting sector.

Adaptation measure	Vulnerability addressed	Benefits/comments
Harvester support	Access to financial resources identified as a major barrier to adapting to the impacts of climate change (e.g., using new equipment, taking safety gear, developing new but longer trails; Ford et al., 2006b; Pearce, 2006; Ford, 2009a, b; Pearce et al., 2010b; Ford et al., 2013b)	▪ Increased viability of resource-harvesting sector ▪ Ability to purchase necessary equipment ▪ Strengthening of existing programs
Co-management of wildlife resources	Wildlife-management regimes identified as reducing the flexibility of communities to cope with climate change impacts on wildlife availability, health and migration timing (Berkes and Jolly, 2002; Berkes et al., 2005; Dale and Armitage, 2011)	▪ Reduce conflict within communities and between communities and government/scientists ▪ More effective and successful wildlife management
Land-skills training	Weakening of transmission of traditional knowledge and land skills, affecting the ability of younger generations to safely use the land in light of changing climate (Ohmagari and Berkes, 1997; Berkes and Jolly, 2002; Ford et al., 2006a; Gearheard et al., 2006; Pearce et al., 2011a)	▪ Preservation of culturally important skills and knowledge ▪ Increased interest in harvesting among youth ▪ Enhancement of safe harvesting and travelling ▪ Key policy goal across Inuit regions
Search and rescue	Increasing dangers of land-based activities reflected in community reports of more accidents, a trend climate change is expected to accelerate; need to provide for adequate search-and-rescue capability (Pearce et al., 2011a, 2012; Pennesi et al., 2012)	▪ Enhanced search-and-rescue capacity
Food-system enhancement	High level of food insecurity creates significant vulnerability to disruptions caused by climate change to traditional food systems (Chan et al., 2006; Beaumier and Ford, 2010)	▪ Targets high levels of food insecurity across Inuit regions
Swim training	Longer open-water season and more boating enhance risks of water-based activities (Giles et al., 2013)	▪ Low levels of swim training in northern coastal communities across age groups
Enhanced weather forecasting	Improve spatial detail and accuracy of weather forecasting, enhance use of forecasts to help inform safe travel (Ford et al., 2010b; Pennesi et al., 2012)	▪ Reported low accuracy of current forecasts

4 ADAPTATION PLANNING IN THE NORTH

The previous section discussed processes affecting the vulnerability of northern coastal communities and gave some examples of adaptations that are being undertaken. This section examines the evolution of public- and private-sector adaptation programs and measures in the North Coast region. The absence of literature evaluating the current adaptation landscape precludes assessment of the effectiveness of programs and measures in reducing vulnerability and building resilience, so the focus here is placed on the adaptation *process*. The final part of the section assesses current knowledge gaps that constrain adaptation in the North Coast region.

4.1 EMERGENCE OF ADAPTATION

The emergence of adaptation during the past decade as an important focus of research and policy has involved the creation of a number of northern-focused federal programs and initiatives for adaptation, all of which have an important coastal dimension. These include ArcticNet (2003–2018), the International Polar Year (2007–2011), the Nasivvik Centre for Inuit Health and Changing Environments (2003–2014), the Northern Contaminants Program (ongoing), the Northern Ecosystem Initiative (1998–2008), and programs designed to explicitly engage northerners in assessing the risks posed by climate change and identify adaptation options delivered by Indigenous and Northern Affairs Canada, Health Canada, Public Health Agency of Canada, Natural Resources Canada, Standards Council of Canada and Transport Canada (Box 7; Health Canada, 2009; Indian and Northern Affairs Canada, 2010; Ford et al., 2011a; McClymont Peace and Myers, 2012).

BOX 7
NATIONAL ADAPTATION PROGRAMMING

A number of federal government departments have developed programs with an explicit goal of advancing climate change adaptation in northern Canada, including coastal regions. This box highlights three of these initiatives.

The Climate Change Adaptation Program for Aboriginal and Northern Communities, delivered by Indigenous and Northern Affairs Canada, was designed to assist communities to prepare for, and respond to, climate changes, including permafrost degradation, coastal erosion, changes to ecosystem structure and function, changes to ice and water quality and quantity, and extreme weather events. Building on climate change adaptation programming in the department that has been ongoing since 2001, the program has supported the planning required to ensure that community infrastructure is designed and maintained to address a changing climate. The program has also provided community-relevant information, guidance, support and partnerships to Indigenous and northern coastal communities, governments and organizations to assess vulnerabilities to, and opportunities resulting from, climate change related to infrastructure, food security and emergency management, and to develop plans and strategies.

The Climate Change and Health Adaptation Program (CCHAP) at Health Canada was developed to support northern First Nations and Inuit communities in conducting research on the effects of climate change on health (McClymont Peace and Myers, 2012). Communities determined the areas of research that were of greatest importance to them; developed the tools and methods to adapt; incorporated scientific, traditional and/or local knowledge; and engaged their members in the results that emerged. The program worked with northern governments and organizations to increase their knowledge and capacity to develop health-adaptation strategies at the community, regional and national levels. Since 2008, CCHAP has funded more than 50 community-driven research projects that, in some cases, led to development of local adaptation strategies. Examples of outputs include film and PhotoVoice products that engage youth and elders; community-based ice monitoring, surveillance and communication networks; and a variety of information products, such as fact sheets on land, water and ice safety, drinking water safety, food security/safety and traditional medicine.

The Northern Infrastructure Standardization Initiative, supported by the Standards Council of Canada, has developed a number of national standards that are directly relevant to land-based infrastructure in northern coastal communities. Building on existing technical guidance on factoring in future climate changes when building on permafrost (Auld et al., 2010), the new standards address 1) thermosyphon foundations (CSA Group, 2014a); 2) moderating the effects of permafrost degradation on building foundations (CSA Group, 2014b); 3) managing changing snow-load risks for buildings in Canada's north (CSA Group, 2014c); and 4) drainage-system planning, design and maintenance in northern communities (CSA Group, 2015). A fifth standard for geotechnical site investigation for building foundations in permafrost is in development (Bureau de normalisation du Québec, 2015; Standards Council of Canada, 2015).

At the regional and territorial levels, the governments of Nunavut and Yukon indicated their intention to promote adaptation to climate change with the release of their climate change strategies in 2003 and 2006, respectively (Government of Nunavut, 2003; Government of Yukon, 2009). These were updated with a formal adaptation strategy by Nunavut in 2011 and Yukon in 2012 (Government of Nunavut, 2011; Government of Yukon, 2012). The Government of Nunavut also established the Nunavut Climate Change Centre. A report released by the Government of the Northwest Territories (Government of the Northwest Territories, 2008) called for the development of tools and best practices to assist communities and governments in developing long-range adaptation planning (Box 8). The report also listed potential adaptation actions, ranging from applying risk-management protocols in assessing infrastructure vulnerability to considering climate change in construction of buildings, roads and permanent bridges, and using thermosyphons to maintain permafrost below building foundations. The effects of permafrost degradation on built infrastructure are prompting adaptation in Nunavik (Box 9; L'Hérault et al., 2013).

BOX 8

INFRASTRUCTURE ADAPTATION IN THE NORTHWEST TERRITORIES

Governments, corporations and communities are undertaking numerous strategies to adapt built infrastructure to permafrost degradation and shoreline erosion in the Northwest Territories. Measures employed by the Northwest Territories Housing Corporation (NWTHC) to adapt housing construction include modifications and repairs to pile foundations adversely affected by permafrost thaw (e.g., increased ground movement and water collection under and around buildings) and the use of new foundation systems designed to better respond to and absorb the additional stress caused by shifting ground beneath buildings (Decker et al., 2008). In addition, engineering designs across the territory are using thermosyphons (that keep permafrost cold through passive heat exchange) and other technologies to preserve permafrost, and design recommendations are increasingly changing (e.g., using larger diameter and deeper pile installations and using increased bond-breaking material in areas where foundations are most susceptible to annual freeze and thaw). The NWTHC is also adapting to a shorter winter-road season by beginning contracts to supply vendors as much as a month earlier than previously (Decker et al., 2008). The addi-tional time allows vendors to assemble materials for delivery, adjust load-movement schedules for the shorter road season and prepare for the possibility of reduced road-weight limits. Additionally, the Department of Transporta-tion is working to rehabilitate airstrip runways affected by permafrost thaw in Inuvik (Decker et al., 2008).

BOX 9

COMMUNITY-LEVEL INFRASTRUCTURE ADAPTATION IN NUNAVIK

Several coastal communities in Nunavik, including Salluit, Puvirnituq, Akulivik, Kangirsuk and Tasiujaq, participated in a permafrost-monitoring and mapping project to inform future development and land-use planning (Furgal and Laing, 2013; L'Hérault et al., 2013). Results included recommenda-tions on where to place new built infrastructure and which developed areas need repair or will need repair in the future. Recommendations were also made on how to adapt construction and design guidelines to better address permafrost degradation. One example is the preparation of pads for construction of new buildings 1–2 years in advance in order to allow the ground to stabilize and avoid damaging ground shift after the building is constructed. Engineers have provided community members with training on how to construct pads that minimize the risk of affecting permafrost (Kativik Regional Government, 2012; L'Hérault et al., 2013). Other examples include a pilot project on the Kuujjuaq airstrip to test the use of more reflective paving material as a means of reducing ground temperatures, and pilot projects in Kuujjuarapik and Aupaluk to test maintenance of culverts in light of changes in freeze-thaw patterns and permafrost thaw (Kativik Regional Government, 2012).

Collaboration and knowledge sharing at the territorial level are occurring through the Pan-Territorial Adaptation Partnership (www.northernadaptation.ca). Guided by 'A Northern Vision and the Pan-Territorial Adaptation Strategy' (Governments of Nunavut, Northwest Territories and Yukon, 2011), the partnership is aimed at sharing knowledge and understanding of climate change among local, territorial, national, Indigenous and international partners in order to develop collaborative activities. The initiative focuses on "work[ing] together on climate change, with a focus on practical adaptation measures" (Governments of Nunavut, Northwest Territories and Yukon, 2011, p. 7), with sovereignty and sustainable communities, adapting to climate change, and circumpolar relations as common priorities for the territorial governments, and involves communities, academia, practitioners and funders at all levels.

Indigenous organizations have also stressed the importance of adaptation. Adaptation has been an important component of work through Inuit Tapiriit Kanatami's Inuit *Qaujisarvingat* (Inuit Knowledge Centre). Nunavut Tunngavik Incorporated, which oversees the implementation of the Nunavut Land Claims Agreement on behalf of Inuit beneficiaries, organized workshops to discuss adaptation to climate change and outline priority areas for action in 2005 (Nunavut Tunngavik Incorporated, 2005), and produced a book assembling terminology on climate in English, Inuktitut and Inuinnaqtun (Government of Nunavut, 2005). In the western Arctic, the Inuvialuit Regional Corporation has identified climate change as a threat to wildlife such as beluga, but also as an economic opportunity with more ship traffic due to loss of sea ice. At a local level, several communities have established roles on climate change projects. For example, in Clyde River, NU, the Ittaq Heritage and Research Centre partnered with federal and territorial bodies to identify adaptations and build capacity to adapt (Case Study 7; Ittaq Heritage and Research Centre, 2015).

CASE STUDY 7

COMPOSITE LANDSCAPE-HAZARD MAPPING IN CLYDE RIVER, NU

The Hamlet of Clyde River (population 934), located on the rugged east coast of Baffin Island, was one of the pilot communities in an adaptation-planning process undertaken by the Nunavut Climate Change Partnership (Box 10). The project was designed, as a close collaboration between the Hamlet Council and the local Ittaq Heritage and Research Centre, to determine how different aspects of the physical environment pose risks and hazards to existing and future infrastructure development, and how climate change may further alter infrastructure vulnerability (Smith et al., 2012b). Rapid population growth and increased housing and other infrastructure developments have led to the expansion of many Nunavut communities beyond the relatively level and stable terrain upon which they were originally situated. A key outcome of this pilot study was the development of a methodology by which landscape hazards can be assessed and then integrated into planning guidelines, thereby increasing the sustainability of northern communities. In addition to a composite landscape-hazards map of the hamlet and surrounding area (Figure 21; Smith et al., 2014), the project produced maps of surficial geology (Smith et al., 2012a) and of periglacial and permafrost geology (Smith et al., 2011).

BOX 10

NUNAVUT CLIMATE CHANGE PARTNERSHIP (NCCP)

The NCCP, also referred to as 'Atuliqtuq: Action and Adaptation in Nunavut', was formed in 2008 as a partnership between the Government of Nunavut, federal government departments and the Canadian Institute of Planners. Activities were guided by three goals:

- Building capacity for climate change adaptation planning with the Government of Nunavut and communities by piloting the development of adaptation action plans in seven communities (Clyde River, Hall Beach, Iqaluit, Arviat, Whale Cove, Cambridge Bay and Kugluktuk) and using the results to develop planning tools for the rest of the territory
- Creating knowledge to inform community climate change adaptation, including knowledge on permafrost degradation and associated landscape hazards, sea-level change, coastal erosion and fresh-water supply, building upon scientific and Inuit knowledge
- Developing tools to collect, publish and share climate change adaptation knowledge among the communities of Nunavut and beyond

The NCCP process has produced community adaptation plans for each of the seven communities and a step-by-step toolkit (Nunavut Adaptation Planning Toolkit) for community planners and local government officials (Nunavut Climate Change Centre, no date).

A subjective scheme of ranking the level of landscape hazards was developed for this study, and similar schemes have been widely adopted for community-hazard mapping in the North Coast region (e.g., Champalle et al., 2013; Forbes et al., 2014). Although a combination of factors is typically assessed to determine the composite-hazard rating, any one landscape factor in this scheme could determine the rating of an area if its potential impact on infrastructure is judged significant. The Hamlet of Clyde River includes areas of low, medium and high hazard (Figure 21), with high-hazard areas characterized by one or more of the following: ice-rich permafrost, stream erosion, thick

FIGURE 21: Composite landscape-hazard map for Clyde River, NU (*from* Smith et al., 2014).

snowdrifts, wet terrain, coastal flooding and steep slopes. Areas of stable sediments, little evidence of permafrost heaving or settling, dry terrain and low slope were typically rated as 'low'. Medium-hazard areas typically represent transition zones between areas of high and low hazard.

The composite landscape-hazard map was presented to the Hamlet Council and informed public discussion on updating the community plan. Discussion points raised in these meetings included the following:

- 'High' and 'medium' hazard levels do not mean that the area cannot or should not be developed, but they do indicate conditions that are likely to require additional engineering or construction considerations (e.g., using steel pilings rather than wooden cribs for building foundations).
- A wide range of adaptation measures, including things as simple as constructing snow fences to reduce drifting around infrastructure, can be employed to reduce hazard risk.
- Areas with lower hazard rating are likely to be the easiest areas to develop and offer long-term stability. However, the harsh environment in Clyde River will be a major influence on building design, maintenance and life span, regardless of landscape hazards.
- The composite landscape-hazard map was designed to inform community decision-making processes. It should not be the sole basis upon which future development decisions are made.

The private sector in the North is also engaging in adaptation, although there is very limited publicly available information on actions taking place (Ford et al., 2014a). The mining sector now considers climate change in the design phase of mines as part of standard environmental-assessment processes (Pearce et al., 2010a).

4.2 CURRENT STATUS OF ADAPTATION PLANNING

Recognition of the importance of adaptation has been followed by analyses of adaptation needs, adaptation planning and, in some instances, implementation of adaptation interventions. For example, the Government of Nunavut established the Nunavut Climate Change Partnership (NCCP) in collaboration with federal government departments and the Canadian Institute of Planners. Building on experience gained from the NCCP (Box 10; Callihoo and Ohlson, 2008; Callihoo and Romaine, 2010; Johnson and Arnold, 2010; Hayhurst and Zeeg, 2010), a strategic plan was developed in 2011 that identifies key themes for adaptation planning in the territory (Government of Nunavut, 2011). There has been a rapid increase in the development of adaptation plans for northern coastal communities (Pearce et al., 2012).

Adaptation planning is an important step for managing the risks of climate change, but many concerns remain. For example, practitioners and decision makers continue to note the need for improvement in planning for the impacts of climate change on infrastructure (Case Study 8; Ford et al., 2014c). There are also concerns arising from the contrasting philosophies about the future, long-term planning and prediction held by northern Indigenous populations and those underpinning western notions of planning (e.g., Bates, 2007; Natcher et al., 2007). For example, a strong disinclination to focus on future risks among some northern Indigenous communities in Canada, reflecting beliefs about the sentience of the natural world, brings unique challenges to anticipatory adaptation planning along the northern coast (Ford et al., 2007; Ford et al., 2010b; Boyle and Dowlatabadi, 2011). Other concerns related to adaptation planning include financial and human-resource challenges, which are more pressing issues than climate change that require community attention and resources; lack of 'usable science' to inform planning; and gaps in understanding (Boyle and Dowlatabadi, 2011; Pearce et al., 2012; Champalle et al., 2013).

CASE STUDY 8

COASTAL PROTECTION AT TUKTOYAKTUK, NT

Tuktoyaktuk, NT is located on a narrow peninsula in the Mackenzie Delta (Figure 22) that is highly vulnerable to large storm surges (Section 2.2.5). Prior to establishing erosion control measures at Tuktoyaktuk, the long-term rates of coastal retreat were on the order of 2 m/year (Solomon, 2005) and reached up to 10 m of shoreline loss during a single storm in August 2000. Erosion is exacerbated

FIGURE 22: Location of various shore protection measures installed at Tuktoyaktuk to help control erosion and flooding (*from* Couture et al., 2002).

by the fact that the coastal sediments are ice-rich and often contain bodies of massive ice.

Beginning in 1976, a series of experimental shoreline protection systems was installed to help slow coastal retreat and protect the hamlet from inundation (Figure 23). The goal of these systems was to provide physical protection of the beach and cliff face from storm waves and to insulate the beach to prevent thawing of underlying ground ice. Longard tubes (woven polyethylene fabric tubes filled with sand) were used initially, but the geotextile had become damaged by 1981 and the integrity of the protection system was lost (Couture et al., 2002). A beach nourishment project using material dredged from the nearshore was put in place in 1987, supplemented over time with sandbags, concrete footings from a demolished school, large stone boulders (rip-rap) and concrete slabs (Figure 23; Couture et al., 2002). These measures have provided some protection from storms, although their long-term efficacy is uncertain. Other possibilities considered for shore protection include wave breakers and the relocation of infrastructure, the implementation of which is challenged by cost, land use and the cultural and economic value of infrastructure (UMA Engineering Ltd., 1994; Johnson et al., 2003).

Challenges to implementation of coastal protection in the North include a shortened construction season, difficulty in obtaining materials such as granular resources, availability of equipment and experienced labour, high transport costs, logistical challenges, more rapid environmental change, and a small tax base for funding shoreline protection.

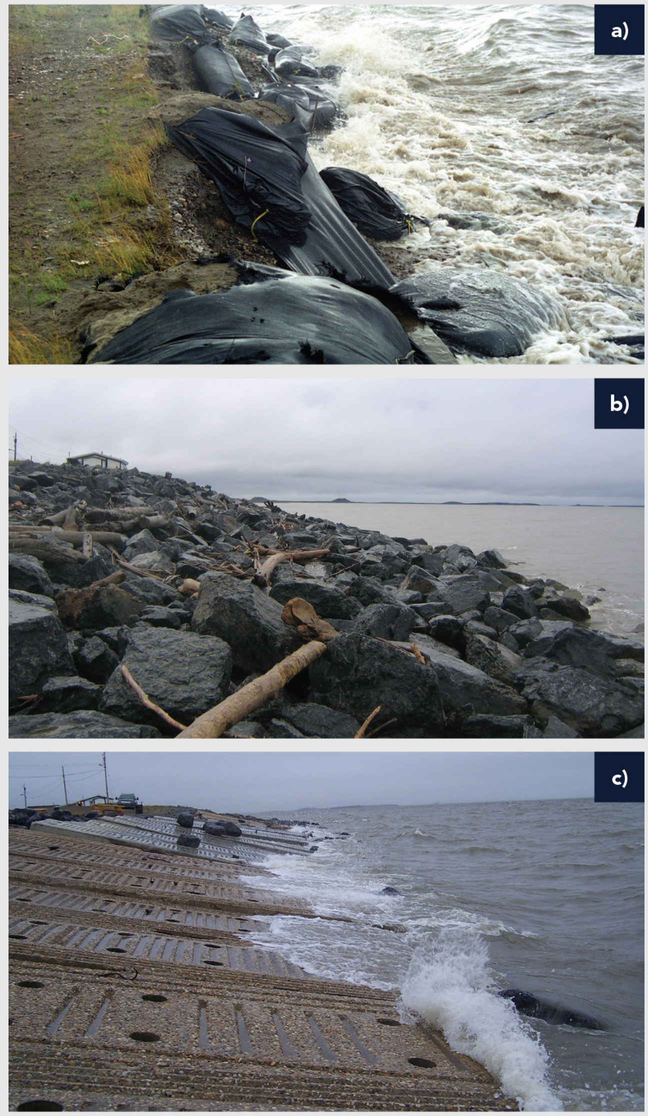

FIGURE 23: Various types of shore-protection measures include **a)** sandbags put in place in 1987, **b)** stone boulders (rip-rap) first used in 1997, and **c)** monolithic concrete slabs that were installed in 1998. *Photos a) and b) courtesy of S. Solomon, and photo c) courtesy of G. Manson.*

Some research argues that a key focus for adaptation should be on supporting and enhancing current adaptive strategies for responding to climate change impacts and assessing the effectiveness of current policies and programs in the context of a changing climate (Boyle and Dowlatabadi, 2011; Ford et al., 2014d). In this perspective, adaptation is less about planning for the future *per se* and more about doing things we should already be doing but better: tackling the underlying socio-economic determinants of climate change vulnerability and building upon traditional knowledge and cultural values. Ongoing policy initiatives and priorities in areas of economic, social, health and cultural development can bring immediate benefits by reducing vulnerability to current climatic variability, change and extremes. Policies intended to broadly enhance adaptability to risk, involving mainstreaming adaptation, are likely to be the most effective means of reducing vulnerability to climate change (Klein et al., 2007; Dovers, 2009; Dovers and Hezri, 2010; de Loë, 2011).

4.3 IDENTIFIED RESEARCH GAPS ON ADAPTATION

A number of knowledge gaps have been identified in the literature as constraining current adaptation action in northern coastal communities. These are addressed in terms of gaps in understanding vulnerability and in understanding adaptation.

4.3.1 VULNERABILITY

Understanding what makes human systems vulnerable or resilient to climate change is necessary for addressing adaptation (Ribot, 2011). For some sectors in the North Coast region, studies have argued that sufficient information on vulnerability exists to begin adaptation (e.g., harvesting and culture), albeit with the need for targeted studies focusing on regions and populations where research has not been conducted (Ford and Pearce, 2012). In other sectors, it is recognized that our understanding of the risks posed by climate change and information necessary for adaptation remain limited (e.g., business and economy, infrastructure and transportation, and health and well-being; Cameron, 2012; Ford et al., 2012a; Wolf et al., 2013; Bourque and Cunsolo Willox, 2014; Ford et al., 2014b).

For all sectors, the long-term dynamics of how projected climate change will interact with future socio-economic conditions are little understood and raises concerns about potential maladaptation, where policies, programs and behaviour actually increase vulnerability in the long term (Barnett and O'Neill, 2010; Ribot, 2011; Ford and Pearce, 2012; McDowell et al., 2013). Completed work creates only a partial understanding of the drivers of vulnerability. A number of knowledge gaps constrain current adaptation, including (Bates, 2007; Ford et al., 2010b; Sayles and Mulrennan, 2010; Cameron, 2012; Ford and Pearce, 2012; Ford et al., 2012b, 2013b; Wolf et al., 2013):

- an absence of research accounting for regional and global determinants of vulnerability;
- a lack of long-term studies to capture the dynamic nature of vulnerability, with research primarily taking place over a limited number of seasons;
- limited engagement with traditional knowledge in vulnerability and adaptation studies, with research primarily reflecting 'western' science approaches; and
- limited research on cumulative effects and how these will affect vulnerability to climate change both today and in the future.

Current understanding of vulnerability is derived mainly from local studies in small communities and focuses on 'traditional' activities. There is a need to develop a broader and more diverse geographic and sectoral knowledge base. The larger regional centres (e.g., Iqaluit, NU and Inuvik, NT) are emerging as hubs of economic development and population growth in northern Canada and have quite different vulnerabilities than smaller communities.

Few studies have evaluated the extent to which vulnerability assessments are actually informing decision making (Champalle et al., 2013). Greater emphasis on stakeholder engagement and effective communication of research findings, and interdisciplinary collaboration to capture the multiple drivers of vulnerability, cost impacts and performance under different climate scenarios would help in this regard (Ford et al., 2014d).

4.3.2 ADAPTATION

Impacts and vulnerability studies focusing on Canada's northern coasts typically recommend adaptation options to moderate risks. However, there remains a lack of research examining the potential for policies or programs to reduce vulnerability under different climatic and socio-economic scenarios, costing actions, examining trade-offs or prioritizing needs. There are also few examples of adaptation being both piloted and evaluated (Champalle et al., 2013; Ford et al., 2014b, c). The lack of policy analysis on such factors likely acts as a barrier to action on adaptation (de Bruin et al., 2009; Smith et al., 2009; Sherman and Ford, 2014).

5 SUMMARY AND CONCLUSIONS

The North Coast region is on the front line of climate change, witnessing the most pronounced warming in Canada and projected to experience continued warming during this century. Impacts have been documented across sectors and in all regions of the North, with climate change posing both risks and opportunities. Communities, decision makers, Indigenous organizations and researchers have all noted concern over climate change. The literature focusing on climate change on Canada's northern coastline has expanded significantly during the last decade, with adaptation emerging as a central focus (Downing and Cuerrier, 2011; Ford et al., 2012a, b; McClymont Peace and Myers, 2012).

It is evident that both sea ice and permafrost are changing rapidly. The open-water season will continue to increase in length, and an ice-free Arctic Ocean in the summer is a possibility by mid-century. A longer ice-free period presents opportunities for marine shipping and could enhance potential for resource development, tourism and port development (e.g., at Churchill, MB). Sea ice is also used for travelling between communities and to access hunting and fishing areas. Combined with stresses to wildlife resources, reductions in the duration of ice cover could have significant social, cultural and economic impacts associated with use of the coastal environment. Coastal infrastructure will be affected by thawing permafrost and coastal erosion, associated with a combined increase in storminess, less protection from sea ice and sea-level change. Taking projected climate changes into consideration for new infrastructure developments will be important. Adaptation actions proposed to reduce climate risks to infrastructure include enhancing building design, investment in coastal protection and land-use planning.

Climate change is occurring in the context of significant social, cultural and economic changes that are already underway due to globalization and will influence the availability and feasibility of adaptation options. For example, the opportunities and challenges posed by climate change to resource development, shipping, tourism and other activities will be determined, in part, by global market prices, profitability, regulations and other government policies. Traditional knowledge, cultural values, social networks and flexible use of resources provide significant capacity to adapt to impacts on subsistence harvesting activities; however, these characteristics are being undermined across communities. Many challenges posed by climate change exacerbate existing vulnerabilities, such as food and housing insecurity, poverty and marginalization.

Adaptation involves actions across scales to enhance resilience, reduce vulnerability and remove barriers to adapting. Cultural revitalization, programming to promote and preserve land skills and knowledge, enhanced local decision-making power, and efforts to address marginalization and poverty build resilience to the impacts of climate change on harvesting activities, culture and health. In many cases, climate change brings renewed importance to ongoing policy priorities.

Examples of governments planning for adaptation and of on-the-ground adaptation actions are evident across much of the North Coast region. Barriers to adaptation include institutional challenges, including regulatory regimes. For example, climate changes are altering the health, availability and migration timing of fish species and wildlife utilized for subsistence and commercial uses. Such complexities highlight the importance of cohesive institutional responses integrating climate change considerations across scales and jurisdictions.

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APPENDIX A

SEA-LEVEL PROJECTIONS FOR SELECTED LOCATIONS IN THE NORTH COAST REGION

Projected relative sea-level changes to 2100 are provided here for 22 locations, shown on the accompanying map (Figure A1), in the North Coast region (*after* James et al., 2014, 2015; Section 2.4.4 of this chapter and *see* Chapter 2 for details of projections). The sea-level projections (Figure A2) are based on the IPCC Fifth Assessment Report (Church et al., 2013a, b) and were generated using vertical crustal motion derived from GPS observations.

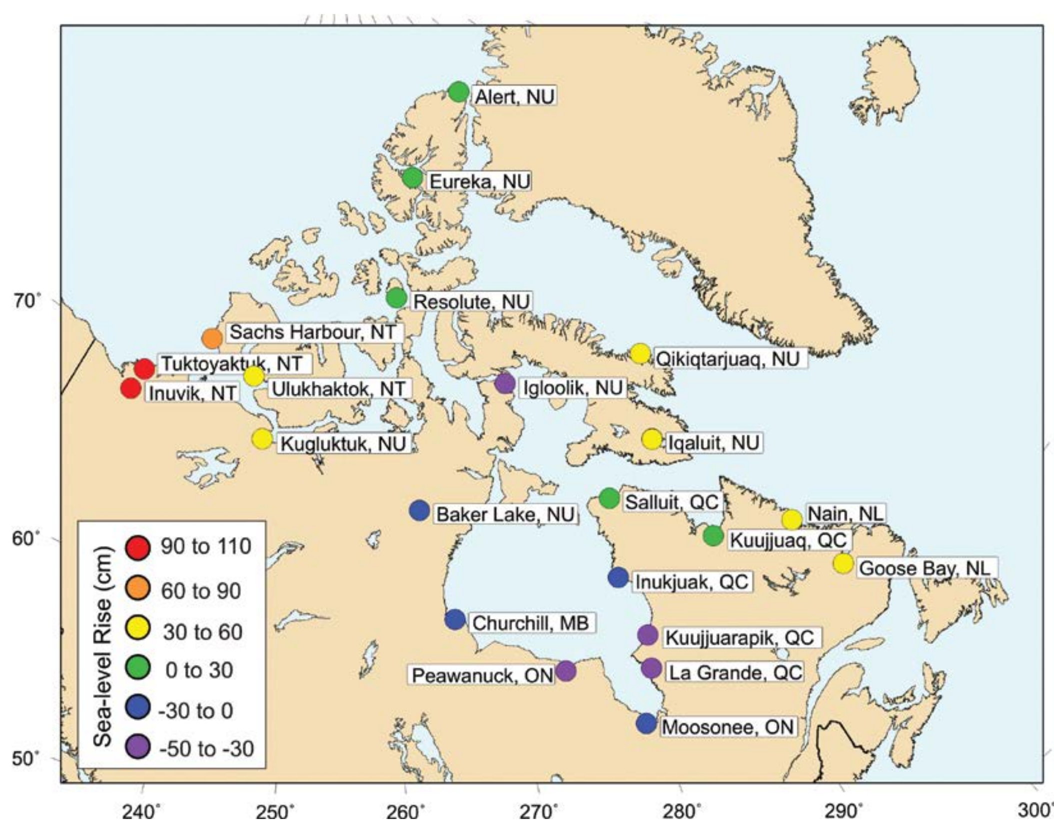

FIGURE A1: Locations for which sea-level projections are provided through the 21st century (Figure A2). Dots are colour coded to indicate the projected sea-level change at 2100 for the 95th percentile of the high-emissions scenario (RCP8.5; *after* James et al., 2014; 2015).

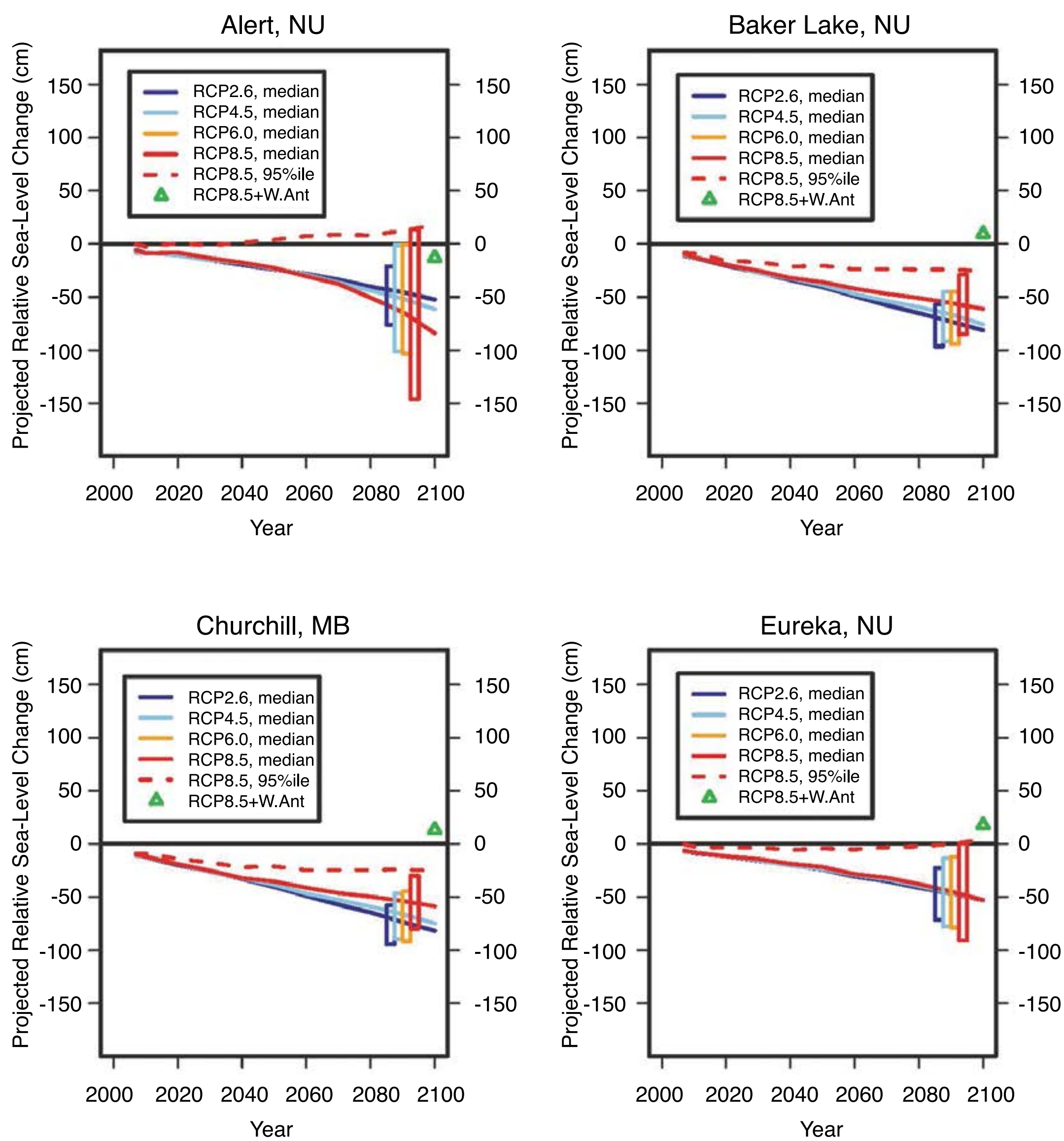

FIGURE A2: Projected relative sea-level changes through the 21st century for selected locations in the North Coast region (*after* James et al., 2014, 2015). RCP2.6 is a low-emissions scenario, RCP4.5 is an intermediate-emissions scenario and RCP8.5 is a high-emissions scenario. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario, in which west Artarctica contributes an additional 65 cm to the median projected value of the high-emissions scenario (RCP8.5+W.Ant; green triangle). Rectangles show the 90% confidence interval (5–95%) of the average projection for the period 2081–2100 and include RCP6.0. The rectangles are staggered for clarity of presentation but pertain to the midpoint time of 2090. The dashed red line gives the 95th percentile value for the high-emissions scenario.

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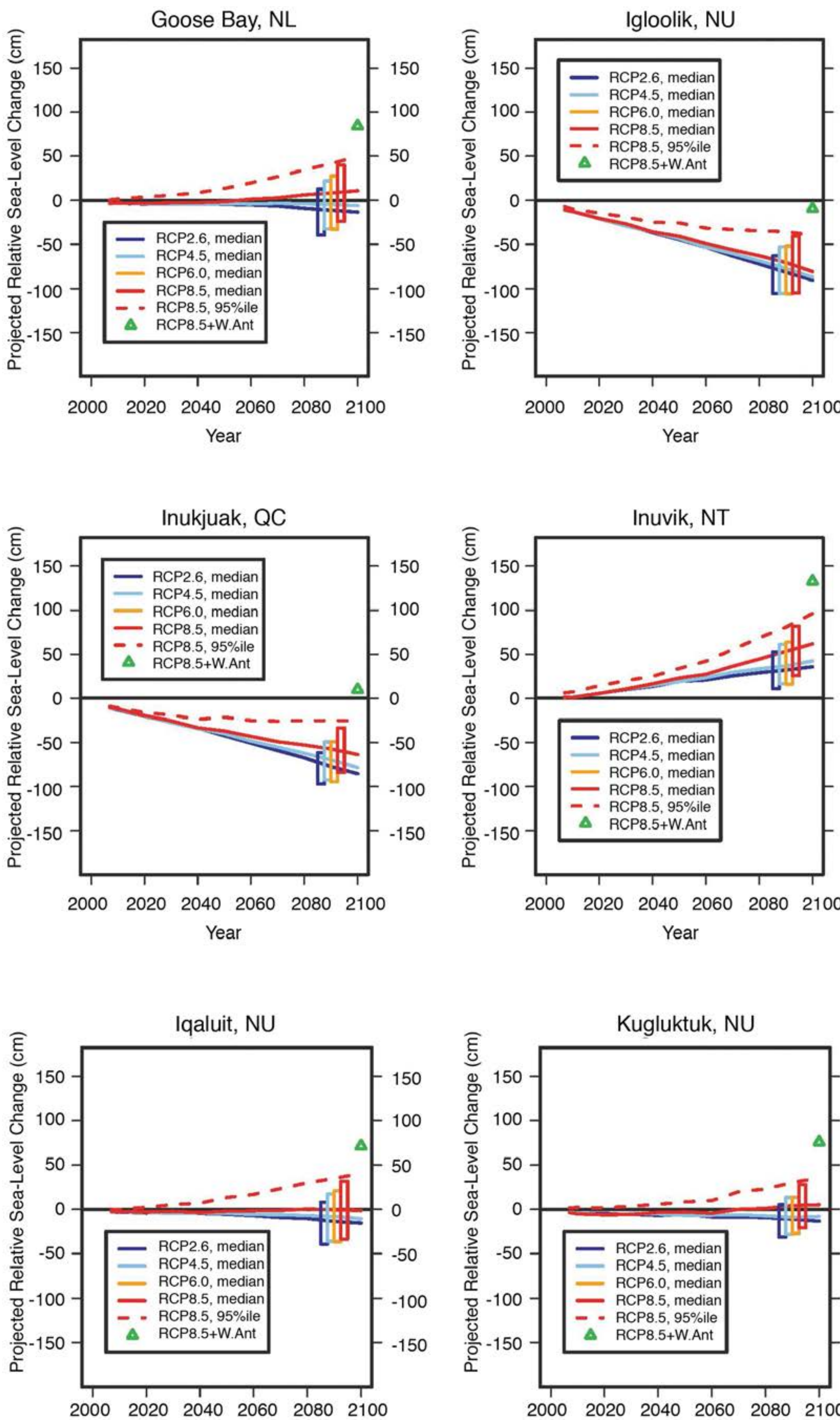

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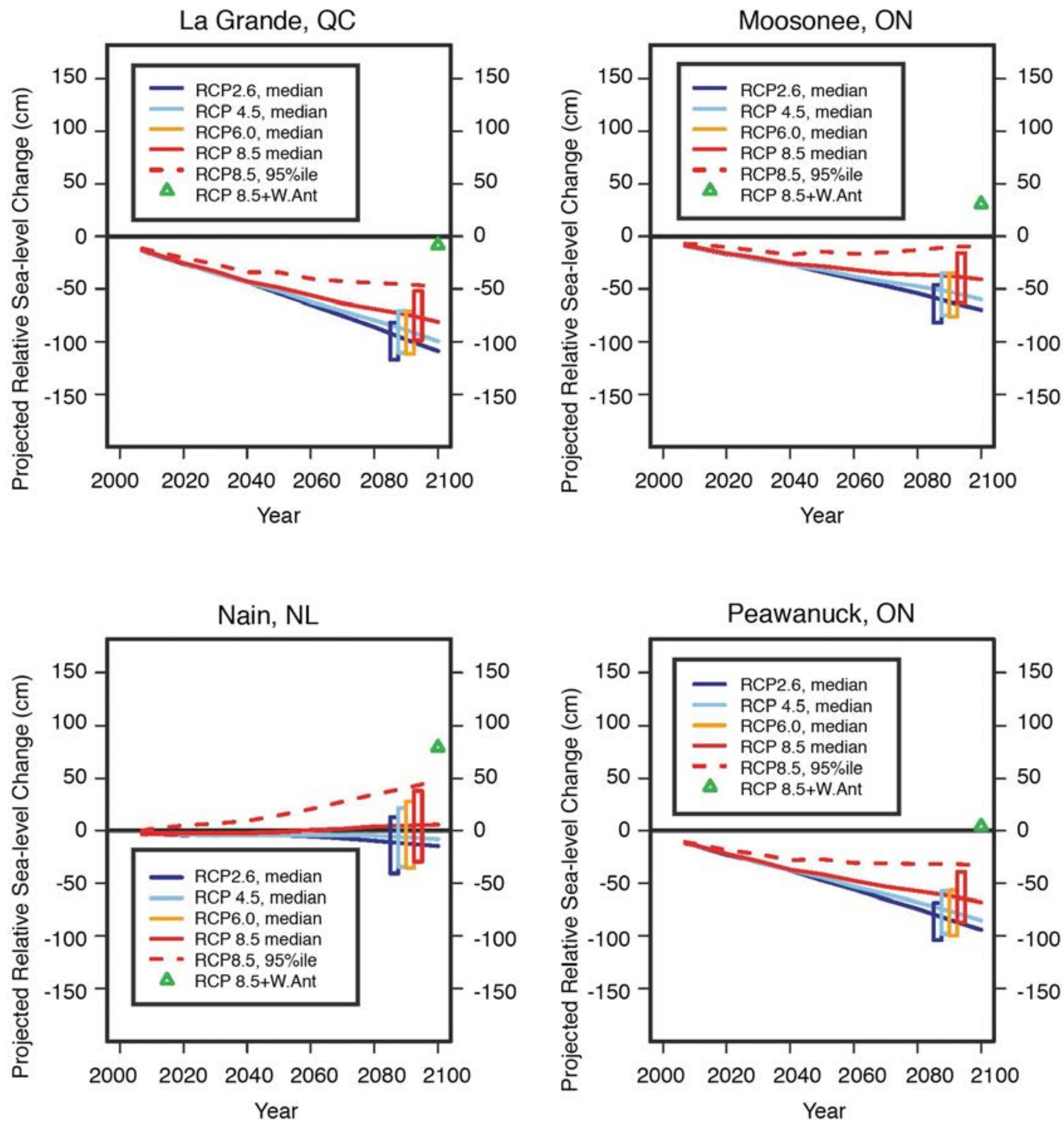

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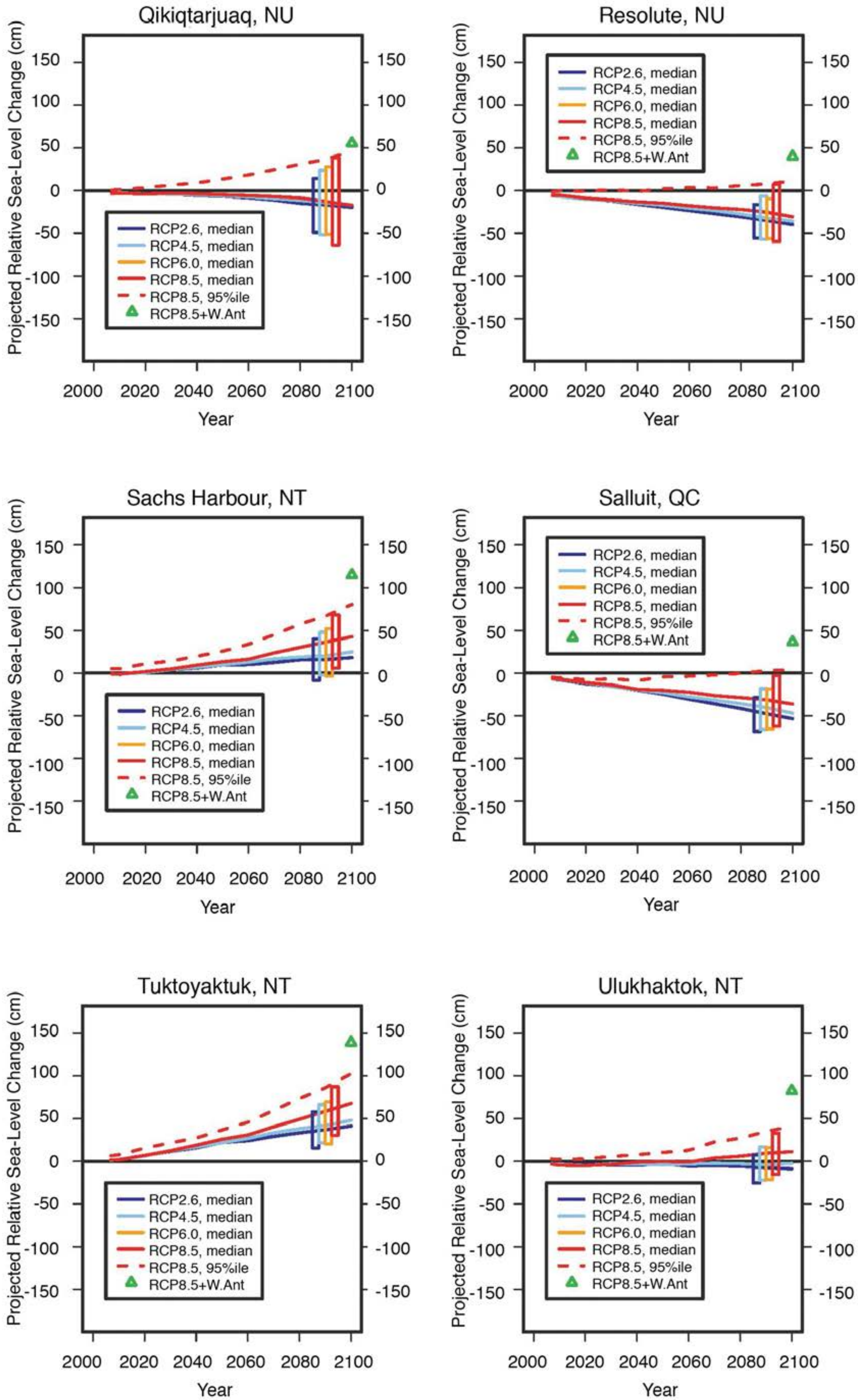
Qikiqtarjuaq, NU
Resolute, NU
Sachs Harbour, NT
Salluit, QC
Tuktoyaktuk, NT
Ulukhaktok, NT
Projected Relative Sea-Level Change (cm)
150
100
50
0
-50
-100
-150
2000
2020
2040
2060
2080
2100
Year
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant