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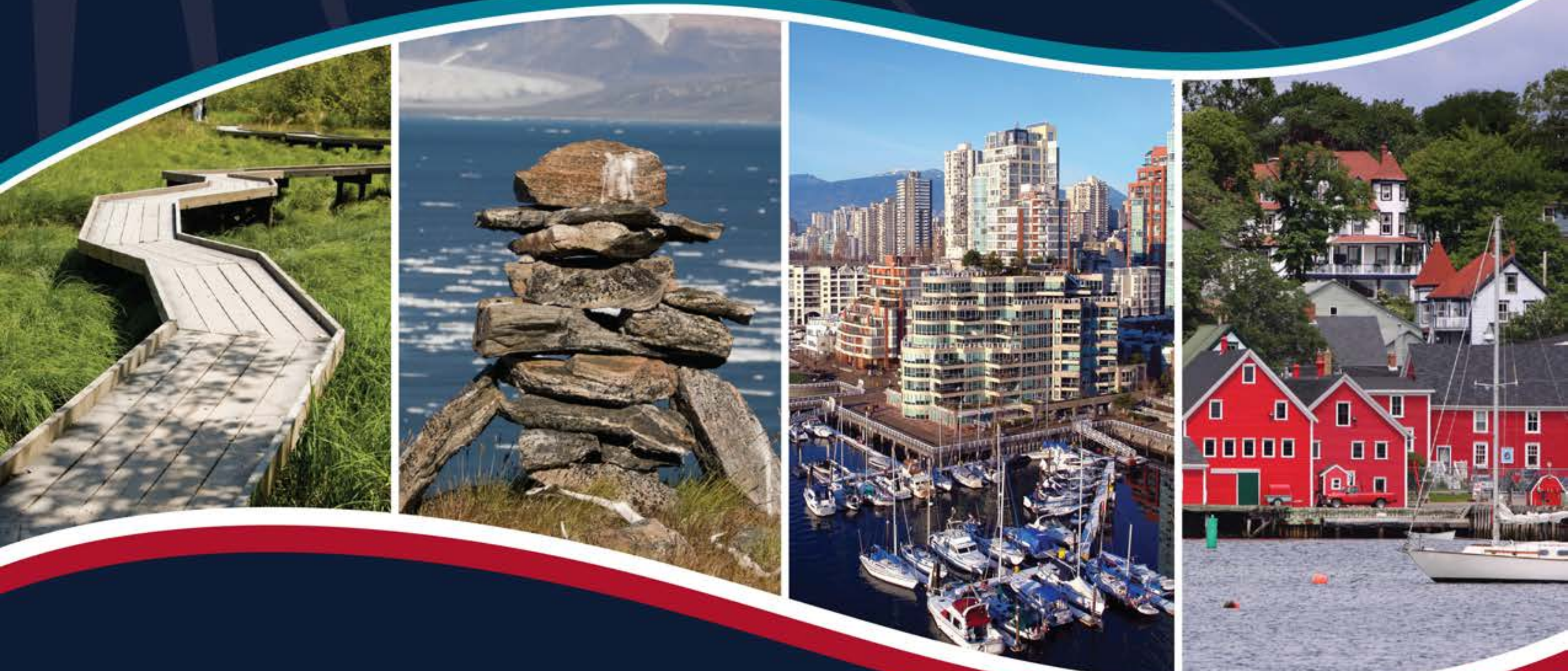
CANADA'S MARINE COASTS in a CHANGING CLIMATE



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CANADA'S MARINE COASTS in a CHANGING CLIMATE

Canada

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SUMMARY

Coasts are an important component of the Canadian identity, economy and culture. Fronting on three oceans—Atlantic, Arctic and Pacific—Canada's coasts, the longest in the world, are diverse and dynamic regions whose biodiversity, beauty and resources contribute to the country as a whole. The impacts of climate change on Canada's coasts, which extend far beyond changes in sea level, present both challenges and potential opportunities for coastal communities, ecosystems and economic activities. How we adapt to the coming changes will be critical to the sustainability and continued prosperity of Canada and its coastal regions. The following points represent high-level conclusions from *Canada's Marine Coasts in a Changing Climate*, and are discussed further in this synthesis:

- Changing climate is increasingly affecting the rate and nature of change along Canada's highly dynamic coasts, with widespread impacts on natural and human systems.
- Recent extreme weather events demonstrate the vulnerability of coastal infrastructure.
- Changes in the extent, thickness and duration of sea ice, both in the North and in some areas of the East Coast region, are already impacting coasts, ecosystems, coastal communities and transportation.
- Sea-level changes will vary significantly across Canada during this century and beyond. Where relative sea level is rising, the frequency and magnitude of storm-surge flooding will increase in the future.
- Knowledge of climate risks and the need for adaptation in coastal areas is increasing, with many examples of local and regional governments in Canada taking action on adaptation.
- A range of adaptation measures will be needed in most settings to address the complex array of changes. Alternatives to hard coastal-protection structures can be effective in addressing coastal erosion and flooding in many areas.
- It is imperative that future development be undertaken with an understanding of the dynamic nature of the coast and changing coastal risks. Monitoring and assessment of the effectiveness of actions taken to date, as well as research to fill data and knowledge gaps, would help inform sustainable planning and development.

INTRODUCTION

> This report takes a landscape approach in examining Canada's marine coasts. While focus is placed on the shoreline as the interface between land and water, the scope of interest extends landward and oceanward to the degree that those areas affect the sustainability and well-being of coastal communities and ecosystems.

Canada is a coastal nation. All provinces and territories, with the exception of Alberta and Saskatchewan, share in the approximately 243 000 km of coastline (Taylor et al., 2014). Indigenous peoples have lived along Canada's coasts and utilized coastal resources for thousands of years, and many First Nation, Métis and Inuit communities retain very close ties to the coast. Today, about 6.5 million Canadians live near our marine coasts, and more than $400 billion in goods are shipped annually through Canadian ports (Association of Canadian Port Authorities, 2013).

This report divides Canada's marine coasts into three large regions: East Coast, North Coast and West Coast (Figure 1). It is important to recognize that there is tremendous variability both among and within these regions. For example, the North Coast region (which includes about 70% of Canada's coastline) is very sparsely populated; the majority of residents are Inuit, First Nations or Métis; and sea ice is a defining element of the coast for much of the year. The East Coast region is characterized by several cities and an abundance of small towns and hamlets, with a diverse economy in which coastal resources continue to play an important role. The population of the West Coast region is concentrated in British Columbia's lower mainland and southeastern Vancouver Island, with the number of residents and built-environment asset value of the greater Vancouver area far exceeding that of any other part of Canada's marine coast.

Science assessments at global (e.g., IPCC, 2007, 2014) and national (e.g., Lemmen et al., 2008; Warren and Lemmen, 2014) scales highlight the importance of understanding and addressing climate change impacts in coastal regions. Globally, coastal flooding could displace hundreds of millions of people in the current century, with the annual costs for adaptation measures such as new dike construction, dike maintenance and beach nourishment estimated to be US$25–270 billion per year by 2100 (Wong et al., 2014). Within Canada, climate change (Box 1) presents a range of risks, with higher temperatures, changing precipitation patterns and storminess, rising sea level and diminishing sea ice being the key climate changes discussed throughout this report. The magnitude, importance and sometimes direction of these changes vary both among and within the three regions.

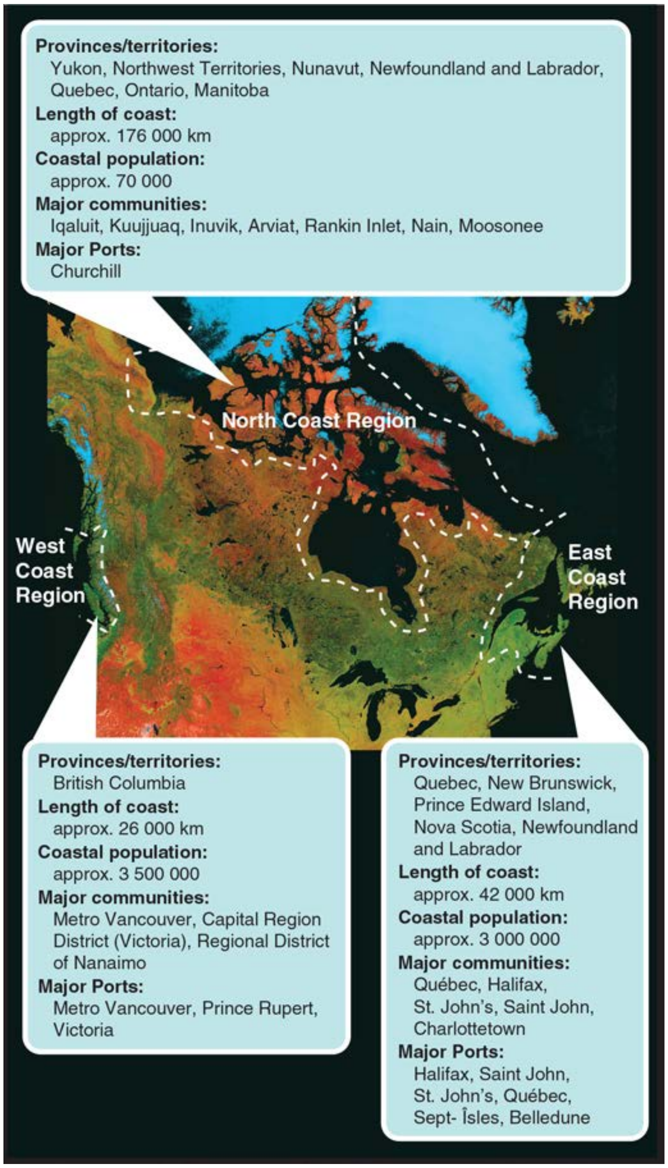

FIGURE 1: The three coastal regions used in this report.

BOX 1
WHAT IS CLIMATE CHANGE?

The term climate change is used in this report to refer to any change in climate over time, whether it is the product of natural factors, human activity or both. Analysis at the global level demonstrates that warming of the Earth's climate system is unequivocal, and that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC, 2013). Climate change is distinct from natural climate variability, which includes short-term phenomena such as the El Niño/Southern Oscillation. The term 'changing climate' is used frequently throughout this report to highlight that these changes are ongoing.

ADDRESSING CLIMATE CHANGE

Enhanced action to address climate change is a global commitment solidified in the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change. Such action involves both reduction of greenhouse gas emissions (mitigation) and adjusting to unavoidable climate impacts (adaptation). Adaptation is undertaken to reduce the negative impacts of climate change and to take advantage of opportunities that may be presented. In human systems, adaptation refers to changes in our decisions, activities and thinking because of observed or expected changes in climate. This report focuses on processes and actions associated with planned adaptation— deliberate decisions based on understanding of ongoing and anticipated climate changes.

Canada's Marine Coasts in a Changing Climate complements previous science assessments in this series: *From Impacts to Adaptation: Canada in a Changing Climate* (Lemmen et al., 2008), which presents a regional analysis of impacts and adaptation for Canada as a whole; and *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (Warren and Lemmen, 2014), which is organized by themes and economic sectors. Readers are directed to these earlier assessments for a more complete description of some of the concepts presented in this report. This synthesis draws on information discussed in the individual chapters of *Canada's Marine Coasts in a Changing Climate*, which include an overview of the geological and physical aspects of the coast (Chapter 2); a chapter on the environmental and societal sustainability of Canada's marine coasts (Chapter 3); three regional chapters that examine issues in Canada's East, North and West Coast regions (Chapters 4, 5 and 6, respectively); and a concluding chapter that addresses frequently asked questions (Chapter 7). The key findings of Chapters 4 to 6 are summarized in Box 2. The rest of the synthesis is structured around high-level conclusions (listed in the 'Summary') supported by examples and insights from an integrative analysis of the chapters of the report.

BOX 2
SUMMARY OF REGIONAL CHAPTER KEY FINDINGS

CHAPTER 4: PERSPECTIVES ON CANADA'S EAST COAST REGION

Air temperatures, sea-surface temperatures and ocean acidity have all increased in the region during the past century, while sea-ice cover has decreased. Projected climate changes through the 21st century include continued warming of air and water temperatures, and increased precipitation, acidification and water stratification. Sea level will rise, with significant regional variability. Sea ice will decrease in area, thickness, concentration and duration, with volume likely to be reduced by more than 95% by the end of the 21st century.

Sea-ice cover and sea-level rise are key determinants of coastal erosion rates. Increases in coastal erosion have been documented along many coasts in the region during years characterized by mild winters and low ice coverage. Future coastal-erosion rates will likely increase in most areas.

There are many adaptation measures that promote the resilience of coastal areas. These include protection, revegetation and stabilization of dunes; maintenance of sediment supply; and provision of buffer zones, rolling easements or setbacks that allow the landward migration of the coastline.

Although hard coastal defence structures may be necessary to address sea-level rise and coastal flooding in some situations, particularly in urban areas, such structures disrupt coastal processes and can exacerbate erosion, sedimentation and coastal squeeze, leading to degradation and loss of coastal habitats and ecosystem services. Retreat, sand nourishment and managed realignment represent alternatives to hard coastal-defence structures.

Experience in the East Coast region has shown that mechanisms such as setbacks, which control or prohibit coastal development, can be challenging to implement. However, it is often even more difficult to remove and relocate buildings from an eroding coastline or flood-susceptible area. Selection of appropriate adaptation options may be particularly challenging in unincorporated areas where summer cottages, secondary homes or principal dwellings are established parallel to the shore in a ribbon fashion.

Provinces and communities across the region have made advances in identifying vulnerabilities to climate change impacts through collaboration with academia, the private sector and nongovernmental organizations. Many have begun planning for adaptation, while others have moved from planning to implementation of adaptation strategies, although this remains a challenge for many. Few are engaged in ongoing monitoring of the effectiveness of implemented adaptation strategies.

CHAPTER 5: PERSPECTIVES ON CANADA'S NORTH COAST REGION

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.

CHAPTER 6: PERSPECTIVES ON CANADA'S WEST COAST REGION

Sea-level rise will not affect all areas of the British Columbia coast equally, largely due to differences in vertical land movement. The largest amounts of relative sea-level rise are projected to occur on the Fraser Lowland, southern Vancouver Island and the north coast. Planning guidance for sea-level rise developed by the British Columbia government provides planning levels that slightly exceed the peak values (95th percentile) of the sea-level projections at 2050. This could be considered a margin of safety that allows for possible additional sea-level rise arising from factors with significant uncertainty, such as contributions from the Antarctic Ice Sheet.

Storm-surge flooding presents a greater threat to coastal communities than sea-level rise alone. Coastal communities are already coping with extreme water levels associated with climate variability (e.g., El Niño/La Niña Southern Oscillation) and storm-surge flooding. The risks associated with these events are expected to increase as sea level rises. Residential, commercial, institutional and municipal property and infrastructure in the region are vulnerable, and communities have begun to take action to reduce the risk through adaptation measures such as shoreline protection.

Marine ecosystems will be affected as species move northward in response to warmer water. Southern species will expand their range northward into British Columbia as the ocean warms, while species that today inhabit the south coast region, including salmon, will also migrate north. In the southern part of the province, warmer ocean-surface temperatures will decrease the habitable range of shellfish and changing ocean acidity will affect their reproductive success. Adaptation in the commercial-fisheries sector will involve shifting the types of species being fished and relocating operations. First Nations, who rely strongly on salmon for cultural uses, often have fewer options for adaptation to changes in distribution and abundance of fish species.

Changing precipitation patterns will affect summer water availability and the timing of salmon runs in some watersheds. Winter precipitation is expected to increase overall, with more falling as rain and less as snow. Less precipitation is expected during the summer and this, combined with reduced snowpack, will decrease the amount of water available for some regions in late summer and autumn. River levels will decrease during this period and water temperature is likely to increase as a result. Increased river temperature would affect the timing of salmon runs because these fish do not enter rivers until water temperatures cool to approximately 15°C.

Climate change adaptation is gaining momentum in British Columbia. Governments have been moving forward on climate change adaptation, particularly regarding sea-level rise and coastal-flooding issues. Notable projects include a cost assessment of upgrading Metro Vancouver's dike system; a risk study for sea-level rise in the Capital Regional District; the City of Vancouver's new Flood Construction Level that considers sea-level rise; the placement of boulders below the low-tide level off the West Vancouver shore to mitigate storm-surge impacts; and the development of a Sea-Level Rise Primer for local governments.

CHANGING CLIMATE IS INCREASINGLY AFFECTING THE RATE AND NATURE OF CHANGE ALONG CANADA'S HIGHLY DYNAMIC COASTS, WITH WIDESPREAD IMPACTS ON NATURAL AND HUMAN SYSTEMS.

Coasts are naturally dynamic environments. While change is most evident in the natural environment, for example arising from intermittent extreme events such as storms that erode beaches and cliffs, and long-term changes in sea level and ecosystems (Chapter 2), the social and economic environments of Canada's coasts are similarly dynamic (Chapter 3). Although Canada's coastal economies were historically based on fisheries, agriculture, forestry and transportation, our coasts have become increasingly urbanized and economically diverse in recent decades. Development of offshore oil-and-gas (Chapters 4 and 5) and increased coastal tourism (Chapters 3, 4, 5 and 6) are examples of changing economic drivers that have affected the economies of coastal communities, and that reflect a broader economic shift toward commerce and innovation.

Changing climate is an additional, and increasingly important, driver of change in coastal regions. While the scientific literature is dominated by studies related to the impacts of extreme weather events (e.g., severe storms) and changes in sea level, there are many other climate-related changes that affect coastal regions. These include changes in temperature and precipitation patterns, storms, wave climate, sea ice, hydrology (including glacier melt) and ocean-water properties (e.g., temperature, salinity, acidification, hypoxia; Chapters 2, 4, 5 and 6). These changes exacerbate existing risks, bring new challenges and, in some cases, present opportunities. The degree and nature of the resulting damages or benefits depend largely on the success of adaptation measures.

Impacts on terrestrial and marine ecosystems remain poorly quantified (Chapter 7, FAQ 7). In some cases, ecosystems may be able to adapt naturally. In salt marshes, for example, if the rate of marsh accretion is able to keep up with sea-level rise, there would be limited impact (Chapters 2 and 4). However, where the rate of sea-level rise exceeds the ability of the marsh to accrete, or where onshore migration is blocked by natural or artificial barriers, loss of habitat and of valuable ecosystem services (including coastal protection) may occur (Chapters 3, 4 and 6). On the Pacific coast (West Coast region), anadromous fish species, such as salmon, may be particularly impacted by the combined effects of increased water temperature and lower river-water levels, affecting both survival and reproductive success (Chapter 6). In all regions, increasing ocean acidity threatens shellfish and other marine organisms, and has the potential to disrupt food chains and impact fisheries, including aquaculture operations (Chapters 4, 5 and 6).

Some ecosystem impacts have direct implications for the livelihoods and cultural well-being of Canada's coastal Indigenous populations (Chapters 4, 5 and 6). These impacts include changes in the distributions of key food species (e.g., salmon and seal) and the ability to access these resources. For example, First Nations commercial fisheries in coastal British Columbia tend to use much smaller boats than those of large-scale commercial operations, thus limiting their range and the ability of First Nations fishers to adapt to climate-related changes in species distribution (Chapter 6). In the North Coast region, changes in sea ice can greatly affect the safety of travel across the ice surface and the ability to access traditional foods (Chapter 5).

While virtually all economic sectors in Canada's coastal regions will be either directly or indirectly impacted by changing climate, the fisheries, tourism, transportation, energy and infrastructure sectors stand out as being particularly climate sensitive (Table 1; Chapters 3, 4, 5 and 6). Although available studies tend to focus on economic risks, there is also recognition of potential benefits, such as longer tourism seasons associated with warmer temperatures (Chapters 3 and 4), and new opportunities for northern shipping and natural-resource development with the reduction in sea-ice cover (Chapter 5). Risks are numerous and generally associated with impacts on the resource base (e.g., fish, forests), infrastructure and supply chains (Chapters 3, 4, 5 and 6). These risks vary regionally and locally.

Climate change, along with globalization, demographic changes and many other factors, ensure that Canada's coasts of today are not the coasts of tomorrow. Even without climate change, coasts are dynamic and always evolving. Rates of change are expected to increase in the future. Understanding the nature of the changes, including the interactions among the various drivers of change, and factoring them into planning decisions are necessary to the development of resilient economies and communities.

TABLE 1: Examples of positive (+) and negative (–) impacts on sectors associated with changing climate.

Fisheries	Region
Shifts in distribution will have both negative and positive implications for the species available to fish and the timing of fishing seasons. (+/–)	East, North and West
Commercially valuable shellfish fisheries, including aquaculture, are vulnerable to acidification, increases in exotic-species invasions associated with warming waters and closures from biological contamination. (–)	East and West
Extreme events, sea-level rise, storm surges and accelerated erosion will impact coastal infrastructure used for fisheries, such as ports, wharves, piers and fish plants. (–)	East, North and West
Reductions in dissolved oxygen and resulting hypoxia can result in fish kills, altered physiological development and growth and migration patterns, loss of habitat for bottom-dwelling fishes and other benthic fauna, and habitat compression. (–)	East and West
Climate change alters the health, availability and migration timing of species utilized for subsistence and commercial fisheries. (+/–)	North, East and West

Tourism	Region
With reduced sea ice in the north, there will be more opportunities for cruise-ship tourism. (+) Associated concerns relate to safety, pollution and culture. (–)	North
Warmer weather will bring longer seasons for tourist visits and summer recreational activities (+) but may reduce cold-weather recreational opportunities. (–)	East, West and North
Tourism infrastructure (e.g., wharves and coastal properties) and cultural resources (e.g., Haida Gwaii and Fortress of Louisburg) are threatened by sea-level rise and more extreme weather. (–)	East, West and North
Increases in algal blooms and decreases in water quality associated with warmer waters may make beaches less attractive. (–)	East

Infrastructure	Region
Existing infrastructure may become less usable with higher mean sea levels leading to higher tides and storm surges, and/or accelerated erosion through increased wave action and/or thermal effects on permafrost coasts. (–)	North, East and West
The highest potential for infrastructure damage in British Columbia will result from the effect that sea-level rise has on increasing the impact of high-water levels and waves during storms. (–)	West
Flooding resulting from storm surges, extreme precipitation events and storms superposed on rising sea levels will cause costly infrastructure damage. (–)	East, West and some parts of the North

Transportation	Region
Reduced sea ice and deeper waters in many harbours present potential opportunities for shipping, although ice risks remain significant. (+/–)	North and East
Flooding of highways by storm surges and storm waves can cause isolation of coastal communities. (–)	East and West
Risk of flooding of low-lying airports may increase as a result of sea-level rise and storm surges. (–)	West
Ferry services can be disrupted due to extreme-weather delays and cancellations, as well as damage from storms (to the wharves or roads that access the ferry terminals). (–)	West and East
Warmer winters lead to increased incidence of fog affecting coastal airports. (–)	North and East
Safety risks for travel across sea ice will increase. (–)	North

Energy	Region
Increased opportunity for oil-and–gas exploration and development associated with reduced sea ice and a longer navigable season. (+)	North
Sea-level rise and storms could affect existing and proposed coastal export terminals and create hazardous conditions for shipping. (–)	East and West
Ice storms and severe winds increase the risk of damage to energy-transmission infrastructure. (–)	North, East and West
Changes in streamflow patterns would affect hydroelectricity production. (+/–)	North, East and West

RECENT EXTREME-WEATHER EVENTS DEMONSTRATE THE VULNERABILITY OF COASTAL INFRASTRUCTURE.

While climate change is a gradual process, many of the most significant impacts of climate change will relate to damages caused by extreme events. Although it is difficult to attribute specific extreme-weather events to climate change (Chapter 7, FAQ 4), it is evident that changing climate is affecting the probability of some climate extremes (Chapter 2; IPCC, 2013). The impacts associated with recent extreme events (Table 2) highlight vulnerabilities of coastal communities and infrastructure. Impacts associated with storms are the most widespread concern, but other types of extremes are important in some regions. For example, drought is a concern along the southern coast of British Columbia, with important implications for water infrastructure (Chapter 6).

The differing climatologies of Canada's three coastal regions are reflected in the differing nature of storm events. The most severe storms in the East Coast region tend to be tropical cyclones, such as Juan in September 2003 and Igor in September 2010, or nor'easters, such as 'White Juan' in February 2004 and the storm of January 2000 (Chapters 2, 3 and 4). In the West Coast region, extreme rainfall events are associated with 'atmospheric rivers' (colloquially referred to as the 'Pineapple Express'), a phenomenon in which a concentrated flow of very moist air from the tropics is transported to the coast (Chapters 2 and 6). These events often cause severe flooding, landslides and sediment loading in drinking-water reservoirs (Chapter 6). Severe storms are less common in the Arctic, particularly in the western and northern areas. Storm surges are a major hazard in some areas, notably the Beaufort Sea coast (North Coast region) and the Gulf of St. Lawrence and Atlantic coast (East Coast region). Maximum storm-surge heights exceeding 1 m occur in all three coastal regions (Chapter 2).

Storm events can cause inland and coastal flooding, wind damage and coastal erosion, all of which impact coastal communities, infrastructure and ecosystems. In extreme cases, individual storm events can result in metres of shoreline erosion (Chapters 4 and 5). Inland flooding associated with post-tropical storm Igor washed out roads and bridges across

TABLE 2: Examples of costly extreme events in Canada's coastal regions described in the Canadian Disaster Database (Public Safety Canada, 2014). Estimated total cost is from source database and is not limited to costs along the coast. Values include the amount paid out by insurance companies and the amount, in dollars, paid out by a Province or Territory due to a specific event. Estimates that include uninsured losses and other costs may be many times greater than the values listed here (e.g., in Chapters 3 and 4).

Region	Location	Event/Date	Description / Impacts
East	Newfoundland and Labrador	Hurricane (Hurricane Igor) September 21, 2010	▪ wind speeds in some areas exceeded 170 km/h ▪ approximately 90 communities were isolated due to washouts and road closures, and 22 communities declared states of emergency. ▪ 300 evacuations ▪ one death ▪ estimated total cost: $51 000 000
East	Halifax, NS and Charlottetown, PE	Hurricane (Hurricane Juan) September 29, 2003	▪ a 1.63 m storm surge occurred while Hurricane Juan made landfall just south of Halifax ▪ water levels reached 2.9 m above chart datum, the highest water level recorded to date at this location ▪ extensive damage to buildings, docks, boardwalks and trails occurred in the Halifax region (especially the downtown waterfront) ▪ eight deaths ▪ estimated total cost: $30 900 000
West	Fraser Valley and Metro Vancouver, BC	Storms and severe thunderstorms January 6–8, 2009	▪ severe rainstorm January 6 to 8 ▪ caused overland flooding, mudslides and landslides until January 31 ▪ estimated total cost: $16 500 000
East	New Brunswick	Tropical storm (post-tropical storm Arthur) July 5, 2014	▪ heavy rain and wind gusts of up to 100 km/hr ▪ widespread road closures ▪ more than 140 000 power customers were affected by outages. ▪ estimated total cost: $12 500 000
East	Nova Scotia	Winter storm ('White Juan') February 18–20, 2004	▪ record-breaking snowfall ▪ four-day state of emergency ▪ nine-hour curfew in place for three nights ▪ thousands were left without power. ▪ estimated total cost: $5 600 000
North	Pangnirtung, NU	Flood June 8–9, 2008	▪ flood damaged two bridges and cut residents off from essential services ▪ estimated total cost: $4 900 000

a wide swath of Newfoundland, isolating more than 150 towns (Chapter 3). An example of an ecosystem impact associated with extreme events is the 1999 storm surge in the Mackenzie Delta, which drove marine waters up to 30 km inland from the coast, resulting in the die-back of 30 000 hectares of shrub tundra and sedge wetlands (Chapter 5). Storm events that cause significant damage with high costs are more common in the East Coast region than along Canada's other coasts, as reflected in the Canadian Disaster Database (Public Safety Canada, 2014, Table 2).

CHANGES IN THE EXTENT, THICKNESS AND DURATION OF SEA ICE, BOTH IN THE NORTH AND IN SOME AREAS OF THE EAST COAST REGION, ARE ALREADY IMPACTING COASTS, ECOSYSTEMS, COASTAL COMMUNITIES AND TRANSPORTATION.

Sea ice is a dominant feature along Canada's northern coasts and a seasonal feature in parts of the East Coast region. For the Arctic as a whole, the extent of sea ice in September (the minimum) has declined by about 13% per decade since the 1980s (Perovich et al., 2014). In the Canadian Arctic, decreases range from 10.4% per decade in Hudson Bay to 2.9% per decade in the Arctic Archipelago (Chapter 5). In those areas of the East Coast region that experience sea ice, the rate of decrease in average annual sea-ice cover has been 2.7% per decade since 1969 (Chapter 4).

In both regions, warmer average temperatures have resulted in delays in the date of freeze-up and advances in the timing of break-up, as well as decreases in ice thickness. At some sites in the North Coast region, the ice-free season has increased by more than 30 days during the past three decades (Chapter 5). These trends are projected to continue or accelerate in the future, with some models projecting a complete loss of summer ice cover in the Arctic before mid-century (Chapter 5). In the East Coast region, projections indicate that the Gulf of St. Lawrence will be free of winter ice by the end of this century (Chapter 4).

Changes in sea-ice cover affect coastal processes and livelihoods (Figure 2). Sea ice dampens wave action, reducing the impact of powerful storms and thereby limiting coastal erosion. However, sea ice can also negatively affect coastal stability and infrastructure. For example, a major storm in Atlantic Canada in January 2000 resulted in mobile sea ice from the Gulf of St. Lawrence being thrust onshore—an 'ice push' event—damaging shorefront buildings and harbour infrastructure,

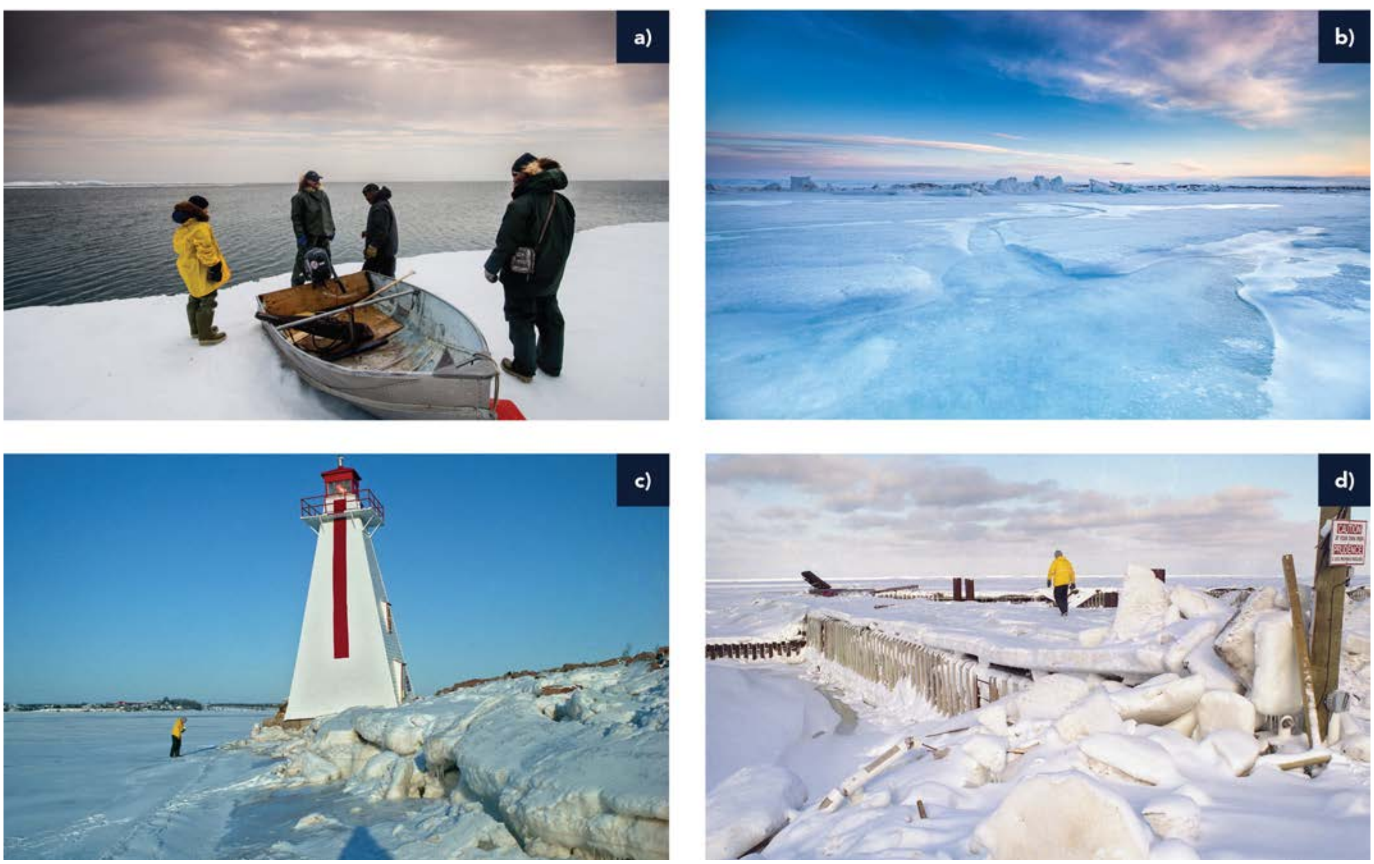

FIGURE 2: Sea ice is a defining characteristic of Canada's North Coast region **a)** and **b)**, and is seasonally important in large parts of the East Coast region **c)** and **d)**, affecting both coastal processes and livelihoods. *Photos courtesy of a) D.G. Clark, b) © Curtis Jones; c) and d) D. Forbes.*

including a lighthouse in Charlottetown Harbour that was knocked off its foundation (Chapter 2). As the extent and seasonal duration of sea ice diminishes, seasonal fetches increase, resulting in larger waves and increased wave energy reaching the coast, leading to increased erosion and risk of flooding (Chapters 2, 4 and 5). In the North Coast region, the greatest increase in fetch is occurring during the fall, which is also often the stormiest period of the year (Chapters 2 and 5).

Changing ice regimes have a direct impact on the livelihoods of Indigenous peoples in the North Coast region. Less predictable weather and ice conditions make travel across the surface of sea ice more dangerous, compromising traditional harvesting activities and, in turn, negatively affecting health and well-being. For example, during the particularly warm winter of 2009–2010, half of the residents surveyed in Nain, NL noted that they could not use typical travel routes, while three-quarters reported being unable to predict ice conditions and being afraid to use the ice (Chapter 5).

SEA-LEVEL CHANGES WILL VARY SIGNIFICANTLY ACROSS CANADA THIS CENTURY AND BEYOND. WHERE SEA LEVEL IS RISING, THE FREQUENCY AND MAGNITUDE OF STORM-SURGE FLOODING WILL INCREASE IN THE FUTURE.

During the current century, global mean sea level is likely to rise between 28 and 98 cm, and increases of more than 1 m are possible (Church et al., 2013). The actual amount of sea-level change experienced at any site will differ from the global average due to a number of factors, with vertical land motion caused by glacial isostatic adjustment being particularly important in Canada (Chapter 2). Because vertical motion varies greatly across Canada, projections of relative sea-level changes by 2100 range from a rise of almost 100 cm in parts of the East and West coast regions to a sea-level fall of almost 100 cm in parts of the central North Coast region (Figure 3).

In areas experiencing sea-level rise, including most of the East and West Coast regions and the Beaufort Sea coast of the North Coast region, its influence on coastal change will increase continuously throughout this century. Rising sea levels will threaten the viability of some low-lying communities (e.g., Tuktoyaktuk, NT) and increase the risk of flooding and inundation of others. For example, 40 cm of sea-level rise in Halifax by 2050 will result in extreme water levels that currently have a recurrence interval of 50 years having a much shorter recurrence interval of less than 2 years (Figure 4; Chapter 2). Coastal stability may be greater in areas of the North Coast region where sea level is falling; however, other climate change impacts, such as changes in sea-ice cover and associated increases in wave energy, will still impact these coasts (Chapter 2).

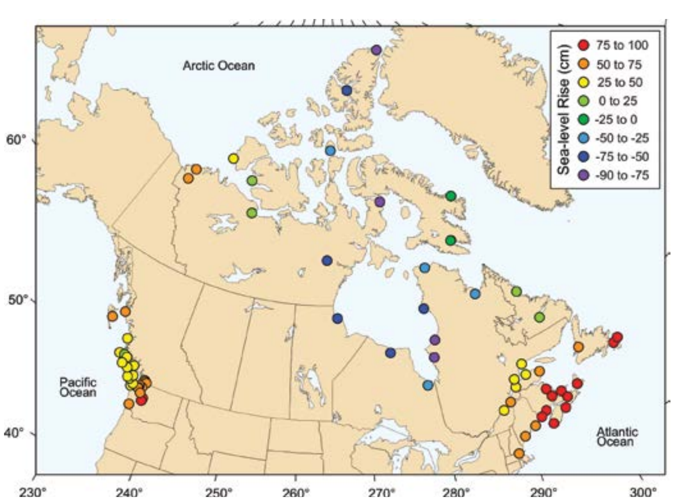

FIGURE 3: Projected relative sea-level change (cm) at 2100 for the median of a high-emissions scenario (RCP8.5) for coastal locations in Canada and the northern United States. *See* Chapter 2 for information on methodology and the climate change scenarios used in this report. Graphs showing projected change in sea level through this century for each of the Canadian sites shown in this figure are found in the relevant regional chapter (Chapter 4, 5 or 6).

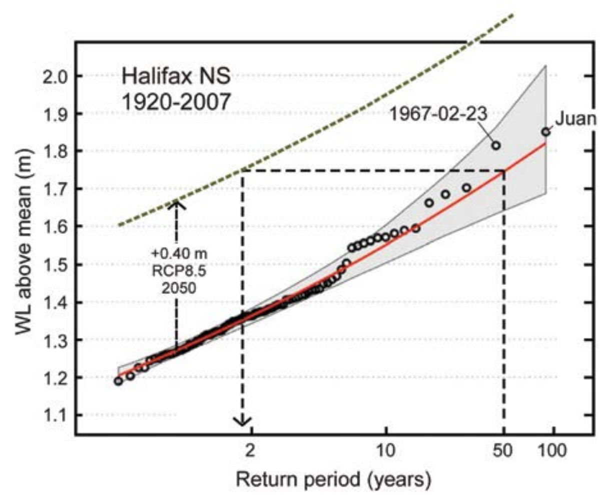

FIGURE 4: Annual maximum hourly water levels (metres above mean) in Halifax Harbour, NS, 1920–2007, and associated return periods in years. The red line is the best fit to the observations, indicating the average recurrence interval for any given annual maximum water level today and the change in return period that results from a rise in mean sea level under a high-emissions scenario by 2050 (*modified from* Forbes et al., 2009; Chapter 2).

While no single value of sea-level change is meaningful for planning purposes across the whole of Canada, the strong regional and subregional patterns evident in Figure 3 allow for practical guidelines to be developed at those scales. The *Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use* for British Columbia is an example of this type of guidance (Chapter 6).

> Sea level has been changing continuously along most Canadian coasts for thousands of years. These changes are related primarily to the fact that, during the last glaciation of North America, the mass of the ice sheets (up to about 4 km thick) depressed the Earth's crust beneath them and displaced viscous material in the mantle (which lies between the Earth's core and its crust). Melting of the ice sheets between about 21 000 and 8 000 years ago resulted in mantle material slowly flowing back and the Earth's crust slowly rebounding. These changes in the elevation of the Earth's crust, which are still ongoing, are known as glacial isostatic adjustment (Chapter 2). They have resulted in crustal uplift in areas near the centre of former ice sheets—along Hudson Bay, for example, where sea level has fallen by more than 200 m in the past 8 000 years and the land is presently rising at 10 mm/year or more. In contrast, sites near or beyond the margin of the former ice sheets have experienced sea-level rise during the same time period and are presently subsiding at low rates—Halifax, for example, is sinking at about 1 mm/year.

KNOWLEDGE OF CLIMATE RISKS AND THE NEED FOR ADAPTATION IN COASTAL AREAS IS INCREASING, WITH MANY EXAMPLES OF LOCAL AND REGIONAL GOVERNMENTS IN CANADA TAKING ACTION ON ADAPTATION.

The number of studies on coastal climate change impacts, vulnerability and adaptation options in Canada has increased rapidly during the past decade. The majority of this research has focused on communities. The direct engagement of stakeholders in many of these studies has contributed to a heightened level of awareness of coastal climate hazards and the need for adaptation in each coastal region (Chapters 4, 5 and 6). As a result, it is increasingly understood that effective planning can help reduce the costs of climate impacts in the future and increase available options (Chapter 7, FAQ 11), and many communities and regions have established adaptation plans, policies and strategies (Table 3).

Adaptation is a shared responsibility, involving all levels of government, the private sector, civil society and individuals (Chapter 7, FAQ 10). All provinces and territories within Canada's coastal regions have specific adaptation strategies or plans that include reference to coastal issues. For example, the governments of Nunavut, Northwest Territories and Yukon have a Pan-Territorial Adaptation Strategy and Partnership that highlights the importance of planning for coastal erosion, and provides a mechanism for sharing knowledge and developing collaborative activities across much of the North Coast region (Chapter 5). Several provinces have developed policies, guidance and tools to inform coastal adaptation planning and practices. One of the earliest Canadian examples of planning for coastal change is the *New Brunswick Coastal Areas Protection Policy*, which was developed in 2002 to help protect public safety, infrastructure, agricultural lands and the biodiversity of plant and wildlife within the region (Chapter 4). As implementing such strategies can be challenging, there may be value in including interim measures that are subject to review and adjustment, as has been done for a large stretch of the Quebec North Shore where construction in areas of high coastal risk is prohibited (Chapter 4). In British Columbia, the government developed a sea-level rise primer and guidelines that have influenced coastal management at the community scale, including in Vancouver (Chapter 6). An important aspect of the BC guidelines is that they have a provision to be adjusted in the future, in light of new scientific results on global sea-level projections.

At the community level, there are many different examples of ongoing adaptation planning in all three coastal regions (Chapters 4, 5 and 6), which often involve other levels of government and nongovernment partners. In the North Coast region, for example, there has been an emphasis on adapting construction and design guidelines to better address permafrost degradation (Chapter 5). In the East and West Coast regions, more attention is being paid to restrictive zoning, including the use of vertical and horizontal setbacks, to reduce vulnerability to sea-level rise and coastal flooding in communities of all sizes. Examples include the City of Vancouver, which in 2013 became the first city in British Columbia to adopt formal consideration of 1 m of sea-level rise in development and planning requirements, consistent with provincial guidelines (Chapter 6); and Beaubassin-Est, NB (population 6200), which introduced a bylaw in 2011 requiring that the minimum ground-floor elevation of any new building be at least 1.43 m above the current once-in-100-years flood mark to account for anticipated sea-level rise (Chapter 4). These efforts to advance adaptation are occurring following a decade or more of rapid expansion of residential and other forms of 'ribbon' development along many coasts, which has increased both exposure and vulnerability to coastal hazards (Chapters 3 and 4).

TABLE 3: Examples of regional and community-level adaptation programs, plans, policies and strategies.

East Coast region	Focus
The Atlantic Climate Adaptation Solutions Association is a partnership among the governments of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador that is working with the Government of Canada to assist Atlantic Canadians to adapt to climate change.	Information and decision-support tools for all climate risks
The Municipality of Les Îles-de-la-Madeleine has a master plan in which it identifies 23 areas where erosion is an issue and where action is deemed necessary.	Coastal erosion
The Municipal Planning Strategy and Land Use By-Law for the downtown Halifax waterfront area prescribes minimum elevation for any ground-floor development.	Sea-level rise and flooding
The New Brunswick Coastal Areas Protection Policy identifies sensitive coastal features, allowing these to continue to function naturally and maintain their buffering capacity, and identifies a limited-activity and -development buffer.	Shoreline protection
Ouranos, a joint initiative of the Government of Québec, Hydro-Québec and Environment Canada, is a consortium focused on regional climatology and adaptation to climate change.	Research and decision-support tools for all climate risks
North Coast region	**Focus**
The Pan-Territorial Adaptation Strategy (Governments of Nunavut, Northwest Territories and Yukon) is a mechanism for the governments to work together on climate change, with a focus on practical adaptation measures.	Building capacity and enhancing action
The Nunavut Climate Change Partnership piloted the development of adaptation-action plans in seven communities (Clyde River, Hall Beach, Iqaluit, Arviat, Whale Cove, Cambridge Bay and Kugluktuk).	Permafrost, sea-level change, coastal erosion, fresh water
Several coastal communities in Nunavik participated in a permafrost-monitoring and -mapping project to inform future development and land-use planning.	Permafrost degradation
SakKijânginnatuk Nunalik: The Sustainable Communities Initiative in Nunatsiavut addresses issues that are central to community well-being and sustainability in the context of a changing climate.	Informing best practices
West Coast region	**Focus**
British Columbia provincial guidelines for development in flood-risk areas identify the need for Flood Construction Levels in line with the increased risk presented by sea-level rise.	Sea-level rise
The Capital Regional District Climate Action Program is working with the public, private and nonprofit sectors to reduce vulnerability to sea-level rise.	Sea-level rise
The City of Vancouver is in the process of implementing their adaptation plan (which was initiated in 2007 through the passing of a city motion), which includes the adoption of formal consideration of 1 m of sea-level rise in development and planning requirements.	Sea-level rise
The Hartley Bay Band Council and Semiahmoo First Nation have carried out climate change vulnerability assessments and adaptation planning using a holistic approach that considers changes in both biophysical and socio-cultural environments.	Species shifts and sea-level rise
The Town of Qualicum Beach is in the planning phase of a comprehensive Waterfront Master Plan that will include planning for adaptation to sea-level rise.	Sea-level rise

A RANGE OF ADAPTATION MEASURES WILL BE NEEDED IN MOST SETTINGS. ALTERNATIVES TO HARD COASTAL-PROTECTION STRUCTURES CAN BE EFFECTIVE IN ADDRESSING COASTAL EROSION AND FLOODING IN MANY AREAS.

In Canada and elsewhere, there has been a tendency to favour hard-armouring protection measures, such as seawalls, bulkheads and dikes, to address issues of sea-level rise, coastal erosion and flooding (Chapters 3, 4 and 6). While hard armouring may be the most viable option in some areas, alternatives such as soft-armouring measures, accommodation and retreat/avoidance (Figure 5) may be more efficient, less costly and more sustainable responses in many situations (Chapter 3; Chapter 7, FAQ 11). Hard-armouring protection, if not properly designed, placed and maintained, can result in maladaptation by increasing impacts in adjacent areas and by contributing to the loss of key ecosystem services. For these reasons, the use of hard-protection measures is restricted in some areas (Chapter 4).

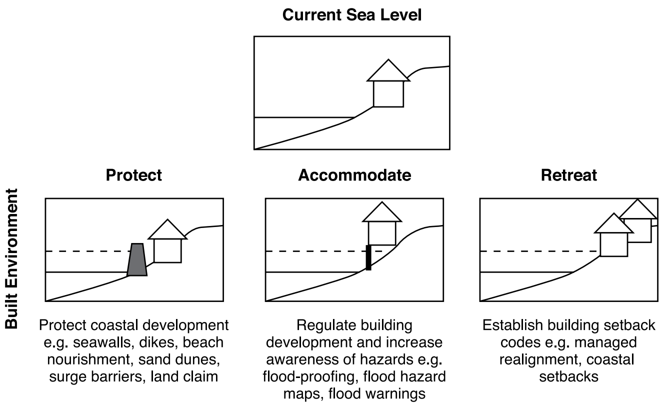

FIGURE 5: Schematic representation of protection, accommodation and avoidance/retreat as options for coastal adaptation (*modified from* Linham and Nichols, 2010, *based on* IPCC, 1990)

Soft-armouring measures include maintaining and/or restoring beaches, marshes and coastal vegetation, all of which can lessen the damaging effects of tides, currents, waves and storms (Chapter 3). There are many examples from the West Coast region, several of which are affiliated with the Green Shores program (Chapter 6). Examples from the East Coast region include restoration of salt marshes and the use of clean dredged sand to replenish protective beaches (Chapter 4). While soft-armouring measures have been demonstrated to be cost effective and environmentally beneficial, the fact that these measures are largely invisible, and therefore poorly understood by the general public, may present a barrier to their use (Chapter 4).

Accommodation responses are designed to lower the risk associated with various natural hazards. They allow for occasional short-term impacts (e.g., impacts from storm events or seasonal flooding) while people continue to occupy and/or use the coastal area. Examples include elevating buildings and ensuring alternative transportation links. Retreat can have considerable economic and social costs, and is generally one of the last options considered. However, managed retreat, which involves planned abandonment and gradual relocation of assets based on understanding of future changes in climate risk, can be prudent. Avoidance through proactive planning may be the most effective means of reducing risk. Harbour and waterfront plans for Gibsons, BC, Charlottetown, PE and Halifax, NS all have provisions for new development that factor in sea-level rise and increased storm-surge flooding, including avoidance of low-lying areas (Chapter 3).

Most adaptation plans that address sea-level rise, coastal flooding and erosion will include elements of all of these approaches (Chapter 3). For example, although coastal erosion represents a major risk to the Îles-de-la-Madeleine, QC, the decision was made to leave 95% of the islands unprotected from natural processes in order to preserve the natural beauty of the archipelago, which is a primary draw for tourists. This will require planned retreat and relocation of some structures. Hard- and soft-armouring measures will be utilized to protect a few town centres and critical infrastructure (Chapter 4).

IT IS IMPERATIVE THAT FUTURE DEVELOPMENT BE UNDERTAKEN WITH AN UNDERSTANDING OF THE DYNAMIC NATURE OF THE COAST AND CHANGING COASTAL RISKS. MONITORING AND ASSESSMENT OF THE EFFECTIVENESS OF ACTIONS TAKEN TO DATE, AS WELL AS RESEARCH TO FILL DATA AND KNOWLEDGE GAPS, WOULD HELP INFORM SUSTAINABLE PLANNING AND DEVELOPMENT.

In addition to implementing adaptation measures to address current risks in coastal areas, enhancing coastal resilience requires integrating changing climate into planning of future development. Activities in coastal regions have been, and will continue to be, major economic drivers for the whole of Canada. There are proposals for major infrastructure developments in all three of Canada's coastal regions (Chapters 4, 5 and 6), many related to improving access to foreign markets. In addition, demand for residential development near the shoreline remains high in many areas (Chapters 4 and 6). The rapidly growing populations of most northern coastal communities (Chapter 5) also increase demands for residential development and other infrastructure, including storm-water drainage systems capable of handling runoff from extreme rainfall events (Chapter 4). There are many policy instruments that can be used to facilitate implementation of plans, including regulations, bylaws, zoning and protective easements, and building codes.

Planning for sea-level change needs to take into account the variability across Canada, the timeframe of interest and the importance of extreme water levels. For planning horizons of less than about 35 years, the amount of sea-level change at a given location is similar under all climate change scenarios, thereby reducing uncertainty. In the latter half of the century, the choice of scenarios becomes more important and therefore should be undertaken with an understanding of risk tolerance (Chapter 3). Projections of future extreme water levels, which are particularly critical for planning future infrastructure, need to consider not only sea-level changes and storms, but also natural oceanographic variability (e.g., El Nino/ Southern Oscillation in the West Coast region that can raise local sea level by tens of centimetres) and other factors, such as wave set-up and run-up. For example, a major storm in January 2000 produced extreme waves that caused severe damage as high as 18 m above mean sea level in southwestern Newfoundland (Chapter 2). Ongoing integrative analysis is helping to map the sensitivity of coasts to sea-level change and other climate-related changes (Box 3) and could be complemented by additional analysis to more fully capture the human dimension of coastal vulnerability.

BOX 3

CANCOAST: A TOOL FOR ASSESSING COASTAL SENSITIVITY

Building on mapping of coastal sensitivity to sea-level rise (Shaw et al., 1998), ongoing work has developed an extensive database to help map sensitivity to inundation, coastal flooding and erosion arising from climate-related changes in sea level, sea ice and storminess along all of Canada's marine coasts (Figure 6). The CanCoast database contains digital-elevation data, projections of sea-level change for 2050, ground-ice conditions for coastal permafrost areas, and information on surficial materials, landforms, tidal range, wave height and recent trends in sea-ice concentrations. Potential applications for CanCoast include hazard mapping and impact assessment, adaptation planning, and analysis of data and knowledge gaps.

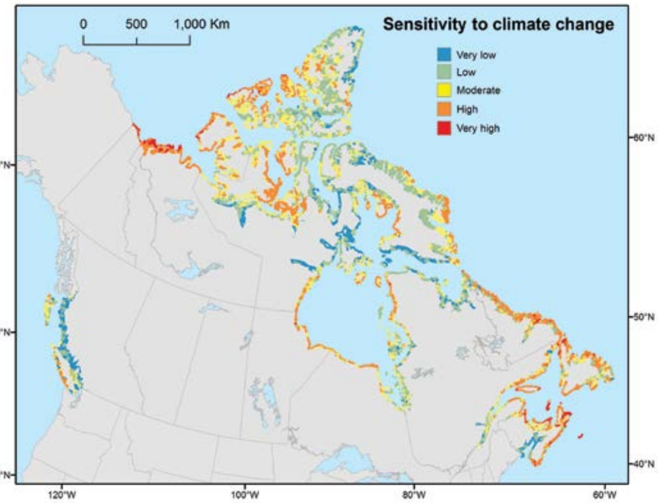

FIGURE 6: Preliminary map of coastal sensitivity to climate change in Canada, developed using the CanCoast database (Chapter 2). Note that some highly sensitive areas (e.g., the Fraser River delta) are not clearly visible at the resolution shown here.

A major need in Canada, and elsewhere, is improved monitoring and evaluation of adaptation measures that have been implemented in order to promote shared learning and identify best practices. Although all the regional chapters of this report include examples of adaptation actions taken at the local and regional scale, none of these have been thoroughly assessed in terms of their effectiveness in reducing climate risks. Additional research and enhanced collaboration related to collection and sharing of data could help address existing spatial gaps in understanding of climate vulnerability, including at the local level (Chapters 4, 5 and 6). Such research could strengthen the business case for adaptation by providing quantitative analyses of the costs and benefits associated with adaptation measures (Chapter 7, FAQ 11).

CONCLUSION

All of Canada's coastal regions are being impacted by changing climate, and these impacts will continue to increase in the future. The resulting risks and opportunities vary within and between regions, reflecting differences in both human and natural systems and in climate sensitivity. Key climate-related impacts emphasized in this report include changes in sea level, sea-ice extent, coastal flooding and ecosystem services. As a highly developed nation, Canada possesses the capacity needed to adapt to these impacts, but adapting in an efficient and proactive manner requires planning that accounts for the changing nature of climate risks. Limited site-specific knowledge and capacity to respond can be barriers to adaptation at the local scale, which may be best addressed through further collaboration between levels of government, as well as with academia and other nongovernment players. Collaboration and innovation are essential for achieving a vision of a sustainable and resilient coastal Canada.

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CHAPTER 1: INTRODUCTION

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PREFACE

Climate is changing—rising air and ocean temperatures, shifting precipitation patterns, shrinking glaciers, declining sea-ice extent, rising sea level and changes in extreme events have been observed globally (IPCC, 2013b) and in Canada (Bush et al., 2014). Climate models project that many of the observed trends will continue over the coming decades and beyond, even with aggressive global mitigation efforts (e.g., IPCC, 2013b). Reducing greenhouse gases is necessary to lessen the magnitude and rate of climate change, but it cannot prevent additional impacts from occurring due to the inertia in the climate system. Climate change impacts will continue to present risks and opportunities (Lemmen et al., 2008; Warren and Lemmen, 2014), and Canadians will need to adapt—make adjustments in their activities and decisions in order to reduce risks and moderate harm, or to take advantage of new opportunities.

Although all regions of the country will be affected by climate change, Canada's coastal regions face unique pressures. Changing sea levels, coastal and inland flooding, higher ocean temperatures and reduced sea ice cause a range of severe and often cumulative impacts. Furthermore, climate change stresses are superimposed upon the challenges already facing many coastal communities, including aging demographics, shifting economies and sometimes conflicting priorities regarding land use and development. Living near the coast also means recognizing its dynamic nature and adapting to an environment that is constantly in flux. It is important to understand the risks and opportunities that climate change presents for coastal regions within this context, in order to adapt effectively.

1 CANADA'S COASTS

Canada's coasts, the longest in the world, are a defining element of our national identity. (Mercer Clarke et al., Chapter 3, this volume)

The marine coastline of Canada fronts on three oceans (Atlantic, Arctic and Pacific) and includes major gulfs and bays (e.g., Hudson Bay and the Gulf of St. Lawrence). Canada's coastline, measuring more than 243 000 km, is the longest in world.[1] It extends from latitude 43°N to 83°N and includes landscapes as disparate as coastal rainforests and tundra barrens (Figure 1), as well as tidal ranges that range from negligible to the highest in the world. Canada's coasts are bordered by numerous straits, gulfs and bays, such as the Salish Sea on the southwest Pacific coast and the Bay of Fundy and Labrador Sea on the Atlantic margin. The large mass of northern islands, known collectively as the Canadian Arctic Archipelago, is divided from the mainland coast by a number of large water bodies and numerous interisland channels and straits, including the Northwest Passage.

FIGURE 1: Photos showing the diversity of Canada's marine coasts. East Coast region: **a)** and **b)**, North Coast region: **c)** and **d)**; and West Coast region: **e)** and **f)**. *Photos courtesy of a) J-P. Savard, b) D. van Proosdij, c) N. Couture, d) D. Evans, e) A. Blais Stevens and f) D. Lemmen*.

Coasts are important to all Canadians for their natural resources, beauty, biodiversity and other contributions to society and culture. Coasts have played, and will continue to play, a key role in supporting national, regional and local economies, and in facilitating the flow of imports and exports to meet the needs of people at home and around the globe. Marine ports in Canada annually ship merchandise worth more than $400 billion (Association of Canadian Port Authorities, 2013). Although Canada's coasts are increasingly urbanized, with the diverse economies associated with most modern cities, natural resources (including fisheries and forestry) continue to play an important role in many regions and are particularly sensitive to climate change. Tourism and transportation are other sectors of the coastal economy with high

1 Published values for the length of coastlines vary greatly, depending on the spatial scale at which measurements were taken. Coastal length is a classic fractal example (Mandelbrot, 1967) and, as such, all values are estimates. Values in this chapter are taken from Atlas of Canada (1972).

sensitivity to climate variability and change. Canada's coastal regions also provide ecosystem services that support the well-being of society and individuals (*see* Chapter 3), and that are especially important to many Indigenous peoples.

This report examines the implications of a changing climate in the three marine coastal regions of Canada: East Coast, North Coast and West Coast (Box 1; Figure 2). The boundaries were chosen to best facilitate discussion of the climate change issues facing each region, rather than being strictly based on geographic or political delineations. While the importance of inland freshwater coasts, such as the Great Lakes, is recognized, these are outside the scope of this assessment.

BOX 1
CANADA'S COASTAL REGIONS

The **East Coast region** includes the entire coasts of New Brunswick, Nova Scotia, Prince Edward Island and the island of Newfoundland; the southern coast of Labrador as far north as Hamilton Inlet; and the coast of Quebec that extends along the estuary and Gulf of St. Lawrence, reaching upriver to Québec. The total length of this coastline is approximately 42 000 km, with a coastal population of about 3 million. Important economic sectors include fisheries, aquaculture, transportation, tourism and manufacturing.

The **North Coast region** encompasses the coasts of the three northern territories, as well as Labrador (north of Hamilton Inlet), Manitoba, Ontario and Quebec along Hudson Bay and Hudson Strait. The region includes 176 000 km of coastline, representing more than 70% of Canada's marine coasts, but is sparsely populated by about 70 000 people. All but one of the 25 communities in Nunavut are located on the coast, and centres such as Inuvik, NT, Iqaluit, NU and Kuujjuaq, QC provide important regional services, including the import and export of goods. Sea ice and permafrost have a strong influence on northern coasts and livelihoods.

The **West Coast region** includes 26 000 km of coastline, all within the Province of British Columbia. The population of coastal British Columbia is approximately 3.5 million, concentrated largely in the lower mainland (Greater Vancouver) and southwestern Vancouver Island. In an analysis of current (2005) assets exposed to climate extremes, Vancouver was ranked 15th most vulnerable among all global port cities, with exposed assets of more than $55 billion (Nicholls et al., 2008), by far the greatest in Canada. Although the provincial economy is diverse, the economies of many small coastal communities remain strongly tied to fishery, forestry and tourism activities.

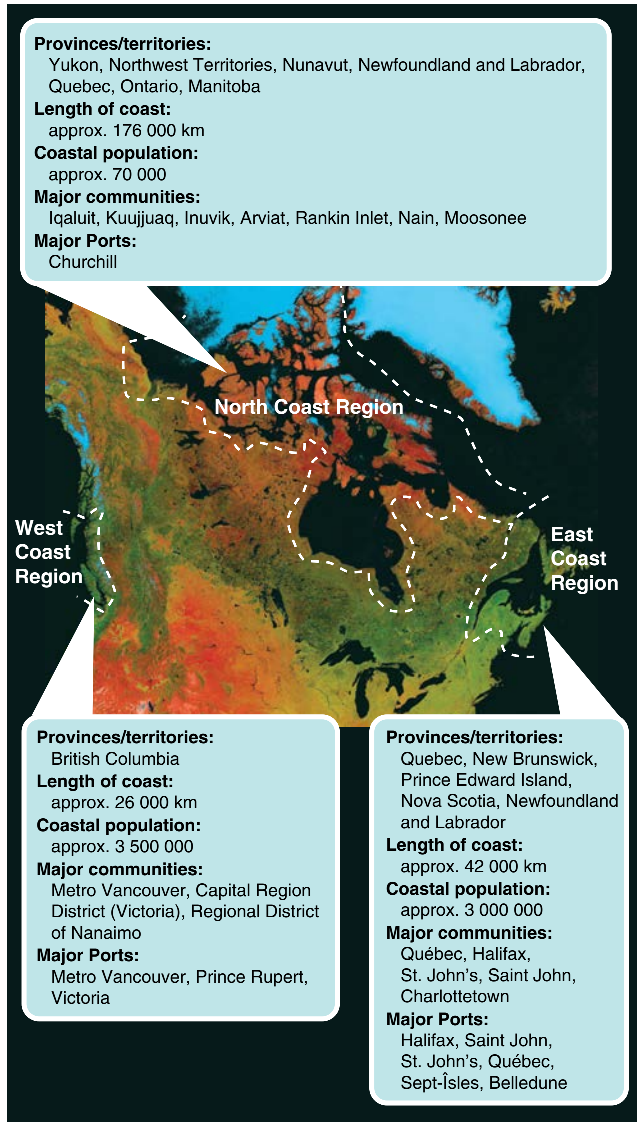

FIGURE 2: Canada's marine coasts, broadly delineating the three regions discussed in this report.

DEFINING COASTS – A LANDSCAPE APPROACH

Derived predominantly from fisheries management and international marine law, the coast is often described as a zone or area along a shoreline, largely marine in focus, whose landward boundary is either determined by the highest anticipated inland intrusion of seawater or designated as a specified distance from the shore, and whose marine boundary extends to the limits of national territorial seas (i.e., 12 nautical miles [nm] seaward from the shore). More integrated (landscape-scale) approaches to coastal management take a broader view of coasts that acknowledges the linkages among terrestrial, aquatic and marine ecosystems, transcends jurisdictional and disciplinary boundaries, and improves understanding (and management) of human-environment interactions and of long-term coastal change (Figure 3; UNEP-GPA, 1995; Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection and Advisory Committee on Protection of the Sea, 2001; Mercer Clarke, 2010).

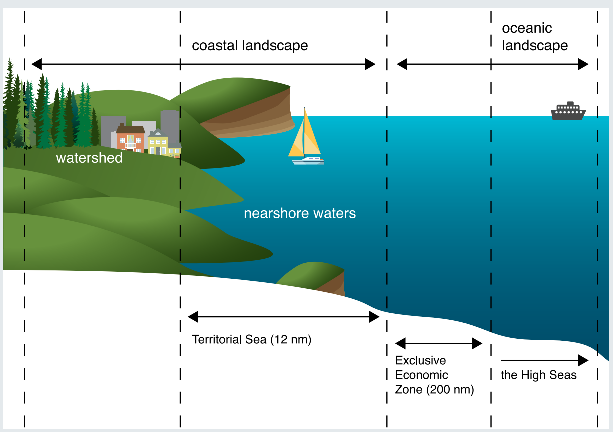

FIGURE 3: The coastal landscape (*modified from* Mercer Clarke, 2010). Abbreviation: nm, nautical mile (22.2 km).

Working at a landscape scale provides opportunities for the collaborative development of new insights and for the effective planning and management of coastal environments (Bekkby et al., 2002; Stewart and Neily, 2008). It also eliminates the need for defined coastal boundaries. This assessment recognizes the importance of this broader perspective in the development of strategies and measures to address climate change. Although the primary focus of the report remains the shoreline, as the interface between land and water, the scope of the report extends landward and oceanward to the extent that such territory affects the sustainability and well-being of coastal communities and ecosystems.

2 CHANGING CLIMATE

> *Warming in the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia.* (IPCC, 2013b)

International and national science assessments have concluded unequivocally that the climate is changing (e.g., IPCC, 2013b; Melillo et al., 2014; Warren and Lemmen, 2014; *see* Chapter 2). Coasts in Canada are already experiencing escalating changes related, in part, to shifting climate and/or changes in severe weather events (Lane et al., 2013). Rising sea level, warming air and water temperatures, storms of greater intensity and reduced sea ice are some examples of the environmental shifts that coastal regions are facing (*see* Chapter 2). These changes will affect regions and communities in different ways, depending on the physiography of the coastline, exposure to wind and waves, presence of natural and built protection (e.g., beaches, dunes, marshes, seawalls, dikes and breakwaters), proximity of the built environment to hazardous conditions, and local preparedness (e.g., Boateng, 2008; Simpson et al., 2012).

While the rate, scope and nature of impacts will vary with location, there are some commonly identified issues, including effects on coastal ecosystems (e.g., wetlands and aquatic ecosystems), infrastructure (e.g., transportation, water supply and discharge, and buildings) and economic sectors (e.g., fisheries, natural resources and tourism). Although emphasis is commonly placed on the risks associated with climate change, there will also be opportunities. Table 1 provides examples of climate-related risks and opportunities for sectors of importance to Canada's coasts, as identified in previous national-scale assessments in Canada.

Comparatively little is known about the economic costs associated with a changing climate along Canada's marine coasts. A national-scale analysis estimated that the cost of flooding of coastal dwellings (only one of many climate change impacts of concern) could be $4–17 billion per year by the middle of this century (National Round Table on the Environment and the Economy, 2011). The significance of economic impacts varies regionally. For example, the *National Round Table on the Environment and the Economy* study noted that, in terms of percentage of total land area, Prince Edward Island's coastal areas are at the most risk, whereas the number of dwellings impacted will be greatest in British Columbia and the per capita costs of dwellings damaged will be greatest in Nunavut.

TABLE 1: Examples of climate change impacts (by sector) in Canada's coastal regions (*from* relevant regional chapters of Lemmen et al. [2008] and sectoral chapters of Warren and Lemmen [2014]).

Sector	Climate-related risks and opportunities
Infrastructure	▪ Risks associated with coastal erosion, storm-surge flooding and sea-level rise, and wind ▪ Failure of dikes and other protection structures, increased construction and maintenance costs
Transportation	▪ Increased maintenance costs of ports, coastal roads and railroads, traffic disruption and delays ▪ Increased marine traffic in the North due to decreased sea-ice
Fisheries	▪ Higher water temperatures and increased acidity that will affect species distribution and ecosystem health, including fish reproduction and distribution ▪ Increasing impacts from invasive species ▪ Potential increase in total biomass of production from wild-capture fisheries
Tourism	▪ Increased duration of warm-weather recreation season ▪ Decreased duration of cold-weather recreation season ▪ Risks to infrastructure and safety associated with extreme weather events
Energy	▪ Seasonal shifts in energy demand: increased summer cooling, decreased winter heating ▪ Risks to energy transmission infrastructure from extreme weather events ▪ Risks to offshore production facilities due to increased storminess and changes in ice risk
Forestry	▪ Increased forest disturbance related to pests, disease and fire ▪ Changes in forest composition and potential for increases in productivity
Mining	▪ Increased risks to transportation infrastructure ▪ Changes in sea-ice conditions that could improve marine access to northern mine sites
Agriculture	▪ Increased duration of growing season ▪ Groundwater salinization as a result of sea-level rise and pumping ▪ Changes in agricultural pests

3 ADAPTATION – PREPARING FOR CHANGE

> *Planning by coastal communities that considers the impacts of climate change reduces the risk of harm from those impacts. In particular, proactive planning reduces the need for reactive response to the damage caused by extreme events. Handling things after the fact can be more expensive and less effective.* (Wong et al., 2014)

Adaptation to climate change is defined as "the process of adjustment to actual or expected climate and its effects" (IPCC, 2014b). Adaptation is needed both to reduce the risks and to benefit from potential opportunities associated with changing climate. There are many different approaches to adaptation, including behavioural changes, operational modifications, technological interventions, planning changes and revised investment practices, regulations and legislation (Warren and Lemmen, 2014). While adaptation in the natural environment occurs spontaneously, adaptation in human systems often requires careful planning and collaboration that are guided by both scientific research and detailed understanding of the systems involved. This guidance is especially important in coastal regions, where there are many actors involved, and the potential for maladaptation (actions that inadvertently increase vulnerability to climate change) is high.

Because adaptation involves changes in both thinking and process, it is by necessity an iterative process that is continually evolving, informed by new understanding, changing socio-economic conditions and practical experience. For example, adaptation choices and effectiveness will be influenced in many cases by the success of mitigation efforts (Box 2).

Specific objectives of adaptation processes can include building awareness and capacity, mobilizing resources, and assessing and implementing options (Figure 4; Eyzaguirre and Warren, 2014). Effective adaptation measures will not only enhance climate resilience, but can contribute to other policy priorities, such as emergency preparedness and economic diversification (Box 3). Indeed, the concept of mainstreaming, advocated by Canada's Federal Adaptation Policy Framework, involves consideration of climate change as one of many factors in all relevant processes, such as policy development, planning exercises and decision-making.

BOX 2
ADAPTATION AND MITIGATION

Although adaptation and mitigation (the reduction of greenhouse gas emissions and enhancement of greenhouse gas sinks) are sometimes portrayed as distinct responses to climate change, they are inextricably linked. The success of mitigation directly affects the need for adaptation, as well as the viability of different adaptation options. Mitigation reduces both the magnitude and the rate of climate change. The greater the reductions in greenhouse gas emissions, the greater the potential for successful adaptation.

For example, scenarios presented in the most recent report of the Intergovernmental Panel on Climate Change (IPCC, 2013b) include a range of plausible futures where mean global surface temperature is likely to increase by 0.3–4.8°C for the period 2081–2100 (relative to the 1985–2005 mean), with associated rises in global sea level of 0.26–0.82 m. Lower increases in temperature are associated with very ambitious greenhouse gas mitigation and would lead to reduced amounts of sea-level rise that would require less investment in adaptation. This relationship becomes even more important when one considers that sea level will continue to change beyond the current century. Although ambitious greenhouse gas mitigation in the coming decades can limit global sea-level rise to about 1 m during the next 500 years, scenarios with only limited mitigation efforts could result in global sea level rising by 1 m to more than 3 m by the year 2300 (Church et al., 2013).

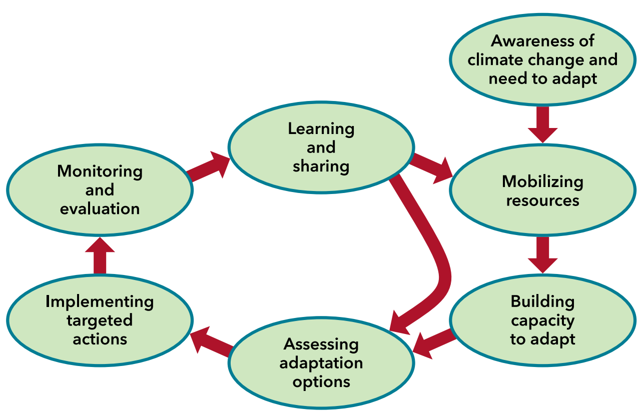

FIGURE 4: The iterative process of adaptation (*modified from* Eyzaguirre and Warren, 2014).

CONFIDENCE AND UNCERTAINTY

Planning for any future activity inevitably involves some degree of uncertainty. The global scientific assessments of the IPCC use predefined terminology to express uncertainty in terms of likelihood, based upon either statistical analysis or expert opinion (IPCC, 2014b, p. 6). In this assessment, we use common-sense language to convey likelihood, rather than using statistically defined terms. This approach is used because it is rare to have quantitative data on the probability of impacts at the national scale, so there is a strong reliance on the expert opinion of the author teams.

Similarly, while other assessments adopt predefined terminology for depicting scientific confidence in findings, this report uses common-sense language. Confidence is greatest where projected impacts are consistent with impacts observed in historical trends and/or where a number of studies have independently arrived at similar conclusions.

Recent years have seen a rapid expansion in literature on the topic of adaptation (Burkett et al., 2014). A number of specific approaches have proven useful in coastal settings globally, including community-based adaptation and ecosystem-based adaptation (Shaw et al., 2014; Wong et al., 2014), with a common goal of enhancing resilience. The most appropriate approaches to adaptation will be location and context specific. In Canada, including along the coasts, there has been a strong focus on adaptation at the community scale (Eyzaguirre and Warren, 2014). The value of ecosystem-based approaches, which involve the use of biodiversity and ecosystem services as part of an overall adaptation strategy, is increasingly recognized in Canada as a means to address some coastal issues (*see* Chapters 3, 4 and 6).

There are also many ways of classifying adaptation actions to address climate change impacts along coasts. In scientific and technical literature, it is common to group coastal adaptation, particularly with respect to addressing sea-level rise and coastal flooding, into four categories (*see* Chapter 3): no active intervention; accommodation; protection (hard and soft measures); and avoidance or retreat. In reality, most coastal adaptation strategies are likely to involve several, and perhaps all, of these groups of actions.

BOX 3

PRINCIPLES FOR EFFECTIVE ADAPTATION

(IPCC, 2014b, p. 25–28)

The *Summary for Policymakers* of the Working Group II (Impacts, Adaptation and Vulnerability) contribution to the IPCC Fifth Assessment Report highlights a number of broad principles that underlie successful adaptation. Those of direct relevance to the issues discussed in this report include the following:

- Adaptation is place and context specific, with no single approach for reducing risks appropriate across all settings.
- Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments.
- A first step toward adaptation to future climate change is reducing vulnerability and exposure to present climate variability.
- Effective adaptation strategies include actions with co-benefits for other objectives.
- Adaptation planning and implementation are contingent on societal values, objectives and risk perceptions.
- Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts.
- Poor planning, overemphasizing short-term outcomes or failing to sufficiently anticipate consequences can result in maladaptation.

4 SCOPE AND FORMAT OF THE REPORT

This assessment, *Canada's Marine Coasts in a Changing Climate*, discusses current and future risks and opportunities that climate change presents to coastal regions of Canada. It highlights what we know regarding vulnerability and the key issues facing each coastal region, with the goal of being a policy-relevant resource to inform regional and national decision-making on coastal management and the development of climate change adaptation strategies. The assessment is based on a critical analysis of existing knowledge, drawing from the published scientific and technical literature (peer-reviewed and 'grey' literature), and from expert (including traditional) knowledge. Although emphasis is on studies conducted within Canada, international sources are incorporated as appropriate. Ecosystem impacts and adaptation, noted in all chapters, are discussed primarily in the context of ecosystem services and the fisheries sector. Key concepts mirror those of past Canadian (Lemmen et al., 2008; Warren and Lemmen, 2014) and international (IPCC, 2014b) assessments of climate change impacts and adaptation. Key terminology is presented in Box 4.

The report is structured by region, with the main chapters of the assessment providing regional perspectives on Canada's East Coast, North Coast and West Coast regions (Chapters 4–6). Each of these chapters provides regional context, then discusses observed and projected climate changes in the region, and climate change risks, opportunities and adaptation approaches. Case studies are used to provide more detail on selected issues, to highlight examples of effective adaptation initiatives and to identify transferable lessons learned. In recognition of the significant differences between the regions, the regional chapters do not follow a common template.

In addition to this 'Introduction', there are two supporting chapters. 'Chapter 2: Dynamic Coasts in a Changing Climate' provides an overview of the diversity and dynamic nature of Canada's marine coasts, discussing past and projected climate change, sea-level change and the impacts and implications of changing mean and extreme water levels. 'Chapter 3: The Coastal Challenge' discusses how ongoing and projected changes may affect coastal environments and coastal societies, and provides an overview of approaches to adaptation, outlining how they are being used along Canada's coastlines. The report concludes with 'Chapter 7: Frequently Asked Questions', which builds on the content of the other chapters, to provide an easily accessible resource that explains, in plain language, the main climate change issues facing Canada's coastal regions.

BOX 4
KEY TERMINOLOGY IN THIS REPORT
(*modified from* IPCC, 2013a, 2014a, p. 5)

Adaptation is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm, or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Adaptive capacity is the ability of systems, institutions, humans and other organisms to adjust to potential damages, to take advantage of opportunities, or to respond to consequences.

Climate change refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or human activity.

Climate variability refers to variations in the mean state and other statistics (such as standard deviations and the occurrence of extremes) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system or to variations in natural or anthropogenic external forcing.

Ecosystem services are ecological processes or functions having monetary or nonmonetary value to individuals or society at large. These are frequently classified as 1) supporting services, such as productivity or biodiversity maintenance; 2) provisioning services, such as food, fibre or fish; 3) regulating services, such as climate regulation or carbon sequestration; and 4) cultural services, such as tourism or spiritual and aesthetic appreciation.

Exposure refers to the presence of people, livelihoods species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

Hazard is the potential occurrence of a natural or human-induced physical event or trend, or physical impact that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Impacts are effects on natural and human systems. The term 'impacts' is used primarily to refer to the effects on natural and human systems of extreme weather and climate events, and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period, and the vulnerability of an exposed society or system. Impacts are also referred to as 'consequences' and 'outcomes'. The impacts of climate change on natural physical systems, including precipitation regimes (e.g., floods, droughts) and the global hydrological cycle (e.g., sea-level rise), are a subset of impacts called physical impacts.

Maladaptation are actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change or diminished welfare, now or in the future.

Resilience is the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.

Risk is the potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazard.

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damage caused by an increase in the frequency of coastal flooding due to sea-level rise).

Storm surge is the temporary difference between the expected water level and that experienced at a particular location due to meteorological conditions, especially atmospheric pressure. Strong onshore winds and low atmospheric pressure can cause a positive storm surge that brings water levels higher than expected. Strong offshore winds and high atmospheric pressure can cause a negative surge that brings water levels lower than expected.

Uncertainty is a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour.

Vulnerability is the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

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CHAPTER 2: DYNAMIC COASTS IN A CHANGING CLIMATE

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1 INTRODUCTION

This chapter focuses on the dynamic nature of Canada's marine coast and the environmental drivers of coastal change in a changing climate. An understanding of how changing climate affects coastal stability, and the nature of the coastal response, provides a basis for assessing potential changes in coastal hazards and the implications for human communities and infrastructure. Whereas the effects of climate change on sea level are widely understood (IPCC, 2013), the secondary effects of sea-level change on coasts continue to challenge our understanding and management practices (Davidson-Arnott, 2005; FitzGerald et al., 2008; Wolinsky, 2009; Wolinsky and Murray, 2009; Wong et al., 2014; Woodroffe et al., 2014). Other aspects of climate change have significant impact on coasts, including changes in storminess, storm surge and wave climate; changing seawater properties, including temperature and pH; and the changing nature, duration and dynamics of sea ice.

The chapter begins with an overview of the diversity and dynamic nature of Canada's marine coasts (Figure 1). Following this is an overview of changing coastal climates, including past and projected future changes in temperature, precipitation, storminess and associated weather events that drive coastal change. It then provides a summary of past trends in sea level and the latest projections of future changes in mean sea level in Canada, and concludes with the implications of a changing climate, including changes in mean and extreme water levels, for the physical state and ecological integrity of the coast.

Although this chapter focuses on the physical environment of coasts, the effects of climate change are much broader in scope, touching ecosystem sustainability, renewable resources, food security, health and well-being, energy, economic prosperity, cultural integrity and other facets of these social-ecological systems. These topics are discussed in subsequent chapters of this report (*see* Chapters 3–6).

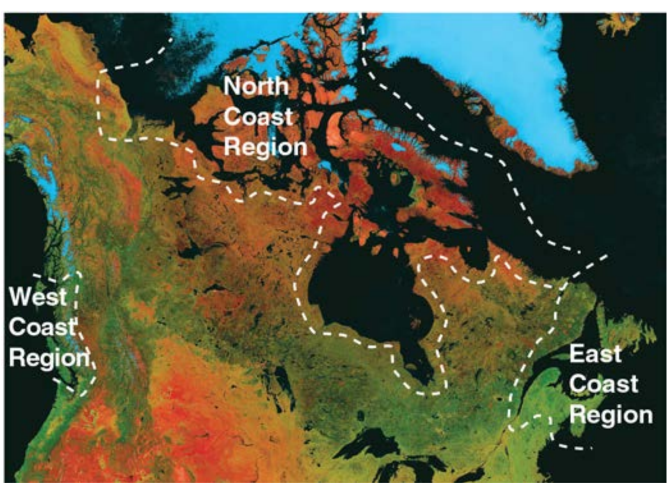

FIGURE 1: Canada's marine coasts, broadly delineating the three regions discussed in this report.

2 COASTAL VARIABILITY

Canada has not only the world's longest coastline (about 243 000 km; Taylor et al., 2014), but arguably one of the most diverse. All provinces and territories, except Alberta and Saskatchewan, have marine coasts. These range from high-energy rock headlands of southern Newfoundland to very low energy, ice-locked, sedimentary coasts in the northwestern Canadian Arctic Archipelago. They include deeply indented fiord topography, cliffs cut in bedrock or glacial/proglacial deposits, beaches, spits and barrier islands, dunes, salt marshes and tidal flats, ice-rich permafrost coasts, and large deltas such as those at the mouth of the Fraser River in British Columbia and the Mackenzie River in the western Arctic. Canada's coasts are affected by tides that range from negligible to the world's highest (in the Bay of Fundy and Ungava Bay). Exposure to wave energy ranges from very low, in well protected settings, to very high, in settings with full Atlantic or Pacific ocean exposure. Variability in coastal geomorphology and processes is high within and between all regions considered in this report (*see* Chapters 4–6).

Sea-level changes in Canada are driven only in part by trends in global mean sea level. Locally, significant variation from the global mean trend can arise from several factors. Among the most important of these is vertical crustal motion, which results in trends in relative sea level varying widely across Canada, from rapid fall in parts of the central Arctic to accelerating rise in the Maritimes. This and other factors influencing local sea-level change are discussed in detail in Section 4 of this chapter.

The importance of sea ice also varies significantly along Canada's marine coasts. In the Arctic, sea ice effectively shuts down or severely constrains coastal dynamics for much of the year, and limits open-water fetch in the summer. Most parts of the east coast are exposed to sea ice on an annual basis, with effects that range from substantial to negligible. On the west coast, thin ice occurs only rarely in protected waters. In all areas where sea ice occurs, it can play an important role in sediment transport, shore-zone morphology and ice-related hazards (Forbes and Taylor, 1994). Climate warming has already affected mean dates of breakup and freeze-up of sea ice and the length of the open-water season (Stammerjohn et al., 2012; Stroeve et al., 2012), with important implications for coastal exposure to storm waves and surges (Vermaire et al., 2013). Reduction of sea ice is an important concern for ice-dependent ecological and human systems (e.g., Gaston et al., 2012; Laidre et al., 2012; Stirling and Derocher, 2012).

Storm climatology (e.g., storm characteristics, severity, seasonal frequency, track mode and variance) varies between Atlantic, Arctic and Pacific coasts (e.g., Wang et al., 2006), and around the Arctic basin (Atkinson, 2005). The Atlantic coast experiences the full range of extra-tropical and tropical cyclonic storm systems, as well as rapidly evolving 'tropical transition events' (storms in the process of evolving from tropical to extra-tropical cyclones). All of these storm types have implications for coastal stability and hazards (Forbes et al., 2004; Parkes et al., 2006). The Pacific coast experiences large, mature extra-tropical storm systems that often stall when encountering the Coast Mountains, creating the potential for prolonged impact. Northern Canada experiences storms moving into the region, rather than forming in place. The most prominent track is from the southeast (Labrador Sea northward to Baffin Island, NU), with a major secondary track coming from the west through the Beaufort Sea (Maxwell, 1981, 1982).

2.1 GEOLOGICAL SETTING

The legacy of past glaciation is apparent almost everywhere in Canada, influencing the evolution and morphology of the coast (Forbes, 2011) and differentiating Canada's coast from much of the coastline of the United States mainland to the south. Large fiords, the product of glacial erosion, dominate the coasts of British Columbia, parts of Newfoundland and Labrador, and the eastern islands of the Canadian Arctic Archipelago (Figure 2). Stiff glacial deposits such as clay-rich till are somewhat resistant to erosion and can form high bluffs, but are ultimately consumed through a combination of basal wave attack and subaerial slope erosion (erosion processes such as freeze-thaw, slope wash and slumping; Manson, 2002; Forbes, 2011). Active glaciation in the Coast Mountains, BC, St. Elias Mountains, YT, and the eastern Arctic continues to feed outwash sediments to the ocean (Forbes, 2011). The extent of floating ice shelves along the north coast of Ellesmere Island, NU, has decreased precipitously in recent years, but some portion of the ice front remains (*see* Chapter 5; Mueller et al., 2003; Copland et al., 2007).

The effects of the last continental glaciation are also paramount in determining the direction and rate of sea-level change in Canada, which is a primary control on coastal evolution. In regions such as Hudson Bay, where the greatest amount of isostatic depression of the Earth's crust by continental ice sheets occurred during the Last Glacial Maximum (20–25 thousand years ago), glacial isostatic uplift is ongoing, local sea level is falling and the coast is emerging. Where coastal emergence has been ongoing for thousands of years, abandoned shorelines are delineated by successions of uplifted beaches (Figure 3; St-Hilaire-Gravel et al., 2010) and coastal communities in these regions face progressive shallowing of their marine approaches (Forbes et al., 2014a), which can be as problematic as local sea-level rise.

In areas marginal to the former continental ice sheet, the postglacial response is regional subsidence, such that former shorelines are now submerged below sea level (Figure 4; Shaw et al., 2002). These submergent coasts can be recognized by bays and estuaries created through the gradual inundation of river valleys, and by spits and barrier beaches formed across the mouths of these bays (Figure 5). The past coastal response to rising sea level in these areas, often characterized by shoreline retreat, provides a guide to the implications of accelerated sea-level rise as a result of climate change (Orford

FIGURE 2: Tingin Fiord, Baffin Island, NU, showing a classic U-shaped cross profile with vertical rock walls, outwash sandur (delta) in the fiord head (head of right arm in centre top of image), ice fields persisting on plateaus and suspended sediment plume from local glacial runoff on far side of left arm. *Photo courtesy of D.L. Forbes, Natural Resources Canada, July 2008.*

FIGURE 3: Raised beaches on Lowther Island, Viscount Melville Sound, NU, record land emergence and variable wave and ice forcing over the past 6000 years (St-Hilaire-Gravel et al., 2010). *Photo courtesy of D.L. Forbes, Natural Resources Canada, August 2009.*

et al., 2001). On the west coast, vertical land motion results from a combination of glacial isostatic adjustment to the former Cordilleran ice sheet and tectonics (James et al., 2000; Clague and James, 2002; Shugar et al., 2014). Present-day ice mass changes in the Coast Mountains and Gulf of Alaska, and sediment compaction on the Fraser River delta (Mazzotti et al., 2009), also play a role.

FIGURE 4: Paleogeography of Atlantic Canada 9000 years ago (*from* Figure 9 of Shaw et al., 2002). Note islands on Georges Bank (lower left), Sable Island Bank, Banquereau and Grand Bank (right), and the large island surrounding the present-day Îles-de-la-Madeleine. Neither Prince Edward Island nor Cape Breton Island was an island at the time.

Coastal reworking of glacial sediments is widespread along much of the coast of Eastern Canada and the nature of the sediments influences the result of this reworking (Forbes, 2011). Gravel and mixed sand-gravel beaches and barriers predominate in this region, except in the southern Gulf of St. Lawrence, where sand-rich glacial deposits, derived from soft sedimentary rocks, support the development of extensive sandy barriers with large dunes (Figure 6a; McCann, 1980; Forbes et al., 2004, 2014b). The coast of the Tuktoyaktuk Peninsula, in the western Canadian Arctic, is formed in a region with extensive Pleistocene sand deposits and characterized by widespread thin sandy barriers migrating landward across a low-relief coastal plain (Figure 6b; Hill et al., 1994; Forbes et al., 2014b). Apart from these regions, sand beaches and barriers, though not uncommon, are localized and associated with specific sources or sinks of sand.

In regions with more resistant bedrock, glacial deposits tend to be dominated by pebbles, cobbles and boulders, leading to the development of gravel-dominated beaches and barriers (Forbes and Syvitski, 1994); these are typically connected to local sediment sources of glacial or proglacial origin. Rising sea levels encountering glacial deposits typically result in the erosion of cliffs that serve as the sediment source for nearby gravel (or shingle) beaches, spits and short barriers (Forbes, 2011); these tend to exhibit high temporal variability in rates of retreat (Orford et al., 2001), posing a challenge for prediction of coastal changes and for sustaining nearshore land use.

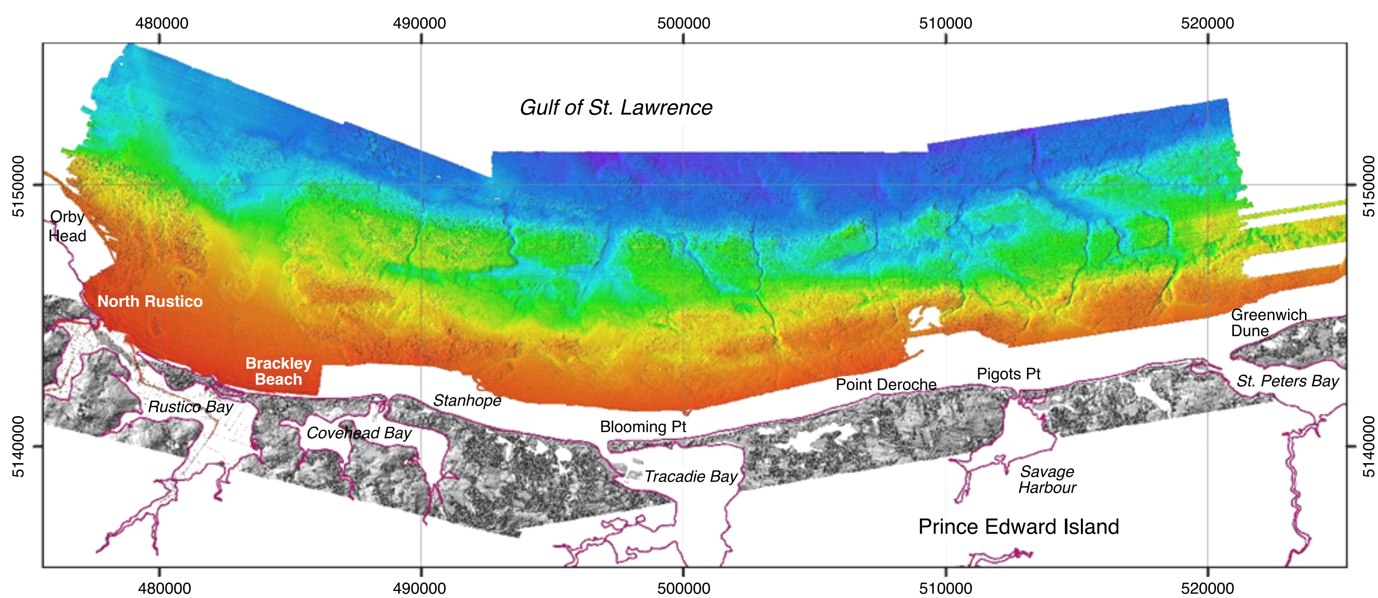

FIGURE 5: Inner shelf bathymetry (colour shaded relief) and coastal topography (grey-scale shaded relief) for the central north shore of Prince Edward Island, showing river valleys inundated by rising relative sea level over the past 8000 years (red outline shows present-day shoreline). Spits and barrier beaches with dunes (e.g., Brackley Beach, Blooming Point) extend across the seaward margins of the estuaries (e.g., Rustico Bay, Covehead Bay, Tracadie Bay) (Forbes et al., 2014b).

FIGURE 6: Sandy beach and dune complexes in Prince Edward Island and on the coast of the Beaufort Sea. **a)** Sandy beach and dune with protective icefoot (narrow band of rough ice stained with red sand) and nearshore ice complex (broad band of clean ice seaward of the icefoot), looking east toward Point Deroche in the distance, north shore of Prince Edward Island. Estuarine lagoon at right has largely infilled over the past century. *Photo courtesy of D.L. Forbes, Natural Resources Canada, March 2000.* **b)** Thin sandy barrier and foredune migrating landward across low coastal-plain tundra, Hutchison Bay, Tuktoyaktuk Peninsula, Northwest Territories. *Photo courtesy of D. Whalen, Natural Resources Canada, August 2013.*

Some parts of the Canadian coast, such as the southern Beaufort Sea, have negligible tidal range and limited intertidal regions. However, positive storm surges contribute to the formation of supratidal flats and, in the region of the Mackenzie Delta, large accumulations of driftwood at the limit of storm-surge flooding. In other regions with tidal ranges varying from microtidal (<2 m) to macro- (or 'hyper'-) tidal (up to 16 m), tidal flats and salt marshes can be very extensive and provide critical habitat for fish and birds (Hicklin, 1987; Galbraith et al., 2002; Hill et al., 2013). Some tidal flats in Canada are dominated by boulders of glacial origin and form distinctive formations such as boulder barricades and garlands (Forbes and Taylor, 1994).

Deltas are widespread river-mouth features that often attract human habitation. Large deltas occur at the mouths of the Mackenzie and Fraser rivers, and there are many smaller deltas such as those of the Coppermine River, in Nunavut; Rivière aux Outardes, Rivière Moisie and Rivière Natashquan, in Quebec; and numerous fiord-head deltas in British Columbia, Newfoundland and Labrador, and Baffin Island. A number of these are occupied by human settlements and infrastructure, which are thereby exposed to combined river and marine flooding. Large deltas such as those at the mouth of the Fraser and Mackenzie rivers are subject to autocompaction and other local subsidence (Mazzotti et al., 2009), which contribute to increased flood risk and potential habitat loss through inundation by relative sea-level rise.

This brief synopsis of coastal variability in Canada is a general overview that illustrates much, but certainly not all, of the range of settings and processes that must be considered in analyzing coastal stability under a changing climate. A Canada-wide analysis of coastal sensitivity to sea-level rise was completed in the late 1990s (Shaw et al., 1998). Areas of high sensitivity to sea-level rise included northeastern Graham Island in Haida Gwaii, BC; the Beaufort Sea coast, including southwestern Banks Island, NT; the coasts of five provinces (QC, NB, NS, PE and NL) in the Gulf of St. Lawrence; and the Atlantic coast of Nova Scotia. An update of this analysis, addressing sensitivity to multiple impacts of climate change, is currently ongoing (Box 1).

BOX 1
CANCOAST: A TOOL FOR ASSESSING CLIMATE CHANGE SENSITIVITY

CanCoast is a tool designed to help facilitate adaptation planning in coastal areas. An initiative of the Geological Survey of Canada (part of Natural Resources Canada), CanCoast is an ArcGIS-based geospatial database that enables coastal data to be collated, archived and analyzed. The geodatabase consists of a high-resolution marine shoreline vector developed from CanVec9 (http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/-/%28urn:iso:series%29canvec) that serves as a base for grouping coastal attribute layers of physical features, materials and processes (such as geology and sea-level change). Once these widely varying attributes have been grouped on a common shoreline, analysis of coastal sensitivity to climate change is possible at varying spatial and temporal scales.

To date, a number of datasets from the Shaw et al. (1998) study of coastal sensitivity to sea-level change have been mapped onto the CanCoast shoreline. These include landforms, tidal range and wave height. Several additional layers have been updated or added, for instance:

- topographic relief is now based on the Canadian Digital Elevation Data (a raster representation of elevation values over all of Canada at 1 km spatial resolution),
- sea-level rise is based on projections of regional sea-level rise for 2050 for representative concentration pathway RCP8.5 from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and
- ground ice conditions for coastal permafrost regions have been added based on the Canadian permafrost map (Heginbottom et al., 1995).

Further details on the various layers in the CanCoast geodatabase are available in Couture and Manson (2016). Using these layers, a new index of sensitivity to climate change, incorporating both inundation and erosion data has been developed (Figure 7). Prospective applications for CanCoast include hazard mapping and mitigation, adaptation planning impact assessment and analysis of knowledge gaps.

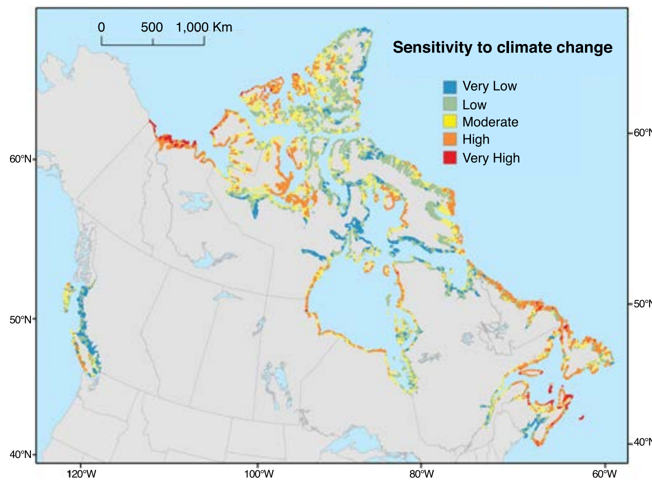

FIGURE 7: Preliminary map of coastal sensitivity to climate change in Canada developed using the CanCoast database. Sensitivity is based on present-day coastal materials, landforms, relief, ground ice, wave height and tidal range, as well as recent trends in total sea-ice concentration and projected changes in sea level to 2050 (Couture and Manson, 2016). Note that some quite sensitive areas (e.g., the Fraser River delta) are not clearly visible at the resolution shown here.

2.2 COASTAL PROCESSES

At the interface between land and sea, the detailed configuration of the shore zone is constantly changing. Shoaling waves rework the bottom across the shore face and nearshore profile. Waves approaching the coast at an angle create longshore currents that carry sediment along the coast and the large-scale dynamics often create rhythmic features at a variety of scales. These can range from beach cusps (with wavelengths from <10 m to >100 m) to large-scale variability in beach width, sometimes with shore-attached bars and ridges (wavelengths up to 10 km or more). This progressive reconfiguration of the shoreline is a natural system response to relatively steady conditions and is not related to a climate-driven trend in sea level, wind or waves (Box 2).

BOX 2
COASTAL SEDIMENT REWORKING, HAIDA GWAII

A spectacular example of progressive reconfiguration of the shoreline can be found on the northeastern coast of Graham Island, Haida Gwaii, BC. It is characterized by the presence of repetitive accretionary bulges (Inman, 1987), also known as large-scale longshore sand waves (Verhagen, 1989; Thevenot and Kraus, 1995) and associated shore-attached bars, with a wavelength of 6–9 km. These are superimposed on a retreating coast (1–3 m/year, up to 15 m or more in a single storm season), with sand reworked onshore, seaward onto the shore face and alongshore (Walker and Barrie, 2006). The longshore sand waves migrate alongshore to the northeast in response to dominant southeasterly storm winds and waves in Hecate Strait (Figure 8). The rhythmic morphology results from large-scale dynamics and feedback in the shore face circulation induced by southeasterly wave forcing at a high angle to the beach (Ashton et al., 2001). The beach waves store a large volume of sand and result from a systematic alongshore variation in the sediment transport rate. Sediment is deposited at the downstream terminus of each wave and a zone of enhanced erosion and re-entrainment exists at the start of the next expansion in beach width. In this way, Kumara Lake was breached and partially drained the last time the erosion zone (now 2 km down drift) passed through that location (Walker and Barrie, 2006).

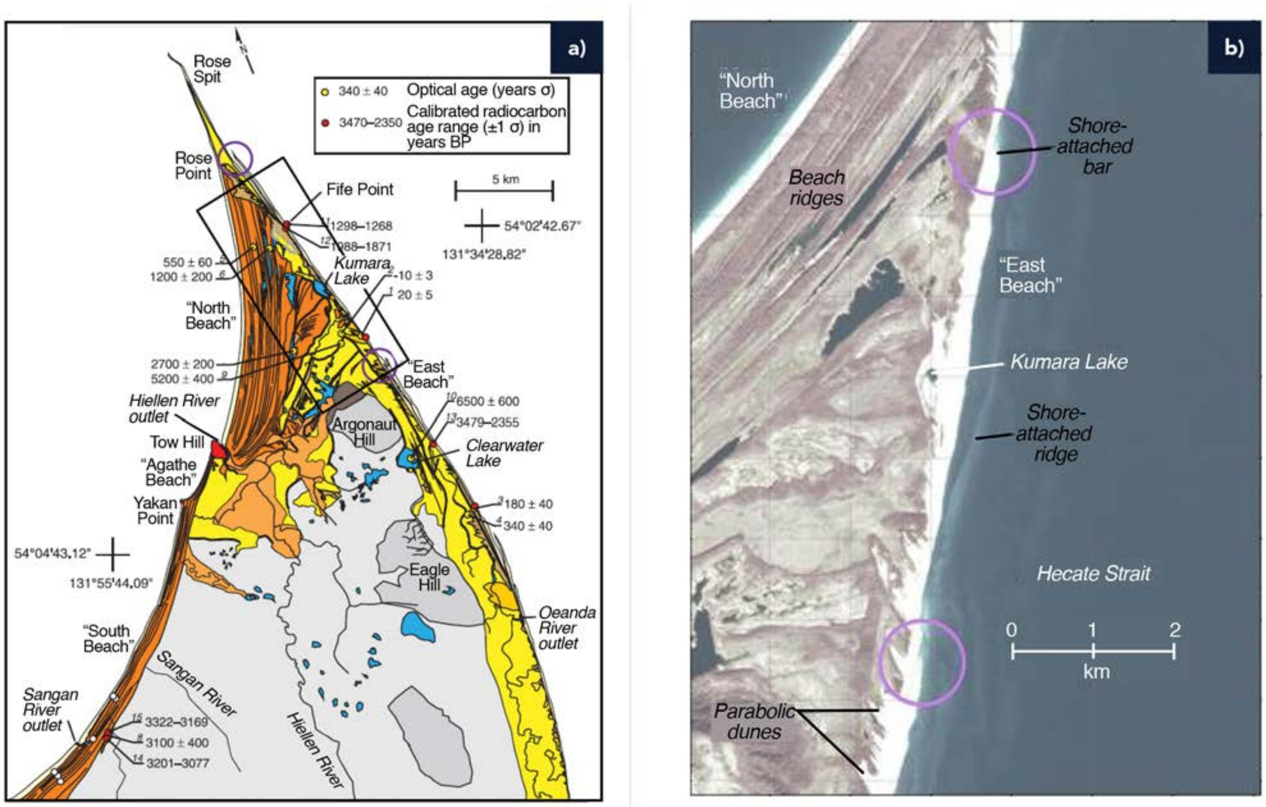

FIGURE 8: **a)** Coastal progradation on northeastern Graham Island, Haida Gwaii, BC, over the past 3000 years (*from* Figure 8 of Wolfe et al., 2008). Purple circles outline advancing tips of longshore sand waves on the eroding eastern shore. Older dates are higher on the coast, indicating emergence due to glacial isostatic adjustment (Section 4.2). Black box shows location of image in part b.
b) Large-scale sand waves with shore-attached bars migrating northward on East beach, with erosional hotspots at the distal ends (purple circles). Also visible are large parabolic dunes aligned parallel to the direction of the dominant winds from the southeast and the multiple beach ridges of North Beach, which record shoreline advance over the past 2000 years (Wolfe et al., 2008). Image source: Spot-3 multispectral and panchromatic imagery, 2007, *from* GeoBase®.

2.2.1 EROSION AND SHORELINE RETREAT

It is a common misconception that the coast changes only slowly. Although hard-rock coasts (such as the crystalline rocks of the Canadian Shield or the granite shores of Nova Scotia) are highly resistant to erosion and coastal retreat, sedimentary rocks are susceptible to erosion, particularly in areas such as Prince Edward Island, where the soft sandstone is quite friable (Forbes et al., 2004), or northern Foxe Basin, NU, where the flat-lying carbonate rocks are broken up by freeze-thaw processes (Hansom et al., 2014). Shore retreat on some parts of the Prince Edward Island coast has averaged 0.5 m/year over several thousand years (Forbes et al., 2004). Extreme rates of natural shoreline retreat (10–15 m/year or more) have been measured in a number of places, including the Atlantic coast of Nova Scotia (Forbes et al., 1997; Taylor et al., 2014), the Arctic coast in the Beaufort Sea (Solomon, 2005; Forbes et al., 2014b) and the Pacific coast at Haida Gwaii, BC (Walker and Barrie, 2006).

There have been few systematic compilations of shoreline erosion for extensive lengths of coast in Canada (e.g., Bernatchez and Dubois, 2004; Solomon, 2005; O'Carroll et al., 2006), but local studies and multitemporal surveys have been undertaken in hundreds of locations. Monitoring of representative sites by the Geological Survey of Canada has been ongoing for many years (Taylor et al., 2014). Solomon (2005) published an extensive compilation for the central Canadian Beaufort Sea coast, based on photogrammetric analysis. Lantuit and Pollard (2008) have documented rates of coastal retreat for Herschel Island, on the Yukon coast, and recent work has extended the coverage (Couture et al., 2008; Couture, 2010; Konopczak et al., 2014). Analyses for more limited reaches of coast have been published for some areas in both southern and northern Canada (e.g., Covill et al., 1995; Forbes et al., 1995a, 1997; O'Carroll et al., 2006; Couture et al., 2014). Extensive site surveys have been undertaken over several years in the St. Lawrence Estuary, Gaspé Peninsula and Lower North Shore of Quebec (Bernatchez and Dubois, 2004). Comprehensive analyses of shoreline retreat and coastal geomorphology for all of Prince Edward Island (Davies, 2011; Webster, 2012), as well as other parts of the Maritimes, have been completed. In the Arctic, a circumpolar synthesis by Lantuit et al. (2012) provided a general analysis of shore-erosion rates for the entire Arctic Basin, including Canada's coast facing directly onto the Arctic Ocean.

The data arising from such monitoring provides a baseline for assessing the impact of sea-level rise on coastal erosion. To date, evidence for accelerated shoreline retreat over the last few decades is generally absent. The highly dynamic nature of these coasts can make it challenging to differentiate impacts attributable to climate change from those that reflect natural coastal variability or coastal response to other drivers, including human interventions (Box 3).

BOX 3

ATTRIBUTION OF SHORELINE RETREAT: PRINCE EDWARD ISLAND

Ongoing sea-level rise contributes to marine transgression (shoreline retreat) on the coast of Prince Edward Island (Forbes et al., 2004, 2014b; Mathew et al., 2010; Ollerhead et al., 2013). This might suggest that observed changes in the aspect of the coast are a result of sea-level rise and changing climate; however, some changes are the result of other natural events, such as depletion of sediment sources, or the result of human intervention (coastal engineering). An example of the latter with an enduring legacy is the realignment of tidal inlets at Rustico Bay, including truncation of the coastal road (Figure 9), which at times has been incorrectly attributed to climate change. In fact, these dramatic changes are primarily a function of inlet expansion, division and migration following artificial closure of the former eastern inlet in the 1950s (Figure 10), and the resulting changes in circulation and sediment dynamics (Forbes and Solomon, 1999). Inlet closure triggered rapid widening and migration of the North Rustico inlet, which culminated in a division of the estuary (separation of Hunter River estuary from the rest of Rustico Bay) and opening a new inlet (Forbes and Solomon, 1999).

FIGURE 9: End of the road on Rustico Island, looking toward North Rustico, Prince Edward Island. *Photo courtesy of D.L. Forbes, Natural Resources Canada, August 1985.*

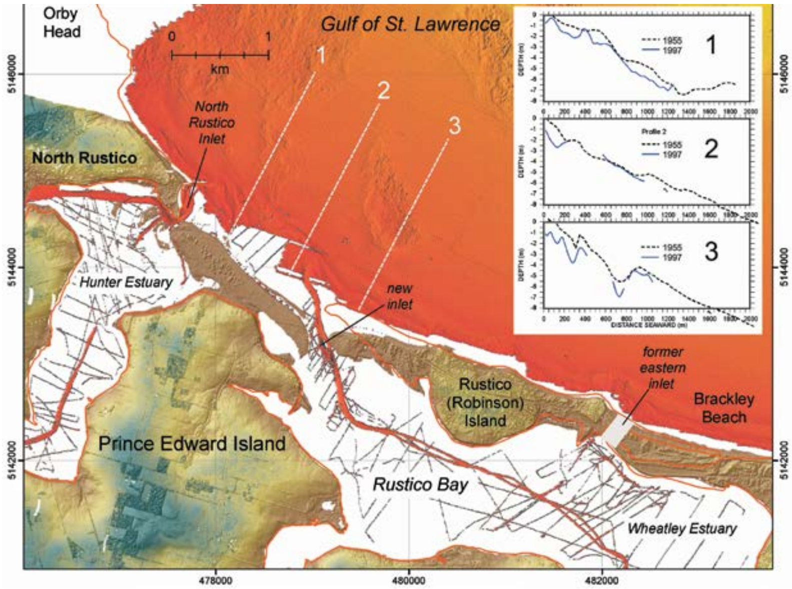

FIGURE 10: Colour shaded-relief LiDAR (light detection and ranging technique) digital surface model (including buildings and trees) for Rustico Bay and vicinity, Prince Edward Island, acquired in 2000 (Webster et al., 2002). Red-toned surface is shaded-relief bathymetry of the estuaries and inner shelf from single-beam, sweep and multibeam soundings (*modified from* Forbes et al., 1999). Sparse single-beam soundings are evident in the estuaries, which were too shallow to carry out a multibeam survey. Rough surfaces on the shore face are exposed bedrock or lag gravel over till. Red line is CanVec shoreline vector. **Inset:** Change in shore face profiles (broken white lines in main figure), caused predominantly by erosion, from 1955 soundings to 1997 sweep and multibeam surveys.

2.2.2 CONTROLS ON RATES OF COASTAL CHANGE

Storms – Storms with elevated water levels and wave action are the most effective agents of coastal change. This was driven home to many North Americans by the impacts of Hurricane Sandy on New York and the adjacent coasts of New Jersey and Long Island in late October 2012. Areas of the Canadian coast are similarly exposed to severe storms. The costs of such storms in Canada can be hundreds of millions of dollars. Hurricane Juan resulted in $100 million in damages and, in BC, a June 2011 coastal storm caused $85 million in damages (Pinna Sustainability, 2013). These values reflect damages only and do not include ‘passive’ costs associated with lost work time and reduced purchasing activity. For example, economic activity was strongly curtailed in Halifax and most of Nova Scotia and Prince Edward Island for a week or more during and following Hurricane Juan. An approximate estimate of a one-week loss of activity is a further $80 million. In Newfoundland, Hurricane Igor has been estimated to have caused up to $200 million in damages (*see* Chapter 3). Less intense storm events that occur in rapid succession, without sufficient intervening time to rebuild sediment stores in smaller dunes, can have cumulative effects that also destabilize the coast (Forbes et al., 2004). The effects of a storm on the coast depend not only on the strength of the storm but also on the total water level (combined tide, surge and waves), the presence or absence of sea ice, local wind direction and fetch, and a range of other factors.

Major historical storms in Atlantic Canada include the Yankee Gale of 3–5 October 1851 (MacDonald, 2010), the Saxby Gale of 4–5 October 1869 and the August Gale of 24 August 1873 (Ruffman, 1999). Over the past 100 years, major storms included 2 October 1923, 21 January 1961 (the ‘Kennedy Inaugural’ storm), 21 January 2000, 29 October 2000, 8 November 2001, 27 December 2004 and others since (Parkes and Ketch, 2002; Forbes et al., 2004; Parkes et al., 2006). Many of the summer and autumn storms were tropical depressions or tropical transition events, whereas the winter events were extratropical but followed similar tracks northeastward along the United States eastern seaboard. The impacts of these storms on the physical environment of the coast have been dramatic. For example, Forbes et al. (2004) documented the transition from high dunes along the north shore of Prince Edward Island in 1765 to wide washover flats in 1880 (possibly a cumulative impact of the 1869 and 1873 storms), from which the dunes had not fully recovered before the storm of 1923. Mathew et al. (2010) described the impact of the latter event and the subsequent growth and onshore migration of high parabolic dunes. Comparable effects of major storms are documented from many parts of the country, including the Nova Scotia Atlantic coast (Taylor et al., 2008), Newfoundland (Catto et al., 2006), the northern coasts of the Gulf of St. Lawrence and St. Lawrence estuary (Bernatchez and Dubois, 2004), the British Columbia coast (Walker and Barrie, 2006; Heathfield et al., 2013) and the Beaufort Sea (Solomon and Covill, 1995).

Sea ice – Sea ice can have both positive and negative effects on coastal stability. Although its presence can inhibit or preclude surface-wave development during storms, storm winds can also move ice onshore, scouring beaches and backshore surfaces including dunes, and damaging infrastructure (Forbes and Taylor, 1994; Forbes et al., 2002). The same onshore ice movement may move nearshore sediment landward, nourishing beaches (Reimnitz et al., 1990). Sea ice on Canadian coasts ranges from often heavy for many areas along the Atlantic coast (Figure 11) and almost absent on the Pacific coast to near-perennial in interisland channels of the northwestern Canadian Arctic Archipelago (Forbes and Taylor, 1994). Recent climate changes have had very significant impacts on the extent and duration of sea-ice cover (IPCC, 2013, Section 3).

In winter, sea ice can be largely immobile (as bottomfast or landfast ice) or highly mobile under tidal or wind forcing. In some situations, ice can ground and pile up on nearshore bars (Forbes et al., 2002, 2014b), protecting the shoreline from direct wave action if open-water storms occur. However, if the seaward face of the ice complex is steep, it can function as a natural seawall, causing wave reflection and turbulence that may produce scour on the inner shore face (Bernatchez and Dubois, 2008).

Sea ice exerts a major control on the morphology of the Atlantic and Arctic coasts. During the major January 2000 storm in Atlantic Canada, the only coast exposed to waves in the southern Gulf of St. Lawrence was the eastern end of Prince Edward Island, as all other coasts of the island and the adjacent mainland were protected by sea ice. On the southwestern coast of Newfoundland, which was ice free, dynamic fetch in the same storm produced extreme waves that caused severe damage to areas as high as 18 m above mean sea level (Catto et al., 2006). In the southern Gulf, the dominant impacts of that storm were related to sea ice that was thrust onshore, overtopping dunes and damaging shorefront buildings and harbour infrastructure, including a lighthouse in Charlottetown Harbour that was knocked off its foundation (Forbes et al., 2004). Coastal flooding was also extensive, contributing to the high level of sea-ice impacts and setting record high-water levels in parts of Prince Edward Island and southeastern New Brunswick. In contrast, in the absence of sea ice, late autumn or early winter storms affecting Prince Edward Island, particularly those with winds from the northeast, can generate large waves that trim the dunes and cut back the beaches to erode underlying till (Forbes et al., 2004, 2014b). The latter represents a step retreat of the coastal substrate that is not recoverable.

Under some circumstances, frazil ice (ice crystals formed under turbulent supercooling conditions) and aggregated

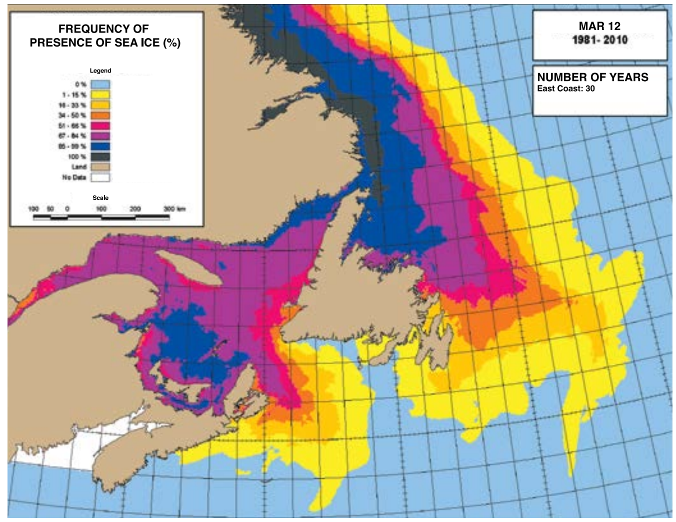

FIGURE 11: Extent of sea ice in the Atlantic region. Colour shading indicates the number of years in the 30 year period (1981–2010) for which sea ice was recorded at that location. The influence of the southward-flowing Labrador Current on moving ice down from Labrador can be seen. Figure *compiled by* the Canadian Ice Service of Environment Canada.

frazil forming slush ice can entrain large volumes of sediment from the nearshore, which sediments can be carried offshore or great distances along the coast (Reimnitz and Maurer, 1979; Forbes and Taylor, 1994). It has been suggested that the recent reduction in multiyear ice and summer retreat of pack ice from the western Arctic coast may enhance offshore transport of ice-entrained sediments (Eicken et al., 2005). This, combined with seaward near-bed currents, can contribute to shoreline retreat through loss of sediment to the inner shelf. Direct or indirect scour over the shore face is caused by grounding ice floes or ice wallowing in shoaling waves.

Permafrost – In northern areas of permafrost terrain that have ice-rich sediments, the erodibility of coastal cliffs is constrained by ice bonding (Kobayashi et al., 1999), and is thus susceptible to warming air, sea and ground temperatures (Overeem et al., 2011; Barnhart et al., 2014a). Erosion on these coasts occurs in many ways, including by sloughing and active-layer detachment failures, by deep undercutting and collapse of blocks defined by polygonal ice wedges (Figure 12a; Hoque and Pollard, 2009), and by retrogressive thaw failure in soils with massive ground ice (Figure 12b; Lantuit and Pollard, 2008, Forbes et al., 2014b). Despite the important role of thermal abrasion and thermokarst processes on ice-bonded coasts, storms are likely still the dominant factor driving shoreline retreat in most places. Those occurring at times of open water with well-developed waves can effect rapid erosion and undercutting (Overeem et al., 2011; Barnhart et al., 2014a).

FIGURE 12: Erosion of permafrost coasts in the western Canadian Arctic: **a)** a deep thermoerosional niche undercutting cliff in ice-bonded sand and associated block failure following a major storm, Tuktoyaktuk Island, NT (*Photo courtesy of S.M. Solomon, Natural Resources Canada, August 2000)* and **b)** retrogressive thaw amphitheatres in ice-rich deposits at King Point, YT (edge of lagoon at left). Note massive ice (indicated by white arrow) in lower part of the main headwall, which is ~5 m high. *Photo courtesy of D.L. Forbes, Natural Resources Canada, July 1992.*

3 CHANGING CLIMATE

3.1 DRIVERS OF CHANGE

Civilization has evolved over the last 10 000 years, during the most climatically stable era of the last million years (e.g., Rockström et al., 2009). The development of complex societies in the Middle East and the Americas appears to have closely followed the stabilization of sea level after 7000 years before present (Day et al., 2012). This relative stability of climate and sea level is changing. As documented in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC, 1990, 1992, 1995, 2001, 2007, 2013) and a large volume of other scientific literature that has been compiled over the last three decades, human activities have led to fundamental changes in atmospheric chemistry, with major implications for the Earth's climate system and human habitat. Indeed, the IPCC Fifth Assessment Report (IPCC, 2013, p. 4) concludes that:

> *Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.*

The climate system (including the atmosphere, ocean and terrestrial surface) exists in thermal balance, meaning that energy coming in is roughly equal to energy going out. Changing the balance—even by a little—results in warming or cooling of the Earth. This balance is the sum total of several climate forcings that are both outside the atmosphere and within the Earth-atmosphere system. Forcings outside the atmosphere relate to astronomical parameters, and consist mostly of periodic variations in Earth's orbit, which cause regular variations in the amount and distribution of solar radiation the Earth receives over periods of tens of thousands of years. Called Milankovitch cycles, these variations on the eccentricity, axial tilt and precession of the orbit are generally considered to be the primary triggers of major ice ages (Hays et al., 1976).

Forcings within the Earth-atmosphere system include changes to the chemical makeup of the atmosphere and changes to the surface of the Earth, particularly its reflectivity. Greenhouse gases in the atmosphere capture thermal energy (heat), causing some of the energy to be retained in the atmosphere when it otherwise would have radiated out to space. Although water vapour is the most effective greenhouse gas, carbon dioxide, methane and other gases are the primary focus of climate change discussions because human activity can change the abundance of these gases in the atmosphere. Their effect on the atmospheric thermal radiation balance (radiative forcing) is strong enough that even relatively small increases in their concentration have noticeable impacts on the climate system. New climate change scenarios presented in the most recent IPCC assessment report, and used in developing the projections of sea-level rise for Canada presented in this report (Section 4), are based on changes in net radiative forcing (Box 4).

Another important forcing within the Earth-atmosphere system relates to alterations of the Earth's surface. These alterations include changes in land use and land cover brought about by human activities such as agriculture, urbanization, deforestation, desertification, and the drainage or creation of wetland areas (e.g., Pielke et al., 2011; Mahmood et al., 2014). Alterations can also include changes in snow and land or sea ice cover in direct response to climate warming (e.g., Flanner et al., 2011). Together these changes alter the reflectivity of the Earth's surface (the albedo), the amount of heat that can be stored and the amount of carbon

BOX 4

IPCC PROJECTIONS OF ATMOSPHERIC COMPOSITION

(Cubasch et al., 2013; p. 147–150 "Description of Future Scenarios"- IPCC Fifth Assessment Report)

The state of the future climate is very much dependent on people and their actions (e.g., population growth, technology development and use, fossil fuel consumption, agriculture, deforestation and other land use activities). Early efforts of the IPCC to project future climate changes focused on the quantity of carbon compounds emitted by human activity. Experts in sociology and economics developed assumptions and scenarios of future trends and patterns of human activity, which were translated into carbon emissions scenarios and provided to the climate system modellers. This process, described in the *Special Report on Emissions Scenarios* (IPCC, 2000), resulted in what are referred to as SRES scenarios.

This approach changed for development of the IPCC Fifth Assessment Report (IPCC, 2013). Recent peer-reviewed research has improved understanding of the range of likely future emission scenarios. A subset of four carbon-concentration pathways, termed Representative Concentration Pathways (RCP), were developed from the full range of possible emission scenarios. The RCPs are not directly based on changing socio-economic factors, but simply specify concentrations and corresponding emissions. The associated climate change scenarios deal with short-lived gases and land-use changes more directly than did the SRES. They provide one low-, two middle-of-the-road–, and one high-emission trajectories. The number in each scenario name corresponds to the *net radiative forcing*, which is the difference between the amount of radiant energy that enters the Earth's atmosphere and the amount that is radiated back out into space, expressed in watts per square metre (W/m^2) for the year 2100. For the highest emissions scenario, RCP8.5, the atmosphere will contain 1000 ppm carbon dioxide by the year 2100 (Figure 13), with an associated radiative forcing surplus of 8.5 W/m^2. For reference, the radiative forcing surplus under the current atmospheric concentration of carbon dioxide is ~2 W/m^2, under which changes in the climate system are already being observed. The *solar constant*, the amount of solar radiation that hits the top of the atmosphere, is approximately 1365 W/m^2. Thus, a radiative forcing change of less than one percent is enough to trigger a major response in the atmospheric thermal state.

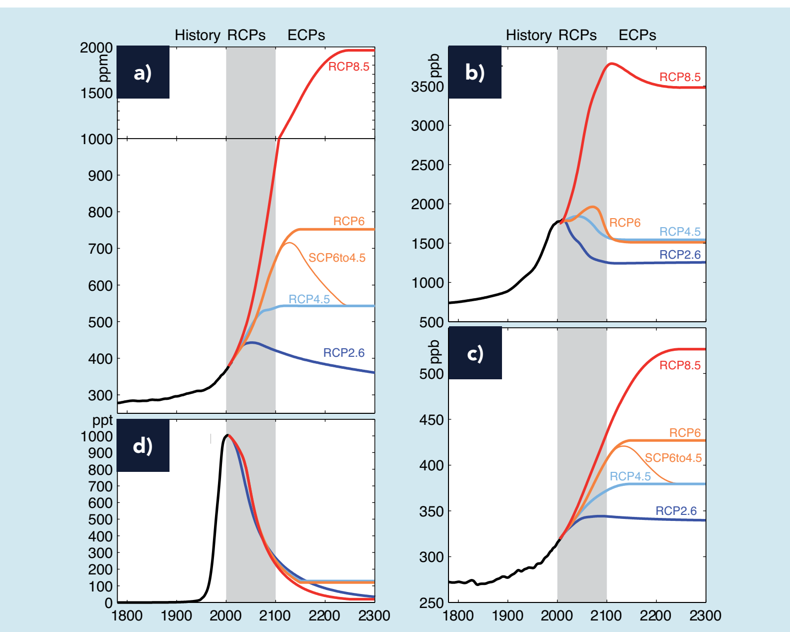

FIGURE 13: Concentrations of greenhouse gases, **a)** carbon dioxide, **b)** methane, **c)** nitrous oxide and **d)** chlorofluorocarbon, determined using the four RCPs and their extensions (ECP) to 2300 (*from* Cubasch et al., 2013, Box 1.1, Figure 2).

that can be stored. For example, ground reflectivity is greatly altered when the surface changes from snow covered to snow free. The growth of cities at the expense of vegetated areas increases the amount of energy released to the atmosphere as heat, rather than stored in evaporation of water. Forests and permanently frozen ground store large amounts of carbon; as they diminish in size, their stored carbon ends up in the atmosphere. The Industrial Revolution, which began about 250 years ago, with its rapid growth in coal combustion, triggered an acceleration in the rate of CO_2 emissions into the atmosphere. Before the Industrial Revolution, land-use alterations associated with agricultural activity going back thousands of years may have initiated changes in atmospheric chemistry (Ruddiman et al., 2014), illustrating the capacity for land-use and land-cover changes to alter the atmosphere.

This section focuses primarily on the atmospheric component of the climate system as it influences coastal processes, including wave climate. For an overview of trends and projected changes in ocean climate for Canada, readers are directed to Bush et al. (2014). Ocean climate changes, acidification, and associated impacts are also addressed in the regional chapters of this report (*see* Chapters 4–6).

3.2 CLIMATE VARIABILITY AND CHANGE

Climate and weather are inherently variable. Higher latitudes exhibit more variability than the tropics. Climate variability is short term and not necessarily related to climate change, although there are established links (e.g., climate warming at high latitudes may enhance climate variability; Francis and Vavrus, 2012). Climate variability also involves spatial linkages (teleconnections), whereby a change in the climate system at one location causes a climatic response at another location some distance from the source of the original change. Teleconnections are best evidenced by regionalized, regular changes in the Earth-ocean system that repeat on a cycle of years to decades (Box 5).

High-profile weather events such as Hurricane Juan (in 2003) or Hurricane Sandy (in 2012) raise the question of whether the event is a product of climate change. There is no way to conclusively link a particular event to climate change. However, taking a probabilistic approach to questions of attribution provides a link to climate change via changing the likelihood envelope. Such changes can be manifest in three possible forms: 'shifted mean' is a shift

BOX 5

CLIMATE VARIABILITY AND ATMOSPHERIC TELECONNECTIONS

The Earth's atmosphere, cryosphere (snow; glaciers; sea, river, and lake ice; and permafrost), ocean and land are internally interconnected through the exchange of heat, freshwater, energy and gases. The cryosphere and ocean, in particular, are able to store large amounts of heat and freshwater. Movements of large quantities of heat within the system can occur episodically and elicit strong feedbacks, resulting in natural variations or 'oscillations' and sometimes referred to as internal climate variability. These are manifested as ocean surface temperatures and atmospheric pressure patterns that vary with a roughly regular cycle. Two prominent oscillations, El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), have been apparent for centuries, and since the 1980s climate researchers have identified several more. These oscillations have periods lasting from months to decades and tend to be confined to fairly specific areas, usually located over oceans. Other examples of importance to Canada include the Arctic Oscillation in atmospheric pressure patterns and the Pacific Decadal and Atlantic Multidecadal Oscillations in ocean surface temperature.

The best known of the teleconnections affecting Canada is the ENSO. El Niño is a periodic change in sea surface temperatures that occurs in the tropical South Pacific, caused when the west-blowing trade winds weaken and allow warm water that is normally pushed to the west to flow back to the eastern side of the Pacific. This causes the waters off Peru and northern Chile to warm, and the waters of the western Pacific to cool. Changes in the surface water temperature in turn alter atmospheric temperature and pressure patterns, affecting winds and storms. For Canada, a positive ENSO (El Niño) means warmer temperatures across the country, whereas a negative ENSO (La Niña) brings cooler temperatures, typically more pronounced during the winter (Shabbar and Khandekar, 1996). During a La Niña phase, for example, the southwestern coast of British Columbia has colder winters (Abeysirigunawardena et al., 2009). Teleconnections also affect precipitation: a positive ENSO elevates the potential for extreme precipitation events on the BC and eastern Maritime coasts, but decreases the potential in central BC, Alberta and northern Ontario (Zhang et al., 2001; Wang et al., 2006). Etkin et al. (2001) identified a link between ENSO and tornado activity in the Prairies and southern Ontario (slightly enhanced activity during a positive ENSO, suppressed during a negative event).

toward more extremes at one end (e.g., more hot days); 'increased variability' is a shift toward more frequent occurrences of extremes of all types; and 'changed symmetry' is a shift in the shape of the distribution (e.g., more cooler but non-extreme days; IPCC, 2012). For example, a rise in sea surface temperatures driven by climate change sets the stage for an increased frequency in tropical cyclone (hurricane) formation. Thus, although we cannot directly connect climate change to a particular storm that may strike Atlantic Canada, we can conclude that there is an increased chance of hurricane formation due to increased sea surface temperatures, which are related to climate change.

3.3 CLIMATE DETERMINANTS

Canada's temperature regime is dominated by the seasonal changes to radiation intensity. The large temperature ranges that accompany this annual radiation progression are well observed at inland locations. Closer to the coast, the strong moderating influence of the ocean reduces the range of temperatures experienced. Seasonality is greater for the Atlantic coast (East Coast region) than for the Pacific coast (West Coast region) in Canada. These differences relate to prevailing west–east flow of air masses. The temperature of Pacific surface waters varies little over the year (Figure 14), and the West Coast region is dominated by Pacific maritime air masses possessing relatively consistent air temperatures. Air masses flowing over the Atlantic coast, by contrast, have largely come from the continent. This means warmer summer temperatures and cooler winter temperatures. Sea surface temperature in the east is also strongly influenced by the Labrador Current, a cold current that flows down the Labrador coast, around Newfoundland and along the southeast-facing Atlantic coast of Nova Scotia. Both of these factors combine to give the East Coast region south of Labrador a relatively large annual sea-surface temperature range (Figure 14).

Northern coastal weather stations show greater seasonal ranges than observed along the Pacific and Atlantic coasts, and much colder temperatures. Arctic coasts are generally situated north of the jet stream and cold air masses tend to reside over them during the winter. Winter cold can be punctuated by episodic warm air advection events from the south that can bring freezing precipitation, fog and melt conditions, all of which prove problematic for northern communities. These events are happening more frequently (Wang, 2006) as the jet stream appears to be exhibiting greater variability (Francis and Vavrus, 2012).

Precipitation patterns are controlled by prevailing atmospheric flow, storm tracks and patterns, and regional topography. The westerly flow that brings moderate temperatures to the West Coast region also entrains moist Pacific air and drives it into the steep topography of the Western Cordillera, resulting in the largest precipitation totals in Canada (>4000 mm annually at some sites) and large precipitation gradients. For example, the southwestern coast of Vancouver Island can receive more than 3000 mm of

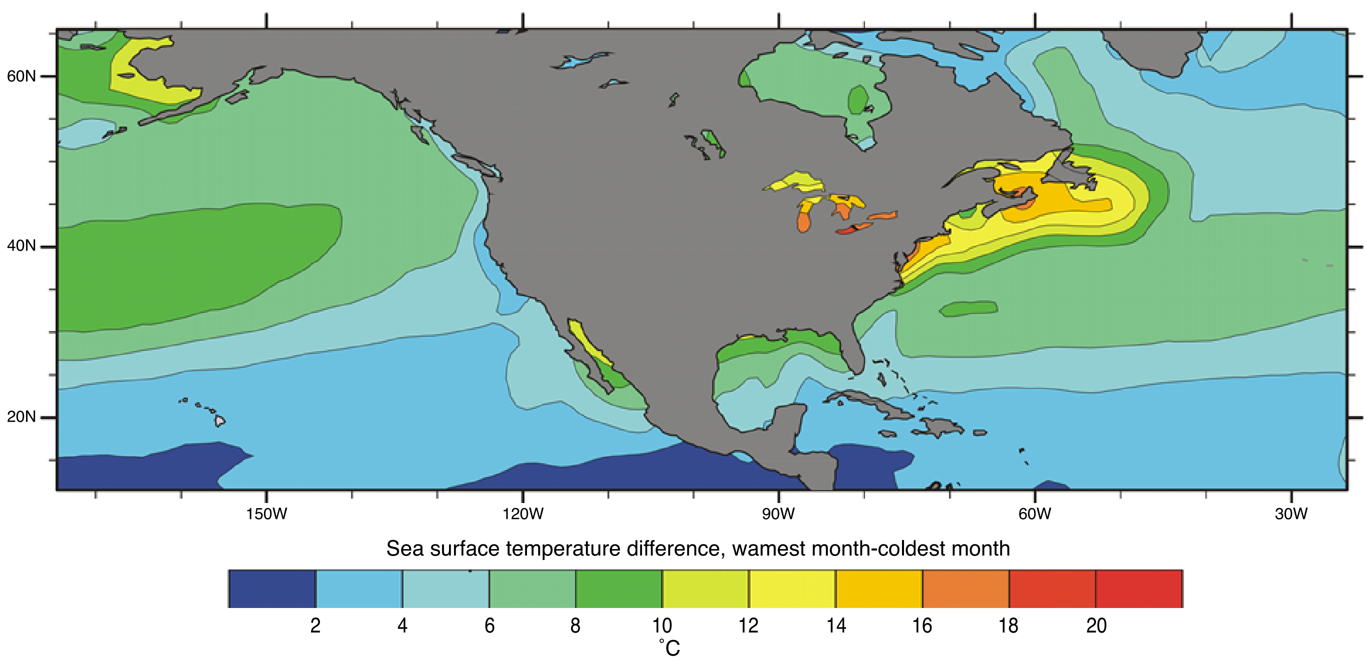

FIGURE 14: Sea-surface temperature difference between the mean warmest monthly and the mean coldest month. Note the much greater amplitude of the range off of the North American eastern seaboard (*figure plotted using data from* Reynolds and Smith, 1995).

precipitation annually, whereas less than 100 km away in Victoria, the annual total averages about 400 mm. Most precipitation arrives in the fall-winter-spring timeframe. A phenomenon unique to the Pacific coast is the 'atmospheric river'—a filamentary structure that draws out moisture from the tropical atmospheric moisture pool and directs it against the North American west coast. Atmospheric rivers result in heavy and persistent rain, and in many areas they represent the extreme weather events (Ralph and Dettinger, 2012). A major flooding event along the central BC coast in September 2010 was caused by an atmospheric river (Pinna Sustainability, 2013).

In the East Coast region, precipitation is largely controlled by storms moving up the eastern seaboard or across the continent. Mean annual total precipitation typically ranges from low values of 800 mm in eastern Quebec and southern Labrador, increasing eastward and exceeding 1600 mm for parts of northern Nova Scotia (Cape Breton) and southern Newfoundland (Natural Resources Canada, 2007). In the East, the majority of annual total precipitation arrives in winter (100–150 mm per month), with the summer months experiencing about half to two-thirds of winter monthly totals.

The western and northern Arctic receive less than 300 mm of precipitation annually. The region sees fewer storms than the eastern Arctic and has much less access to moisture due to the annual covering of sea ice that restricts evaporation from the ocean. The eastern Arctic (Baffin Island, northern Quebec and Labrador) experiences more frequent storm incursions via the Labrador Sea and Davis Strait into Baffin Bay. As a result the region also experiences more precipitation, approaching 1000 mm annually for local areas such as the southeast coast of Baffin Island.

3.4 TRENDS AND PROJECTIONS

Historical trends and projections for temperature and precipitation in Canada as a whole, summarized by Bush et al. (2014), provide important context for the following discussion of observed and projected changes in coastal climate.

3.4.1 TRENDS

Whereas temperature and precipitation data for Canada's East and West Coast regions extend back more than 100 years, instrumental records for much of the Arctic only extend back to about 1950. Vincent et al. (2012) provide detailed information on trend analysis for Canada as a whole. For coastal areas there is an upward trend in both daily maximum and daily minimum temperatures, for both the East Coast and West Coast regions, for the period 1900–2010, with minimum temperatures showing greater warming than maximum temperatures (Figure 15). Available data for northern coastal regions are not sufficient to determine long term trends.

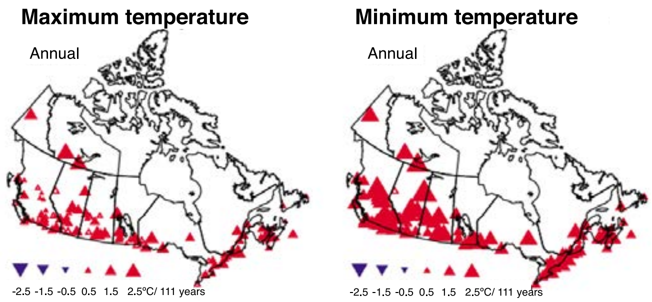

FIGURE 15: Trends in annual mean of the daily maximum and minimum temperature for 1900–2010 (Vincent et al., 2012).

For a recent 50 year period (1950–2003), daily temperature maxima show weak to moderate increasing trends in all seasons on the Pacific coast (not statistically significant in fall). The pattern is similar along the Atlantic coast, although it is statistically significant only in summer. The Arctic exhibits strong warming trends in the western and south-central regions in winter that become statistically nonsignificant for the east. Fall trends are moderate but significant throughout the east and central north. Summer and spring show some areas that exhibit stronger trends (Vincent et al., 2012). Wang et al. (2014b) extracted information about occurrence of extreme (one in 20 year return) high and low temperatures from weather stations across Canada. Temperatures were averaged for the decades of the 2010s and the 1960s then compared. Results indicate weak increases (+2°C) or no difference at stations on all three coasts. The most coherent groupings are increases in both maximum temperature and minimum temperature for the central Nova Scotia region.

Annual precipitation trends for the 1950–2003 period (Vincent and Mekis, 2006; Mekis and Vincent, 2011) indicate significant increases for most stations in all three coastal regions. The snow-to-rain ratio has decreased (i.e., more precipitation coming as rain) at almost all locations on the Pacific and Atlantic coast, whereas in the North, the ratio has increased.

Indices provide another measure to consider changes in temperature and precipitation. Analysis of a series of indices, such as number of frost days, snow-to-rain ratio and others, by Vincent and Mekis (2006) reveals, amongst other things, that over the 1950–2003 period, the Pacific coast exhibited decreasing frequency of cold days and cold nights, and an increased frequency of warm nights. Small trends in the number of consecutive dry days are also noted, particularly for the Maritimes area of the East Coast region. Trends in heavy precipitation (>10 mm) and very wet (>95th percentile) days are not strong anywhere except at some stations in Newfoundland, the Maritimes and one in the Gaspé. An analysis by Zhang et al. (2001), focusing on heavy precipitation events, similarly found few long-term trends, although an indication of increasing frequency of heavy snowfall events was noted. Note that the study is now 15 years old, a period long enough for changes in the observed trends to have occurred.

3.4.2 PROJECTIONS

Global projections of changes in surface (2 m) air temperature for the period up to 2035[1] presented in IPCC (2013) indicate a mean increase of <1°C is projected for both winter (DJF) and summer (JJA) for the Pacific coast. The Atlantic coast also shows a small increase in summer and a slightly larger increase (1.0–1.5°C) in winter. The North is projected to continue experiencing dramatic change, with winter-time air temperatures in coastal regions increasing as much as 3°C in many places. Projected summer temperature increases are on the order of 1.0–1.5°C.

A more detailed study for North America by Šeparović et al. (2013) used a high-resolution regional climate model nested within the global model outputs for the period 2071–2100. Most models suggest temperature increases of 2–3°C for both the Atlantic and Pacific coasts at this time period. Similar increases are projected for the Arctic in summer; however, all models indicate a much larger temperature increase in the Arctic winter, ranging from 6° to as high as 14°C. Analysis by Feng et al. (2012), focused on the Arctic, yielded similar findings, with projected summer temperature increases (1–3°C for coastal regions of northern Canada) and projected winter increases of 8–10°C for the period 2080–2099.

With respect to precipitation, the Šeparović et al. (2013) analysis for the period 2071–2100 shows increases of 10%–20% in winter precipitation for the Atlantic and Pacific coasts. The North shows much larger potential increases, particularly in the eastern Arctic, with increases up to 80% being projected. For the summer period several models suggest as much as a 20% reduction in precipitation for the Pacific coast. No particular trend is indicated for the Atlantic coast, while increases of up to 20% are indicated for many parts of the Arctic.

As many weather impacts in Canada relate to weather extremes (e.g., Warren and Lemmen, 2014), it is important to understand projected changes in extreme events. Casati and de Elia (2014) examined projected extreme temperature values (annual and seasonal maximum and minimum) to detect changing values or frequency of occurrence for extremes. Their results indicate increases in the value of temperature extremes, but not necessarily an increase in their frequency of occurrence. Projected changes to atmospheric river events for the United States Pacific coast have been analyzed by Dettinger (2011), with findings relevant for Canada's West Coast region. Under a high-emissions scenario, significant changes were found in the extremes associated with atmospheric rivers. Years with multiple atmospheric river events increased, as did water-vapour transport rates and associated storm temperatures. In addition, analysis found that the length of the season in which most atmospheric rivers occur is expected to increase.

3.5 STORMS AND SEA ICE

3.5.1 STORMS

Canada and its coastal regions are subject to a wide range of storm types and impacts (Stewart et al., 1995). Strong winds are generally of greatest importance in coastal regions, as these drive damaging wave states and storm surges. Distant storms can drive swells of longer period into the coastal environment, presenting a greater hazard for marine traffic. Precipitation events associated with storms can also prove problematic. In the North, the impact of a storm is determined by the extent and mobility of sea ice.

Storms in the Pacific region consist typically of occluded extra-tropical cyclones that have been spawned over the mid- or western Pacific and have moved under the influence of the jet stream into the BC coastal region. This area does not experience tropical cyclones (typhoons or hurricanes), and even under extreme climate change scenarios the broad circulation patterns of the North Pacific are projected to maintain sea-surface temperatures off the North American west coast that are too cool to support tropical cyclone activity. Frontal zone passages do occur on the Pacific coast, but are often relatively diffuse compared to frontal passages in central or eastern Canada. However, frontal zones in the West Coast region are important as they spawn secondary storm systems. A typical storm pathway involves a primary system moving up into the Gulf of Alaska and stalling there, bringing significant moisture to the northern BC coast. In some cases, a secondary storm system is spawned at the confluence of the warm and cold fronts, which moves around the primary system to the south, and can bring strong winds and heavy precipitation to Vancouver Island and the southern BC coast.

The summer is a relatively storm-free period on the Pacific coast, as the jet stream tends to produce a ridge of high pressure over BC, resulting in fair weather for much of southern coastal BC in summer. Moving north, this pattern is generally maintained, with increasing amounts of summer precipitation. The majority of precipitation is steady rain rather than showery precipitation associated with convective activity. Thunderstorms are rare in the West Coast region.

For the East Coast region, large-scale climatic controls include the prevailing upper-level winds, which move storm systems into the region from farther west. Storm systems formed over the plains of North America have often progressed to a rapidly intensifying mature phase by the time they reach the east coast. Although storms moving through

1 Values are the average for the period 2016 to 2035. Note that projections for this near term period are virtually the same for all climate change scenarios.

this region tend to move fairly rapidly, they are nevertheless capable of generating significant precipitation and winds. These events occur primarily in winter and spring. The East Coast region has two other major storm tracks that do not affect other parts of Canada. The first are storms that form along the United States eastern seaboard, proceed along the coast to the northeast and enter eastern Canada 36–48 hours after initial formation. These storms can move and develop very rapidly, with the strongest systems termed 'nor'easters' (e.g., Davis et al., 1993). 'White Juan', which impacted much of the Atlantic provinces in February of 2004 with record snowfall amounts and strong winds, was a very strong nor'easter. Strong winds associated with the storm generated severe marine conditions including swell and storm surge. The second unique storm track affecting the East Coast region is the typical path followed by tropical cyclones (hurricanes) that strike the United States eastern seaboard and Gulf of Mexico. Typically, hurricanes do not directly strike eastern Canada, with Hurricane Juan in September 2003 being a notable exception. Instead, they encounter the mainland United States coast farther south, at which point the storm weakens fairly rapidly, losing its tropical-cyclone form. This begins the extra-tropical transition phase, altering the storm from a tropical cyclone to an extra-tropical cyclone. Despite this weakening, these remain strong storms and generally continue along a northeasterly trajectory into Canada's East Coast region. Because of their greater diameter, some tropical and post-tropical storms can affect a wide swath and be almost as damaging as full hurricanes.

Maxwell (1981) identifies two main storm tracks in the Canadian Arctic. The most prominent of these is from the east, into Baffin Bay via the Labrador Sea and Davis Strait. This is an offshoot of two major North American storm tracks, one extending in the mid-latitudes from the Rockies to Eastern Canada and the other extending up the Atlantic seaboard. Storms on these tracks typically move into the Atlantic, where the track splits. Most storms continue south of Greenland and on across the Atlantic Ocean. However, some turn north toward Baffin Bay and some on this path stall over Hudson Bay. The second major storm track identified by Maxwell (1981) is from the west into the Beaufort Sea and Amundsen Gulf, affecting the western archipelago and the mainland coast of the Yukon, Northwest Territories and western Nunavut.

Some storms on Baffin Island result in wind events and some are precipitation events producing snow, freezing rain or rain (Roberts et al., 2008; Hanesiak et al., 2010). Storm winds can drive wave and swell responses that propagate into and fracture sea ice (Asplin et al., 2012), enhancing ice decay and introducing additional moisture and heat into the atmosphere, which can set the stage for more frequent cloudiness or fog. The large expanses of open water now found in the Arctic Ocean and marginal seas can provide the thermal gradients necessary to drive powerful storms of great areal extent, as was observed in August 2012, in the western Arctic Ocean including the Chukchi and Beaufort seas (Simmonds and Rudeva, 2012).

Storms and storm winds exert a variety of impacts on northern coasts. Many areas of the eastern Beaufort Sea region feature shallow inner-shelf bathymetry. This is favourable for the development of storm surges that, when combined with the large expanse of low-relief area in the Mackenzie River delta, can result in flooding over large areas (Pisaric et al., 2011) and can drive water level anomalies as far as 100 km upriver from the coast (Marsh and Schmidt, 1993).

3.5.2 SEA ICE

A dominant feature of Canada's North Coast region is ice: sea ice, permafrost and glaciers (Forbes and Hansom, 2011; *see* Chapter 5). The presence of sea ice promotes coastal cooling in summer and also facilitates cooler temperatures in winter, as the sea-ice cover reduces moisture and energy transfer with the atmosphere, thereby reducing the moderating influence of the ocean. The east coast of Canada also experiences sea ice, but with a shorter season (Figure 16). The seasonal duration of sea ice is decreasing on almost all Canadian coasts, from the Gulf of St. Lawrence (Forbes et al., 2002) to the Arctic Archipelago (St-Hilaire-Gravel et al., 2012) and the Beaufort Sea (Manson and Solomon, 2007; Overeem et al., 2011). For the entire Arctic region, sea-ice area and thickness are decreasing, with summer ice-extent reductions on the order of 12% per decade for the past three decades

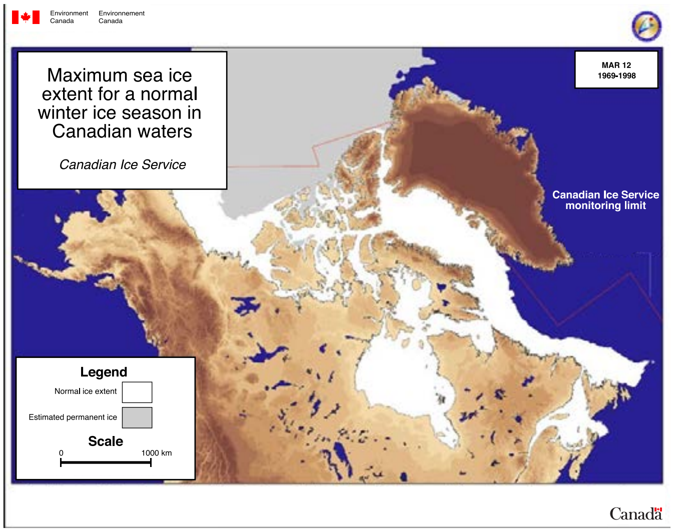

FIGURE 16: Average maximum ice extent for the years 1969–1998. Note that March 12 is taken to be the date of maximum ice extent (Environment Canada, 2013).

(Stroeve et al., 2012; *see* Chapter 5). At present, projections from climate models suggest that the Arctic Ocean may be ice free during summer by about 2040 (Wang and Overland, 2009). However, even a substantially reduced summer ice cover will have profound implications for Arctic coasts (Barnhart et al., 2014b).

3.5.3 CHANGES IN STORM ACTIVITY

Detecting changes in storm frequency is difficult due to a number of factors, including how a storm is identified and classified, and analytical methods. In the case of tropical cyclones, different monitoring agencies (United States, Japan, Hong Kong/China) define maximum windspeed differently. A common approach to storm analysis is to identify and track storms individually and develop summary statistics for different areas (Mesquita et al., 2009, 2010). Other approaches focus on developing statistics of meteorological parameters associated with storms, such as strong winds (Atkinson, 2005). In addition, it is important to consider the length of record to distinguish between trends and cyclical variability. For example, it is recognized that tropical cyclone (hurricane) frequency in the Atlantic Basin exhibits a rough cycle with periods of less or more activity related to the Atlantic Multidecadal Oscillation (Enfield and Cid-Serrano, 2010).

Despite these challenges, it is evident that the mid-latitude storm track is shifting farther north (IPCC, 2013), bringing on average a greater frequency of storms to the Canadian North and a greater proportion of storms entering Canada from the west. The jet stream strength and position are the primary determinants of the strength and trajectory of extra-tropical cyclones. Alterations in the jet stream will be felt locally as a changed climate (e.g., more/less frequent storms, more frequent incursions of warm air). A station-based assessment of frequency and rates of pressure drops at stations across Canada—a surrogate for storm activity—found increased winter storm activity in the southern Arctic and a weak decrease along the southern Pacific and Atlantic coasts (Wang et al., 2006). More frequent, but less intense summer storm activity was noted for the Atlantic coast.

It is possible that there are links between reduced sea ice and the occurrence of extreme weather events to the south (Francis and Vavrus, 2012, 2015). Reduced sea ice provides a greater expanse of open water, warming the polar atmosphere and possibly weakening the east-west strength of the jet stream. This, in turn, alters the jet stream form, leaving it more able to meander to the north and south and to create 'blocking' patterns (Box 6), which can result in stalled weather systems (e.g., rainy weather stretching over two weeks). During such times, extreme events can occur in the form of prolonged periods of rain, drought, heat or cold. This idea is not without controversy (Barnes, 2013; Fischer and Knutti, 2014) but constitutes an area of active research, which reflects the complexity of many Earth systems.

It is more difficult to quantify future changes in storms and circulation than it is for changes in temperature and precipitation. For storms, climate change means not so much an increase in total hemispheric counts, but rather changes in storm tracks and the length of time that large-scale atmospheric-flow regimes favour particular weather patterns. Recent work using a high-emissions scenario (RCP8.5) projects a general decrease in storm activity over eastern and western Canada, but an increase in storm activity in the North during the fall (Chang, 2013).

BOX 6
BLOCKING PATTERNS

A blocking pattern is an excessively wavy flow pattern in the atmosphere that does not favour the usual movement of weather patterns from west to east. Instead, weather systems 'stall', remaining relatively stationary or moving slowly over a particular region (which can be quite large). A blocking pattern can remain in place for as long as three weeks, and during this time the areas affected by the block receive very persistent weather. Figure 17 illustrates a typical mid-Atlantic blocking event from February 1987, which resulted in an extended period of cold temperatures in Atlantic Canada. A west coast example occurred in September 2012 under the influence of a very persistent ridge pattern that provided for weeks of sun, extending into what should have been the beginning of fall. Likewise, the following year, a persistent trough pattern caused warm, moist air to be pumped into the Vancouver Island region from the southwest, bringing warm temperatures and moderate rain for several weeks. Recent research has suggested that warming in the Arctic has resulted in a weakening of the east-west strength of the jet stream (Francis and Vavrus, 2012), allowing it to meander more and increasing the frequency of blocking patterns.

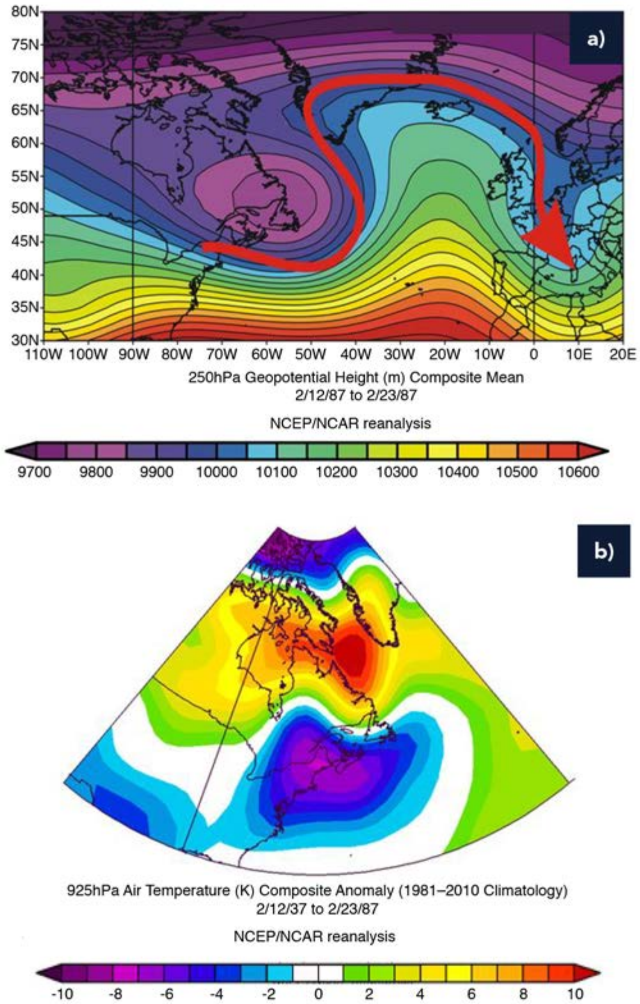

FIGURE 17: **a)** Upper atmospheric flow pattern during a typical mid-Atlantic blocking event. Contour lines connect points of equal elevation of that pressure surface (250 hPa) above the surface. The large arrow depicts the general position of the jet stream for the period 12–23 February 1987. **b)** Regional temperature anomalies for the same period depicted in part (a). The presence of the blocking event resulted in a protracted period of cold temperatures for most of the East Coast region, as shown by the negative temperature anomalies, and also a strong warm anomaly over northern Labrador–Hudson Bay and Southern Baffin regions. Data and plot obtained using the National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Physical Science Division's retrieval and display tool for online climate data.

4 CHANGING SEA LEVEL

One of the most significant consequences of climate change is sea-level rise (Stern, 2007; IPCC, 2013). Global, or absolute, mean sea level is projected to rise by tens of centimetres, and possibly more than a metre, by the year 2100, due primarily to thermal expansion of the oceans and increased melting of land ice (glaciers, ice caps and ice sheets; e.g., IPCC, 2013; Church et al., 2013a). Sea-level rise leads to increased frequency of coastal flooding and may lead to increased amounts of coastal erosion. Thus, projections of sea-level change are important for forecasting risk to populations, for planning infrastructure maintenance and development, and for habitat management (e.g., Nicholls et al., 2011).

4.1 HISTORICAL SEA-LEVEL CHANGE

Globally, sea level rose at a mean rate of 1.7 ±0.2 mm/year between 1901 and 2010, while between 1993 and 2010, sea level rose at a faster rate of 3.2 ±0.4 mm/year (Church et al., 2013a). However, there was considerable variability in the rate throughout the 20th century (Church and White, 2006). Sea-level change is observed at a global network of tide gauges, supplemented in recent decades by satellite observations. The long-term trends in sea level that are observed at tide gauges vary substantially from one location to another. Some of the variability is due to oceanographic effects affecting the elevation of the sea surface, but a predominant control on relative sea-level change is vertical land motion (Box 7).

BOX 7

ABSOLUTE AND RELATIVE SEA-LEVEL CHANGES

(Bush et al., 2014, p. 53)

Global sea-level change is commonly discussed in terms of 'absolute' sea level, meaning that it is referenced to the centre of the Earth. At coastal locations, the sea-level change that is observed or experienced relative to a fixed location on land is known as relative sea-level change. Relative sea-level change is the combination of absolute sea-level change and vertical land motion, both of which can vary from one location to another. Land uplift decreases relative sea-level rise and land subsidence increases relative sea-level rise. In determining relative sea-level changes across Canada, vertical land motion (uplift and subsidence) plays a prominent role, although regional variations in absolute sea-level change are also important.

The predominant cause of vertical land motion across much of Canada is glacial isostatic adjustment (GIA), which causes surface uplift or subsidence due to the delayed effects of the last continental glaciation (Figure 18). During the last ice age, ice sheets loaded the surface of the Earth, including most of the Canadian landmass. Beneath the ice sheets, within the interior of the Earth, mantle rock flowed downward and outward, and the surface of the Earth sank. At the periphery of the ice sheet, and immediately beyond it, the land rose in response to mantle material flowing outward from under the ice sheets. After deglaciation, the process was reversed and the land started to rise where it had been depressed under the ice sheets. Outside the region of former glaciation, peripheral regions began to subside. The process of GIA is still occurring, causing uplift in areas close to the centre of former ice sheets, such as Hudson Bay. In areas near the margins of former ice sheets, GIA is causing land subsidence.

Other factors also generate significant vertical land motion. Motion along major faults can result in either uplift or subsidence. Sediments deposited in large deltas (e.g., the Fraser River and Mackenzie River deltas) near the mouths of large rivers undergo compaction, causing subsidence of the delta surface. At a local scale, surface subsidence can be caused by compaction of unconsolidated sediments and by groundwater withdrawal. On Canada's west coast, tectonics, sediment processes and GIA, including the crustal response to present-day glacier changes, all affect vertical crustal motion and relative sea-level changes. In Canada's eastern and northern coast regions, GIA is the major cause of vertical crustal motion on a regional scale. In the High Arctic and eastern Arctic, the crustal response to present-day glacial changes is also extremely important.

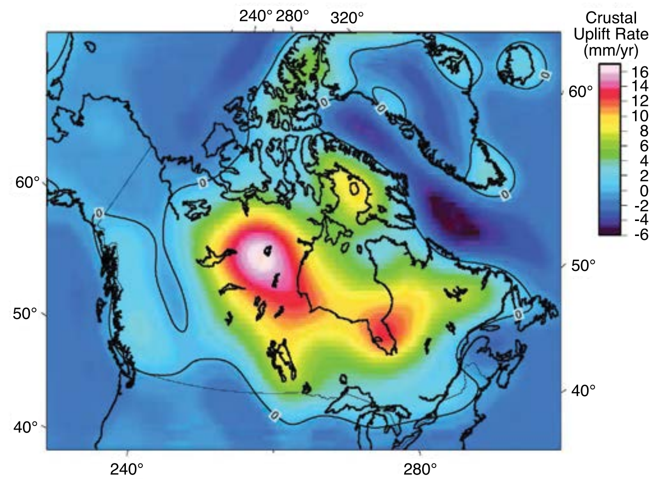

FIGURE 18: Vertical land motion, in millimetres per year, generated by glacial isostatic adjustment, based on the ICE-5G model (Peltier, 2004).

The effects of vertical land motion are evident in tide gauge records (Figure 19). Where the land is rising rapidly due to GIA, such as at Churchill, MB, sea level has been falling rapidly at a rate of 9.3 mm/year. Where the land is sinking due to GIA, such as much of the Maritimes and along the coast of the Beaufort Sea in the Northwest Territories and Yukon, sea level is rising faster than the 20th century global average. At Halifax, sea level has risen at the rate of about 3.3 mm/year through the 20th century. During the past half century, sea-level rise has averaged 2.4 mm/year at Tuktoyaktuk, NT. The west coast of Vancouver Island is observed to be rising slowly, probably due to active tectonics, and sea level at Tofino has fallen at a rate of 1.6 mm/year.

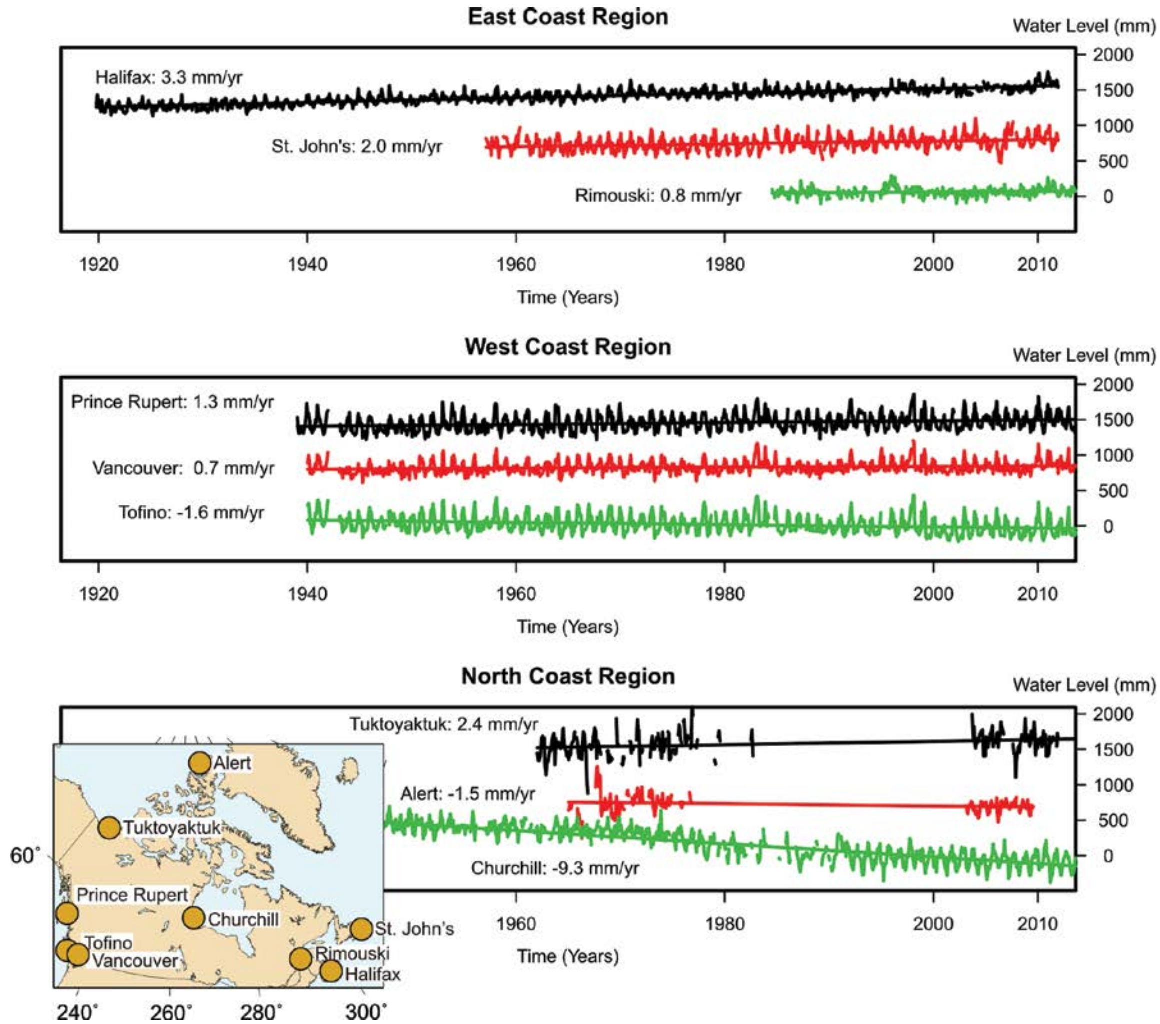

FIGURE 19: Long-term trends of relative sea-level change in Canada observed at representative tide gauges. Tide gauge data *obtained from the* Permanent Service for Mean Sea Level at http://www.psmsl.org/data/obtaining *and accessed* 19 September 2014.

4.2 FUTURE SEA-LEVEL CHANGE

Of particular importance for adaptation planning are projections of relative sea-level changes. Relative sea-level projections will differ from global sea-level change due to local vertical crustal motion caused by GIA, tectonics and other factors. Sea-level projections also require consideration of dynamic oceanographic changes and the Earth's response to present-day ice-mass changes, including spatial variations in the redistribution of glacial meltwater in the oceans.

Projections of relative sea-level changes for coastal Canada, based on the scenarios and global projections of the IPCC Fifth Assessment Report (IPCC, 2013), have been published by James et al. (2014, 2015). The following section summarizes the methodology and results of that analysis.

4.2.1 GLOBAL SEA-LEVEL RISE

The global sea-level rise projections presented in the IPCC Fifth Assessment Report and referred to here (Figure 20) are based on the Representative Concentration Pathways (RCP) scenarios (Moss et al., 2010; Boxes 4 and 8). Several of the new RCP scenarios are roughly comparable (in terms of global increases in mean annual temperature by the year 2100) to SRES (Nakićenović et al., 2000, Box 4), which were the standard used for climate change analysis during the last decade (Table 1; further discussion of SRES and RCP scenarios can be found in IPCC (2013) or Bush et al. (2014)). The median projected sea-level rise of the highest emission RCP scenario (RCP8.5) is 1.7 times larger than that for the lowest emission RCP scenario (RCP2.6; Figure 20).

TABLE 1: Projections of changes in global mean temperature and sea level under Representative Concentration Pathways scenarios (RCP; IPCC, 2013) and most closely associated *Special Report on Emissions Scenarios* (SRES), with respect to median temperature increase by 2100 (Rogelj et al., 2012).

RCP Scenario	Likely global surface temperature increase for 2081–2100* (°)	Likely global sea-level rise for 2081–2100* (m)	Comparable SRES
RCP2.6	0.3–1.7	0.26–0.55	None
RCP4.5	1.1–2.6	0.32–0.63	SRES B1
RCP6	1.4–3.1	0.33–0.63	SRES B2
RCP8.5	2.6–4.8	0.45–0.82	SRES A1FI

* relative to 1986–2005

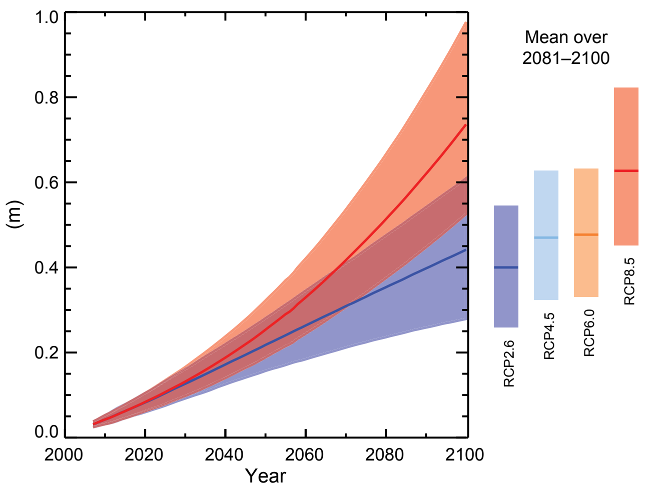

FIGURE 20: Projected sea-level rise during the 21st century relative to 1986–2005 for RCP2.6 (low-emissions scenario) and RCP8.5 (high-emissions scenario; Figure SPM.9, IPCC, 2013). The lines indicate the median projection and the shading indicates the assessed range (5th–95th percentile, or 90% confidence interval). The projected mean sea-level rise over 2081–2100 is given on the right for all four RCP scenarios.

The possibility of global sea-level rise exceeding 1 m by 2100 cannot be rejected. Sea-level projections based on simple relationships between global atmospheric temperatures (or heat flux) and global sea-level rise, termed semi-empirical projections (Rahmstorf, 2007), estimate larger amounts of sea-level rise by 2100 (e.g., 75–190 cm, Vermeer and Rahmstorf, 2009; 60–160 cm, Jevrejeva et al., 2010). However, recent advances in understanding the processes of ice sheet stability, combined with the very large variability of the semi-empirical results, led the authors of the IPCC Fifth Assessment Report to assign low confidence to such predictions (Church et al., 2013a). The implications of larger amounts of projected global sea-level rise are considered further in Chapter 3 in the context of tolerance to risk.

As noted above, global sea-level rise has contributions from a variety of components. Church et al. (2013a) provide estimates of the contributions to global sea-level rise from thermal expansion of the upper layer of the ocean (referred to as the steric effect); mountain glaciers and ice caps, the Greenland and Antarctic ice sheets; and land-water storage (groundwater depletion and water reservoir impoundment). Contributions from the West Antarctic Ice Sheet are a particularly important factor, but are poorly constrained (Church et al., 2013a). Analyses of the additional amount of sea-level rise that might be produced from instability of the marine-based West Antarctic Ice Sheet at 2100 (Pfeffer et al., 2008; Katsman et al., 2011; National Research Council, 2012; Bindschadler et al., 2013) arrive at a mean upper-end estimate of 64.6 cm. The *Summary for Policymakers*, which is the contribution of Working Group I to the IPCC Fifth Assessment Report (IPCC, 2013, p. 25) states:

> *Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. However, there is medium confidence that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.*

To account for this possible additional contribution to global sea-level rise this century, the analysis in this report considers one additional scenario beyond those used in the IPCC Fifth Assessment Report (Box 8; Table 2). In all, this report focuses on the sea-level projections for four scenarios, summarized in Table 2. Discussion of the relevance of these scenarios for determination of risks to coastal management is presented in Chapter 3, as well as the regional chapters of this report.

BOX 8
GLOBAL SEA-LEVEL RISE SCENARIOS USED IN THIS REPORT

Projections of sea-level rise presented in this chapter and used throughout this report focus on four scenarios of global sea-level rise. Three of the four, RCP2.6, 4.5 and 8.5, are identical to those presented in the IPCC Fifth Assessment Report (IPCC, 2013). The fourth RCP scenario considered by the IPCC, RCP6.0, is associated with projections of global sea-level rise very similar to, but slightly larger than, RCP4.5 (Figure 20). Both are considered intermediate-emissions scenarios and only RCP4.5 is presented here to simplify the visual presentation of sea-level rise projections.

In addition to the model-based RCP scenarios, this report also presents a scenario to evaluate the effect a partial collapse of the West Antarctic Ice Sheet would have on relative sea-level change in Canada. The high-emissions scenario RCP8.5, the most likely scenario to be associated with ice-sheet collapse, is augmented by an additional 65 cm of sea-level rise originating from West Antarctica. Here termed the 'high-emissions plus Antarctic Ice-Sheet reduction' scenario, it provides the largest amount of global sea-level rise and represents a possible upper bound to global sea-level rise by 2100, based on information contained in the IPCC Fifth Assessment Report (Table 2; IPCC, 2013). For planning purposes, the scenarios may be considered in the context of tolerance to risk of sea-level rise (Chapter 3; Parris et al., 2012).

TABLE 2: Scenarios utilized in this report for generating relative sea-level rise projections.

Scenario	Descriptive scenario name
RCP2.6	Low-emissions
RCP4.5	Intermediate-emissions
RCP8.5	High-emissions
RCP8.5 plus 65 cm from partial West Antarctic ice-sheet collapse	High-emissions plus Antarctic ice-sheet reduction

4.2.2 VERTICAL LAND MOTION

As discussed previously, vertical land motion strongly influences changes in relative sea level. Land uplift will reduce the amount of sea-level rise experienced at a site; conversely, land subsidence will add to the amount of relative sea-level rise. Present-day land uplift or subsidence is measured using Global Positioning System (GPS) technology, or more generally Global Navigation Satellite Systems. The position of an antenna, generally fixed to bedrock, is monitored on a continuous or repetitive basis over many years by tracking the navigation satellite constellation(s). The long-term uplift rate is obtained from the vertical position time series.

The density of GPS stations varies significantly across Canada (Figure 21), with most having data spanning 5–15 years. Uplift rates (the methodology is presented in James et al., 2014) are generally coherent across Canada. In the East Coast region, vertical motion ranges from uplift of ~1–4.5 mm/year for Quebec sites to subsidence of up to ~2 mm/year at some locations in Nova Scotia. On the west coast, uplift rates vary from subsidence of about 1 mm/year in Puget Sound to almost 4 mm/year in the middle part of Vancouver Island, and smaller amounts of uplift further north. The west coast of Vancouver Island is rising due to accumulating strain from the subduction of the Juan de Fuca plate beneath North America. The largest variation in vertical land motion is observed in the Arctic. Hudson Bay is rising at a rate of 10 mm/year or more, resulting in falling relative sea level. Significant portions of the Canadian Arctic Archipelago are rising a few millimetres per year, whereas the isostatically subsiding Beaufort Sea coastline in the western Arctic is sinking at a rate of 1–2 mm/year. Sparse GPS observations from the eastern Arctic and High Arctic indicate uplift rates of a few millimetres per year arising from a combination of GIA and crustal response to present-day ice-mass change.

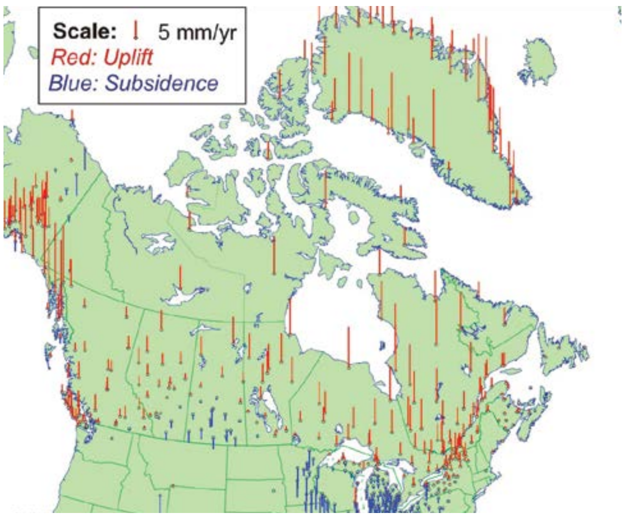

FIGURE 21: Crustal-uplift and subsidence rates determined from GPS-derived data (in millimetres per year; Craymer et al., 2011).

4.2.3 EFFECTS OF PRESENT-DAY ICE-MASS CHANGE

Meltwater from glaciers, ice caps and ice sheets is not distributed uniformly throughout the world's oceans (Farrell and Clark, 1976; Mitrovica et al., 2001, 2011). As a glacier or ice sheet melts, the reduced mass of the remaining ice causes the land under and adjacent to a shrinking ice sheet to rise because the Earth's crust reacts like an elastic object and springs back. Additionally, the shrinking ice mass exerts a reduced gravitational pull on the surrounding ocean water, causing the nearby ocean surface to fall (Figure 22). The effect can be very significant for sites close to meltwater sources. Canada hosts significant volumes of mountain glaciers and ice caps in the North and, on a global scale, is relatively close to the Greenland ice sheet. Western Canada is also influenced by the rapidly wasting mountain glaciers and ice fields of the Coast Mountains and the Gulf of Alaska. Thus, for Canadian localities it is particularly important that sea-level projections incorporate the effects of present-day ice-mass change.

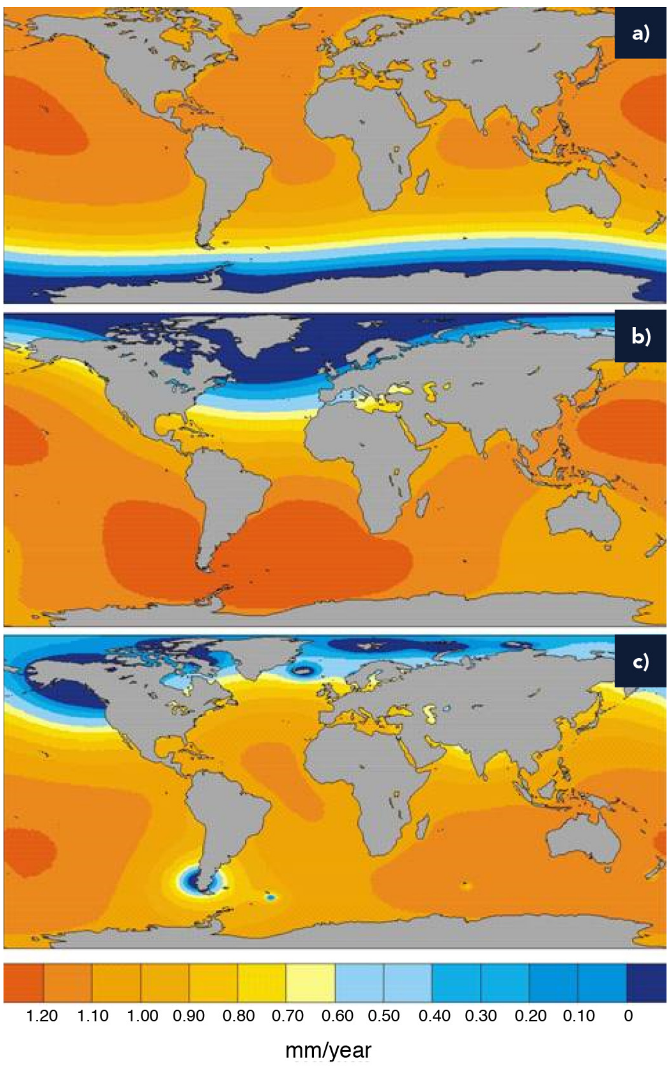

FIGURE 22: The amount of relative sea-level rise, in millimetres per year, for an assumed 1 mm/year contribution to global sea-level rise from **a)** Antarctica, **b)** Greenland, and **c)** mountain glaciers and ice caps (*from* Mitrovica et al., 2001). Close to a source of sea-level rise, relative sea level will fall. At greater distances the sea-level rise is smaller than the global average. At even larger distances, sea-level rise is slightly higher than the global average.

4.2.4 REGIONAL OCEANOGRAPHIC EFFECTS

Global ocean currents generate 'dynamic' sea-surface topography of more than 1 m in amplitude. Changes to ocean currents can lead to changes in the sea-surface topography and hence to changes in local relative sea level. A robust feature of such dynamic sea-level changes is that sea-level rise due to the weakening of the Gulf Stream is predicted for northeastern coastal North America in the coming century (Yin et al., 2010; Yin, 2012; Church et al., 2013a). For the western Arctic, dynamic oceanographic changes in sea level are projected to be nearly as large as in the East Coast region, while on the Pacific coast they are expected to be relatively small. In contrast, a large ENSO event can raise sea levels by several tens of centimetres in the West Coast region (Section 4.3; Thomson et al., 2008).

4.3 PROJECTIONS OF SEA-LEVEL CHANGE IN CANADA

4.3.1 PROJECTIONS OF RELATIVE SEA-LEVEL CHANGE

Relative sea-level projections were generated for 69 coastal communities and other locations in Canada and the northern United States by James et al. (2014; Figure 23) based on the IPCC Fifth Assessment Report (Church et al., 2013a, b). The projections incorporate contributions to global sea-level rise from the steric effect, land ice and anthropogenic influences such as groundwater pumping, as described above, and also include the spatially varying effects of dynamic oceanography and present-day ice-mass changes. Vertical land motion determined by GPS was utilized to determine projected relative sea-level change (Mazzotti et al., 2008; methodology presented in James et al., 2014).

Spatial differences in projected relative sea-level change are similar to historical sea-level changes and largely follow the pattern of vertical land movement. The largest amounts of projected sea-level rise, which exceed 75 cm for the median projection of the high-emissions scenario at 2100 (red dots on Figure 23), occur where the land is presently sinking due to GIA in the East Coast region. Large amounts of projected sea-level rise are also present in Puget Sound in northern Washington State. Other areas where the land is also sinking, or rising at low rates due to GIA, and that feature projected sea-level rise larger than 50 cm (orange dots) include the Beaufort Sea coastline, some regions of Newfoundland and Quebec, and, on the Pacific coast, the Fraser River lowland and northern British Columbia. Active

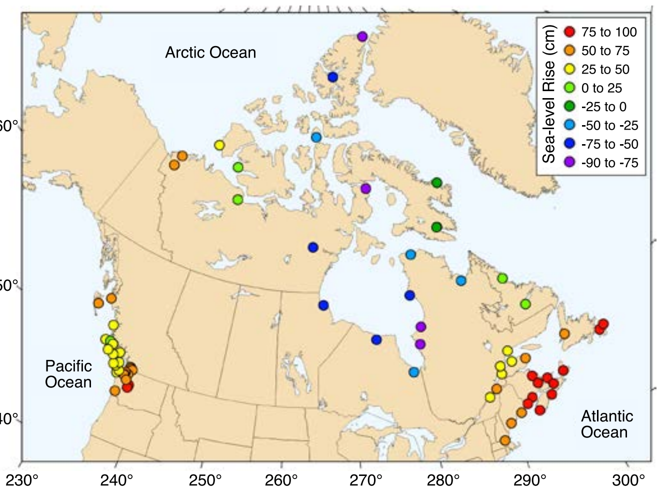

FIGURE 23: Projected relative sea-level change at 2100 (in cm) for the median of the high-emissions scenario (RCP8.5) at 69 coastal locations in Canada and the northern United States (James et al., 2014, 2015). Values range from -84 to 93 cm, and refer to the average conditions in the period 1986–2005.

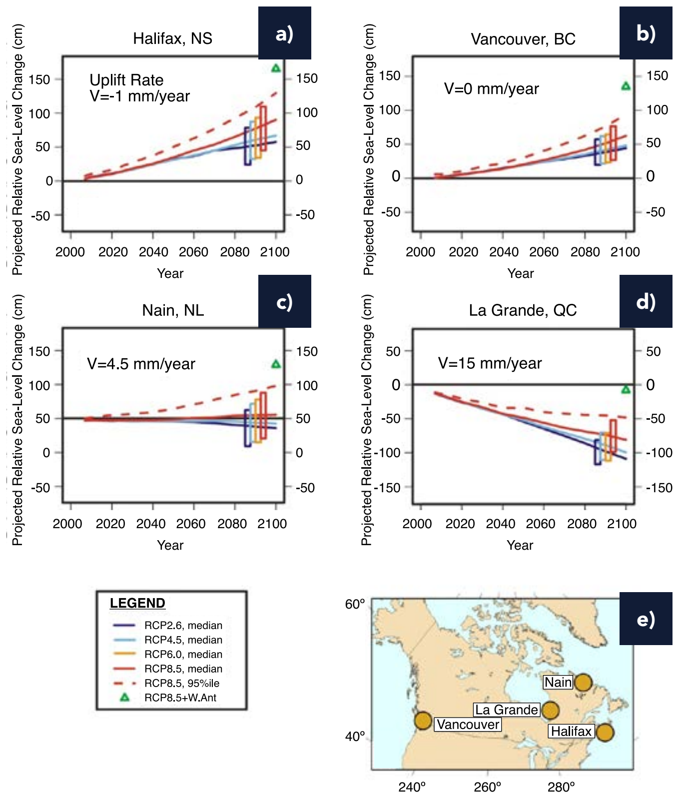

FIGURE 24: Projected relative sea-level change, based on the IPCC Fifth Assessment Report (Church et al., 2013a, b) and utilizing vertical (V) crustal motion (uplift rate, given to nearest 0.5 mm/year) derived from GPS observations indicated in each panel for **a)** Halifax, **b)** Vancouver, **c)** Nain and **d)** La Grande 1 (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 interval (5th–95th percentile) of the average projection over 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.

tectonics and, on the Fraser River delta, sediment consolidation (Mazzotti et al., 2009), contribute to vertical crustal motion in the west. Where the land is presently rising fastest, in Hudson Bay and the central Canadian Arctic Archipelago, sea level is projected to fall by more than 50 cm (dark blue and purple dots on Figure 23). In the High Arctic and eastern Arctic, the effects of present-day ice-mass changes (of Arctic glaciers and ice caps, and the Greenland ice sheet) contribute to reduced amounts of projected sea-level rise or small amounts of sea-level fall. This is especially pronounced at Alert, the northernmost location of this region, where proximity to the Greenland ice sheet contributes to large projected sea-level fall due to the elastic crustal uplift caused by the projected reduction of the Greenland ice sheet and Arctic ice caps.

Figure 24 summarizes the sea-level projections for all scenarios for Halifax, NS; Vancouver, BC; Nain, NL; and La Grande 1, QC. These scenarios span a range of vertical crustal motion from about –1 mm/year (Halifax, sinking) to 15 mm/year (La Grande 1, rising rapidly). The high-emissions plus Antarctic Ice-Sheet reduction scenario is notable in providing projections of relative sea-level change exceeding 150 cm at Halifax at 2100 and predicting only negligible sea-level fall at the fastest rising location of La Grande 1 (especially when contrasted with the low-emissions scenario, which anticipates about 50 cm of sea-level rise at Halifax and more than 100 cm of sea-level fall at La Grande 1). Further details on regional variability of projected sea-level changes are presented in Chapters 4 (East Coast region), 5 (North Coast region) and 6 (West Coast region) of this report.

4.3.2 EXTREME WATER LEVELS

One of the most serious consequences of sea-level rise is its effect on extreme water levels. These are typically associated with storm surges superposed on high tides. Contributions from seasonal and annual variability and wind waves also play a role. In the Pacific, large ENSO events can lead to sea-level changes of several tens of centimetres (Thomson et al., 2008). A storm surge is defined as the difference between observed water level and the predicted astronomical tide, and results from variations in atmospheric pressure and wind. Storm surges in Canada have maximum heights of 1 m or more on all three coasts (Bernier and Thompson, 2006; Manson and Solomon, 2007; Thomson et al., 2008). Extreme water levels (combined tide and surge) will be even higher in future as a result of sea-level rise (Box 9). Extreme water levels are a critical consideration in coastal management and climate adaptation planning, as discussed in Chapter 3.

BOX 9
HISTORICAL AND PROJECTED FUTURE EXTREME WATER LEVELS – EXAMPLE FROM HALIFAX, NOVA SCOTIA

The historical frequency distribution for the annual maximum hourly water level (largest hourly water level during each calendar year) arising from the combined effects of tide and surge at Halifax in metres above the mean is shown in Figure 25 for the period 1920–2007 (Forbes et al., 2009). The record extreme water level of 1.87 m was associated with Hurricane Juan in 2003. The previous record water level in Halifax Harbour was about 4 cm lower and occurred during a winter storm in 1967. Assuming that storm frequency, intensity and storm tracks do not change (i.e., assuming the shape of the extreme water-level distribution expressed by the red line in Figure 25 remains the same), the peak water level for a 1 in 50 year storm can be obtained by adding 1.74 m to any future mean water level. For example, assuming a rise in sea level from 2010 to 2050 of 40 cm, or roughly the upper limit of the high-emissions scenarios (RCP8.5) from James et al. (2014), the distribution curve will be shifted upward by that amount (broken brown line following the same curve) and the 1 in 50 year water level in 2050 will be 40 cm higher (far exceeding the current record water level). The 2050 curve is located much further to the left, showing that the current 1 in 50 year extreme water level would have a return period (average recurrence interval) of less than 2 years in 40 years time, and that today's maximum recorded water level (the level associated with Hurricane Juan) would occur on average more than once every 5 years. Extrapolating to the end of the century, these levels would occur even more frequently. Where climate change brings about a change in the storm climatology, this would also alter the shape of the extreme water-level distribution. However, in almost all cases sea-level rise will remain the dominant factor (Bernier and Thompson, 2006; Bernier et al., 2007).

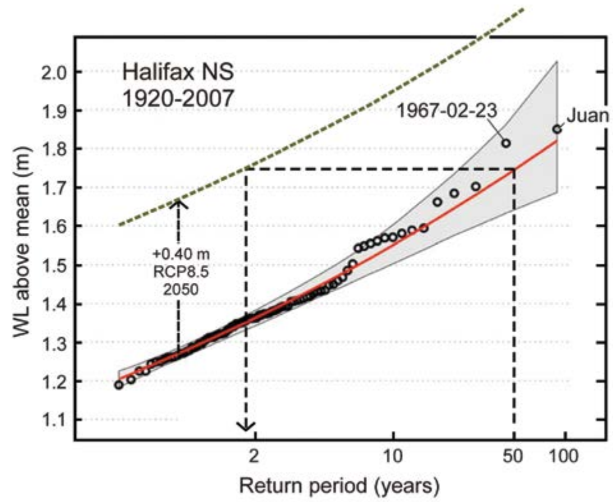

FIGURE 25: Annual maximum hourly water levels (WL; metres above mean) in Halifax Harbour, NS, 1920–2007, and associated return periods in years. The red line is the best fit to the observations achieved with a mathematical model (generalized extreme values distribution) with a 95% confidence interval (shaded envelope; *figure courtesy of K. Thompson, Dalhousie University*). This plot indicates the average recurrence interval for any given annual maximum water level today and the change in return period that results from a rise in mean sea level (*modified from* Forbes et al., 2009).

With more thermal energy in a warmer atmosphere, there is an expectation of increasing storminess on a global scale. However, at any one location, storminess may or may not increase, depending on the position relative to storm-source regions and tracks. There is *high confidence* that increases in extreme water levels will primarily be the result of increases in mean relative sea level and reductions in sea ice, but *low confidence* is attached to region-specific projections of storminess and associated storm surges (IPCC, 2013).

Interannual and seasonal variability, harbour seiches, wind waves, setup and runup are all factors contributing to extreme water levels. Ocean-surface heights vary on time scales from hours to years due to atmospheric and ocean circulation, and variability. The latter may arise from ENSO, PDO and NAO events (Box 5), seasonal warming and runoff, storms, and changes to ocean circulation. On the Pacific coast, sea level generally rises during a positive phase of the PDO in the summer and a warm (positive) phase of El Niño in the winter (Abeysirigunawardena and Walker, 2008). Extreme ENSO events can result in coastal sea-level changes of a few tens of centimetres, as indicated in Figure 19 (e.g., the large positive excursion in sea levels at the West Coast region sites at the end of 1997 and beginning of 1998). Together these factors produce short-term, large-amplitude variability that causes peak water levels to vary substantially throughout the year and from year to year. Its strong variability is superimposed on the slow rise in mean sea level, which leads to incrementally higher water levels over time where relative sea level is rising.

Globally, wind speed and wave height have increased in recent decades (Young et al., 2011). Ocean waves are a combination of swell travelling from large distances and locally generated wind waves. Over most of the world's oceans, ocean-wave energy is dominated by swell (Fan et al., 2014), although the swell contribution drops to around 50% for most seasons in the North Atlantic. Long-term (decadal) changes in wave height in the northern hemisphere (wave heights are closely associated with ENSO and PDO events in the Pacific and with the NAO event in the Atlantic) show increases in both ocean basins over the past 50 years (Gulev and Grigorieva, 2004, 2006; Wang et al., 2012). Projections of wave heights as yet give mixed results (Hemer et al., 2012, 2013; Fan et al., 2014; Wang et al., 2014a; Vose et al., 2014), although in much of the Arctic, including the Beaufort Sea, the combined effects of winds and projected reduced sea-ice concentrations give projected increases in wave heights (Khon et al., 2014). Modest swell has been observed in recent years in the Beaufort Sea and has been linked to sea-ice reductions (Thomson and Rogers, 2014). Increased wave heights contribute to increased wave setup and runup and larger waves may have greater erosive power.

Changes in sea-ice cover have important implications for wind waves reaching the coast and, therefore, an effect on extreme water levels in the North and East Coast regions. Nearshore sea ice prevents waves from breaking directly onshore and reduces wave run-up (Forbes and Taylor, 1994; Allard et al., 1998). Ice further offshore reflects waves and reduces the amplitude of waves before they reach the shoreline (Wadhams et al., 1988; Squire, 2007). More open water will lead to larger waves even if the winds are unchanged. Thus, in areas where there are projected reductions in sea ice, such as Atlantic Canada and the Arctic, there is the potential for increased extreme water levels due to wave run-up.

4.3.3 SEA-LEVEL PROJECTIONS BEYOND 2100

Global sea level will continue to rise beyond 2100. Projections presented in Figure 26 are based on carbon dioxide concentrations at 2100 (Church et al., 2013a). Estimates of projected global sea-level rise to 2500 range from less than 1 m for low-emissions scenarios[2] (including RCP2.6) to 1–2 m for intermediate-emissions scenarios (including RCP4.5) and several metres for high-emissions scenarios (including RCP8.5, Figure 26). *Medium confidence* is attached to the projections to 2300 and *low confidence* beyond that year (IPCC, 2013).

The general patterns of projected relative sea-level change in Canada beyond 2100 will be similar to the patterns of historical sea level and projections noted during the current century. The amount of sea-level rise is highly dependent on future atmospheric concentrations of carbon dioxide.

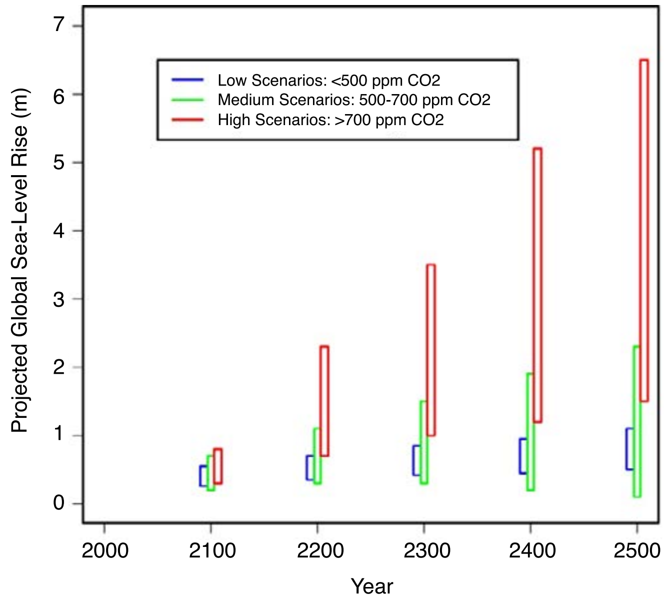

FIGURE 26: Projected global sea-level change from 2100 to 2500, based on carbon dioxide concentrations at 2100 (*based on* Figure 13.13 of Church et al., 2013a; *see* footnote 2).

Locations where the land is rising quickly will experience reduced sea-level rise, or sea-level fall, depending on the rate of land uplift and on the amount of global sea-level rise. In contrast, locations that are presently sinking will experience relative sea-level rise larger than the global value. Portions of the Maritime provinces, the Beaufort Sea coastline and the Fraser River lowland are most susceptible to relative sea-level rise larger than the global mean.

5 COASTAL RESPONSE TO SEA-LEVEL RISE AND CLIMATE CHANGE

5.1 PHYSICAL RESPONSE

In this section, we consider the implications of sea-level rise and climate change for coastal erosion and shoreline retreat, for short-term storm flooding and long-term inundation of natural and developed coasts. The importance of these impacts for coastal management is discussed in subsequent chapters (*see* Chapters 3–6).

The rise of mean sea level projected for coming decades (Section 4) will have little effect on many natural coasts, which will adjust naturally to the changing range of water levels and wave conditions. However, in some low-lying areas the impacts of mean sea-level rise will be more evident, pushing salt marshes landward up valleys (assuming available accommodation space), driving the landward migration of spits and barrier beaches with associated dune systems, killing trees

2 Low-, intermediate- and high-emissions scenarios defined in this section are based on CO_2 concentrations and with reference to Figure 13.13 of Church et al. (2013a), and do not correspond exactly to definitions used elsewhere in this report.

through saltwater intrusion and converting subaerial tundra to saline marshland. The specific response of these dynamic components of the coastal system will depend in part on a wide range of factors such as changing sea-ice extent, wave conditions, biological productivity and sediment budgets. Evidence for slow inundation of low-lying tundra along the Beaufort Sea coast and in the outer Mackenzie Delta is clear from flooded ice-wedge polygons that are typical features of this landscape, but cannot form under water (Figure 27).

FIGURE 27: Ice-wedge polygons inundated by rising sea level, Beaufort Sea coast near Hutchison Bay on the Tuktoyaktuk Peninsula, Northwest Territories. *Photo courtesy of D. Whalen, Natural Resources Canada, August 2013.*

Changes in mean sea level and shoreline erodibility (which depends on geology, wave energy and other factors) are the two dominant controls over long-term stability or migration of marine shorelines because they influence sediment supply. In the absence of other factors, rising sea level eventually inundates backshore topography, with the rate of shoreline retreat depending on the change in sea level and the land surface slope, as reflected in the long-term evolution of coasts in Atlantic Canada (Figure 4). However, if the sediment supply is sufficient to counteract the landward migration associated with sea-level rise, then the shoreline may remain stable or advance seaward as it aggrades to keep pace with the rising sea level (Curray, 1964). Examples of this can be seen in areas of local sediment abundance in various regions undergoing submergence in Canada. Small-scale barrier beaches on the west coast of Banks Island (Figure 28), a large foreland at the northern end of Baffin Island, Nunavut (St-Hilaire-Gravel et al., 2015), and many small, bayhead, prograded paraglacial barriers in Atlantic Canada attest to the importance of sediment supply (Forbes et al., 1995b; Orford et al., 2001; Forbes, 2011).

FIGURE 28: View looking north of a prograded barrier beach at Lennie Harbour, west coast of Banks Island, Northwest Territories, showing how excess sediment supply to this embayment has counteracted the effects of rising sea level. Older beach ridges on the inner part of the barrier (at the right) formed at lower sea level and have lower crest elevation than the active storm ridge at the left. *Photo courtesy of D.L. Forbes, Natural Resources Canada, July 2002.*

Shallow sloping shores subject to wave action are dynamic systems involving complex wave transformation and nearshore circulation. Rising sea level will induce a redistribution of sediment along such coasts—in its simplest form, sediment will be eroded and may be deposited offshore until a new equilibrium shore face is established. This is the premise behind a simple geometric model proposed by Bruun (1954, 1962). Although several underlying assumptions of the model are rarely satisfied, it is nevertheless widely, and often inappropriately, used owing to its simplicity (Cooper and Pilkey, 2004; New Zealand Ministry for the Environment, 2008). Some of the factors that can alter the shoreline response include complexities in the nearshore profile (outcropping bedrock, varying rock types), alongshore wind trends and variability in longshore transport, sand losses landward into coastal dunes or barrier washover.

Forecasting coastal retreat is not simple and requires analysis of the impacts of storm events and changes in historical erosion rates in conjunction with sea-level rise (Cambers, 2009; Daniel and Abkowitz, 2005; Gibbs and Hill, 2011; Government of Western Australia, 2006; New Zealand Ministry for the Environment, 2008). Additional factors include storm sequencing (Phillips, 1999; Forbes et al., 2004), changes in rates of freeze-thaw and winter slope degradation (Bernatchez and Dubois, 2008), changes in rates of thermal abrasion in ice-rich permafrost (related to rising air, sea and ground temperatures; e.g., Aré [1988], Wobus et al. [2011], Barnhart et al. [2014a]) and in wave energy (related to changing sea-ice distribution; e.g., Overeem et al. [2011], St-Hilaire-Gravel et al. [2012], Barnhart et al. [2014b]). Some data necessary for such analyses, such as historical aerial photographs, and wave and storm records, may be readily available, whereas others, such as projections of future storm frequency, severity and wave regime will need to be developed for a particular site. Complexities associated with coastal retreat include variable longshore transport (e.g., East Beach in Haida Gwaii; Box 2 and Figure 8), landward transport of sediment, which can be significant on transgressive (retreating) coasts (Davidson-Arnott, 2005; Rosati et al., 2013), inherited erosional-shore face profiles and changes in lithology as the coast retreats.

Recent work with respect to predicting changing coastal profiles may provide better tools for understanding coastal retreat. Theoretical work by Wolinsky (2009) and its application to wave-dominated coasts (Wolinsky and Murray, 2009) suggests a new approach to modelling of long-term coastal behaviour. A model proposed by Leont'yev (2003, 2004) adopts a profile retreat approach accounting for ground ice that shows some promise for projections of shoreline retreat on permafrost coasts in the Beaufort Sea.

Field evidence for coastal response to climate change and sea-level rise includes several studies that have documented accelerated coastal erosion on some of the most susceptible parts of Alaska's North Slope (Mars and Houseknecht, 2007; Jones et al., 2009; Overeem et al., 2011; Barnhart et al., 2014a). Until recently, studies of Canadian coasts did not reveal a statistically significant acceleration of coastal erosion (e.g., Solomon, 2005; Konopczak et al., 2014). However, new observations point to significant acceleration of coastal retreat in some parts of the Canadian Beaufort Sea region (Whalen et al., 2012) and Prince Edward Island (Webster, 2012). It is important to recognize that comparisons over different time intervals or for individual decades make it difficult to differentiate between a possible change in trend, as opposed to a reflection of decade-scale variability (Forbes et al., 1997). Areas with the highest shoreline-retreat rates in Canada (primarily the red zones in Figure 7) have been responding to rising sea level for a very long time and recent acceleration of sea-level rise may not yet be sufficiently large or sustained to cause a measurable response in coastal processes. The high spatial and temporal variance of shoreline retreat (Box 10) also makes detection of changes in erosion rates challenging.

BOX 10

TEMPORAL VARIABILITY OF EROSION RATES

Multitemporal photogrammetric analysis for 12 km of the north shore of Prince Edward Island demonstrates distinctive patterns of spatial and temporal response to rising sea level as a function of coastal geology and geomorphology (Figure 29; Forbes et al., 2002; Forbes et al., 2004). This shows the importance of local geological factors in addition to storm and wave forcing in determining the rate and variability of coastal change. The high temporal variability makes it difficult to detect a change in the long-term rate of coastal recession attributable to recent climate change.

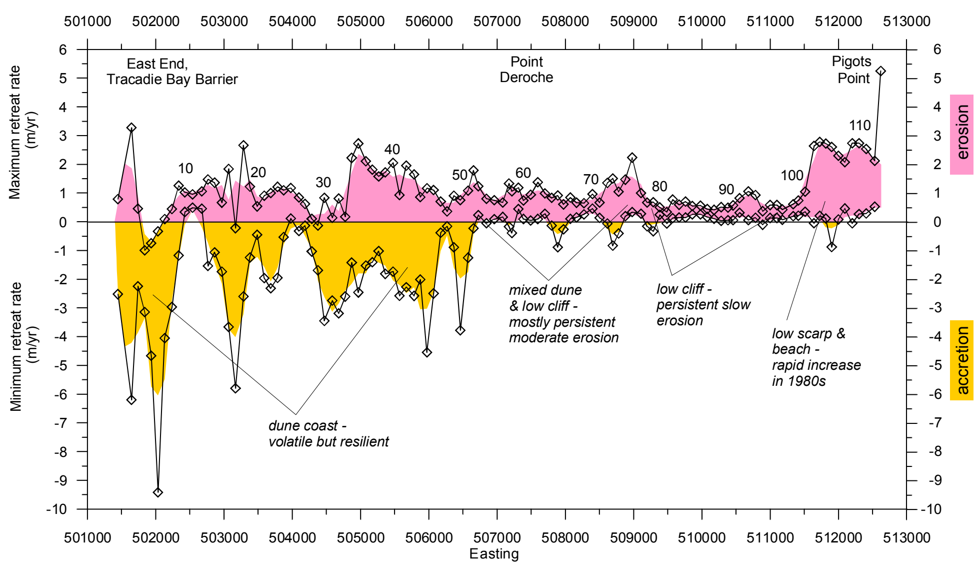

FIGURE 29: Envelope of erosion/accretion rates for airphoto intervals from 1935 to 1990 at 112 transects along 12 km of barrier-dune and low-cliff coast between eastern Tracadie Bay and Pigots Point, north shore of Prince Edward Island (Forbes and Manson, 2002). Negative values represent accretion, which consists primarily of dune recovery rather than shoreline advance.

5.2 ECOLOGICAL RESPONSE

5.2.1 COASTAL SQUEEZE

An important consideration in the response of coastal systems to sea-level rise is the potential loss of important habitat through a phenomenon known as 'coastal squeeze'. Coastal components such as estuaries, mud flats, and tidal marshes, which provide valuable ecosystem services, occupy the transition zone between the land and the sea. Under conditions of rising sea level, intertidal flats and marshes can maintain area by accreting vertically to keep pace with the rise in sea level or by migrating landward as rising water levels gradually expand upslope.

Tidal marshes have the potential to accrete vertically through increased biological productivity and feedback between the growth of salt marsh vegetation and sediment accumulation, but the response can be complex (McKee et al., 2012) and there may be a substantial lag in the marsh response (Kirwan and Murray, 2008a). Establishment of new marsh area upslope (or upvalley) can compensate for flooding of the original marsh platform by conversion of previous land or freshwater wetland areas to salt marsh in the new range of appropriate tide levels. The introduction of tidal flooding in previously nontidal wetlands can also enhance sedimentation rates (e.g., Orson et al., 1990). The extent of the new marsh system is dependent on the landward slope providing room for migration of the coastal system. Although high backshore relief can limit landward migration of flats and marshes, artificial barriers such as roads, causeways, seawalls, dikes and foundation fill are the dominant causes of coastal squeeze. The upper limits of various intertidal vegetation zones associated with particular frequencies of tidal flooding (such as mud flat, low marsh, transitional marsh and high marsh) shift landward as sea level rises (Box 11). If the high marsh biome is prevented from moving inland by natural or artificial barriers, but the transitional marsh shifts landward into the high-marsh zone, this will result in loss of high marsh and an overall loss of marsh area (Kirwan and Murray, 2008b; Hill et al., 2013).

In Nova Scotia, more than half of the 33 000 ha of salt marsh is diked (Roberts and Robertson, 1986). This suggests that, although rates of natural marsh accretion in the outer Bay of Fundy may be keeping pace with historical sea-level rise (Chmura et al., 2001), accelerated sea-level rise may pose a risk of marsh loss through coastal squeeze (Chmura, 2013). To address this concern, Torio and Chmura (2013) have developed a 'coastal squeeze index' to rank the threat of squeeze to specific marshes or groups of marshes under various sea-level rise scenarios and physiographic settings. In many cases, a combination of sea-level rise and coastal squeeze with other factors leading to marsh degradation may result in rapid marsh zone loss over a few decades (Hartig et al., 2002).

Coastal squeeze is not limited to marsh environments but can affect other components of the coastal system, from estuaries and eelgrass beds to beaches. Coastal protection structures that attempt to fix the shoreline in place can be threatened over time as the beach in front becomes narrower or disappears. In this way, the negative impacts of coastal squeeze can increase the exposure and possibly the stability of the barrier structures themselves, or critical infrastructure they may be protecting, as the natural sedimentary buffer provided by a beach is diminished (Jolicoeur and O'Carroll, 2007; Bernatchez and Fraser, 2012).

5.2.2 COASTAL DUNES

Dunes develop on coasts with excess sediment supply and winds capable of moving sand onshore to be stored in a dune system. Dune development and maintenance requires a sand supply, a positive sediment budget and, typically, vegetation to trap and hold the sand in the dunes. Carter (1991) distinguished between sand-fixing vegetation such as *Atriplex* spp. and sand-building grasses such as *Ammophila* spp. or *Elymus arenarius*. Established dunes may be colonized by a wide variety of other herbaceous and woody plants, which progressively diminish the mobility of the dunes (McCann and Byrne, 1989). In some cases, dunes also invade or overwhelm forest or woodland behind the beach (Heathfield et al., 2013).

Dunes provide valuable ecosystem services in the form of coastal protection, as both natural seawalls and erosional buffers, storing sand which is mobilized in storms and may be subsequently returned to the dunes (Ollerhead et al., 2013), thus forming "self-compensating coastal systems" (Carter, 1991). Permeable dune systems may also help to impede saline intrusion by supporting a lens of fresh groundwater that is readily recharged by precipitation and discharges into the beach or nearshore. Coastal sandy beach-dune complexes host a range of distinctive habitats and plant communities, and provide important nesting habitat for species such as piping plover (*Charadrius melodus*) and some songbirds. Small freshwater wetlands in dune slacks represent another distinctive dune-related habitat.

The sensitivity of dunes to climate change may relate to sea-level rise and erosion, possible changes in the wind regime and the response of dune vegetation to changes in seasonality, temperature, precipitation, CO_2 and other factors such as disturbance and management strategies. Canadian dune systems, at least in the east and north, are affected by winter freezing and snow cover, which can limit sand mobility (when the beach and dune faces are frozen) and retard the growth of dune grass (McCann, 1990). Under a warmer climate, the season of active sand mobility and biological productivity may be longer, and productivity may increase. The northern range of *Ammophila* spp. may also expand.

BOX 11
COASTAL SQUEEZE

The intertidal zone of the Fraser River delta, in British Columbia, is an area of high ecological value. Eelgrass (*Zostera marina* and *Zostera japonica*) meadows, mud flats and associated diatom biofilms, and various zones of the vegetated tidal marshes provide spawning habitat and sustain invertebrates, fish, and birds of various species in large numbers. The sedimentary and biological response of these components of the intertidal system to sea-level rise is not only complicated by additional factors such as reduced sediment supply (from channel dredging) and grazing of the dominant low-marsh grass *Scirpus americanus* by geese (Kirwan et al., 2008; Hill et al., 2013), but also moderated by biomass productivity, sediment trapping and vertical accretion. The landward transgression of the marsh vegetation zones is blocked by dikes across most of the Fraser Delta front, leading to substantial marsh loss over the coming century under a range of sea-level rise scenarios. Using 'median' and high rates from older projections of sea-level rise (IPCC, 2001), Kirwan and Murray (2008b) computed marsh losses of 15%–35% on Westham Island (central Fraser River delta front), of which they estimated 70% was attributable to the presence of the dike (Figure 30). The dominant high-marsh grass, *Scirpus maritimus*, is more productive than *S. americanus*, so preferential loss of high marsh zones also prejudices overall growth and sediment trapping capacity (Hill et al., 2013). The same study concluded that a 55 cm rise in mean sea level would result in a 41% loss of high marsh, 15% expansion of the transitional marsh zone, 22% loss of low marsh (to open water) and an overall marsh loss of 20%, with a biomass productivity reduction of 21%.

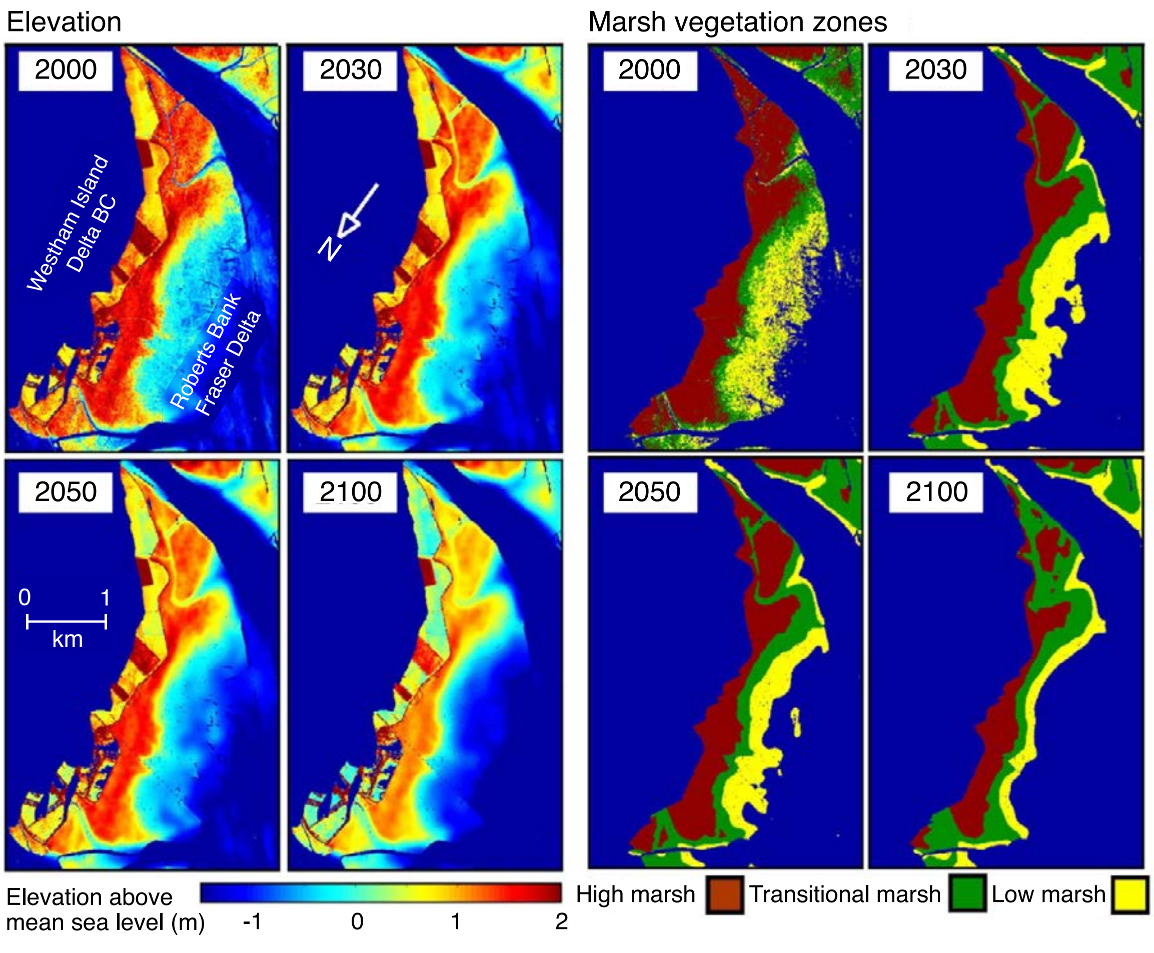

FIGURE 30: LiDAR-derived digital elevation model and projected marsh vegetation zones, Westham Island, Fraser River delta, British Columbia, under 'median sea-level rise scenario adjusted for local subsidence' (*modified from* Kirwan and Murray, 2008b). Note loss of both high and low marsh zones, where much of the high-marsh loss is due to the presence of dikes and coastal squeeze.

Even under the present climate regime, coastal dunes in parts of Canada are vulnerable to widespread degradation in response to major storms and storm sequences (Forbes et al., 2004; Mathew et al., 2010), although former livestock grazing may have played a part in the breakdown of dunes in the 19th and early 20th centuries. The modern dunes along parts of the north shore of Prince Edward Island have redeveloped over the past 90 years since the last major episode of breakdown but some areas, such as the barrier across Tracadie Bay, are still breached by extensive washover channels (Figure 5). With accelerated sea-level rise and a reduction of winter sea ice in the Gulf of St. Lawrence, combined with a less well-developed or long-lived nearshore ice complex and icefoot, the probability of storm surges with major waves and dune scarping is increased (Forbes et al., 2002, 2004). On the Pacific coast, foredune erosion on the west coast of Vancouver Island is driven by climate variability, including elevated water levels, storms and surges associated with ENSO and PDO events. With positive PDO, ENSO episodes and associated impacts on the beach-dune system have been more frequent and intense, with a recurrence interval for local dune erosion of 1.53 years (Heathfield et al., 2013). However, with falling relative sea level and a high onshore sand supply, there is rapid shoreline progradation, enhanced by the sediment trapping capacity of large woody debris (Eamer and Walker, 2010).

5.2.3 COASTAL WETLANDS, TIDAL FLATS AND SHALLOW COASTAL WATERS

Tidal saline, brackish and freshwater wetlands provide major ecosystem services: coastal protection; provision of spawning and nursery habitat for aquatic species, including commercial fish; critical nesting and feeding habitat for many types of birds; nutrient absorption; and sediment retention. Furthermore, coastal salt marshes may represent important sinks for carbon, storing more carbon per unit area than freshwater peatlands and releasing little in the way of greenhouse gases (Chmura et al., 2003).

Salt marsh stability under climate change is affected by changes in sea level and flooding frequency; changing salinity, temperature, pH and freshwater inputs; nutrient and pollutant loads; sediment supply, plant productivity and accretion rates; coastal squeeze; frontal erosion; direct and indirect effects of sea ice; and disturbance from avian grazing, drainage, excavation, infilling, diking, and other development in land use. Where sediment supply and biological productivity are sufficient, salt marshes can accrete at rates sufficient to keep pace with sea-level rise, developing thick sequences of organic-rich sediment or peat (e.g., Shaw and Ceman, 1999). However, where the supply of mineral sediment is limited, organic accumulation may not be able to keep pace with the rate of sea-level rise and a gradual drowning of coastal wetlands may occur.

The implications of rising temperatures, changes in precipitation, salinity and CO_2 for salt marsh productivity are equivocal (McKee et al., 2012). Outcomes may vary with species composition, antecedent conditions, specific combinations of salinity and CO_2 and proximity to limiting conditions for individual species (Erwin, 2009). The timing and quantity of freshwater delivery to marshes may also have an important influence on marsh growth and this may depend not only on regional precipitation and water balance, but also on development and other changes in land use within adjacent drainage basins (Scavia et al., 2002). Some coastal wetlands located in the vicinity of large deltas or in areas of regional glacial isostatic subsidence, such as Nova Scotia, are competing with rates of local relative sea-level rise significantly higher than the global mean (Adam, 2002). Even if they have been keeping pace in vertical growth with past rates of sea-level rise, this is no guarantee that they will continue to do so with accelerated sea-level rise over coming decades. Rising sea levels also increase the probability of extreme surge and flooding events that may introduce saltwater into previously freshwater systems (e.g., Pisaric et al., 2011).

Because ice rafting is believed to enhance rates of sediment delivery to salt marshes (Wood et al., 1989; van Proosdij et al., 2006), a future reduction of sea ice with warmer climate may also result in lower sediment supply. The role of ice in the redistribution of, and colonization by, salt marsh cordgrass (*Spartina alterniflora*; van Proosdij and Townsend, 2006) and in the dispersal of macro-invertebrates in tidal flats (Drolet et al., 2012) may also be affected by its diminished occurrence (*see* Chapter 4). At the same time, reduced ice cover may increase rates of edge erosion by waves in winter.

Tidal flats, particularly in the Bay of Fundy and Fraser River delta, provide critical feeding habitat for migratory birds (Hicklin, 1987; Hill et al., 2013). Globally, there is concern about projected losses of intertidal habitat for birds (Box 12; Galbraith et al., 2002).

BOX 12

ECOLOGICAL IMPACTS IN THE FRASER RIVER DELTA

The presence of dikes and rising relative sea level over the tidal flats and salt marshes of Roberts Bank (Fraser River delta, British Columbia) suggest that coastal squeeze may lead to significant loss of surface area available to migratory and overwintering birds (Hill et al., 2013). Furthermore there is a potential conflict between the need for land backing the intertidal flats to conserve avian habitat and the high value of the land in demand for other uses. Hill et al. (2013) summarized projections of key impacts on major components of the intertidal system as follows:

- Marsh – negative impacts (*low–moderate confidence*): erosion of marsh due to coastal squeeze and increased wave attack, mitigated by natural marsh accretion up to a threshold rate.
- Mud flat – negative impacts (*low confidence*): projected 45%–63% reduction in area due to coastal squeeze, may be mitigated by sedimentation over present marsh area, but exacerbated by increased storminess and storm-wave action.
- Eelgrass – no impact (*moderate–high confidence*): high rates of eelgrass expansion suggest that eelgrass would migrate landward to keep pace with changes in depth.
- Biofilm – negative impacts (*low confidence*): area likely to decrease with reduction in area of mud flat; however, higher wave energy may lead to coarsening of the sediment and reduced biofilm productivity.
- Predation on birds – negative impacts (*low confidence*): likely to increase due to landward migration of optimum feeding grounds.

The low level of confidence reported for most of these impacts suggests the need for more work on the direct biophysical and secondary ecological impacts of climate change in coastal intertidal and subtidal systems.

5.3 VISUALIZATION OF COASTAL FLOODING

Interest in extreme water levels relates to questions not only about how high or how frequently flooding will occur, but also to what will be flooded. Extensive work has been undertaken over the past 15 years to simulate present and future flood events in communities or other settings where valued assets, including important habitat, may be affected (Box 13; *see* Chapter 3; Webster and Forbes, 2006; Bernier et al., 2007; Forbes et al., 2009; Bernatchez et al., 2011).

6 SUMMARY AND SYNTHESIS

Canadian marine coasts are highly variable and naturally dynamic systems. The impacts of climate change, currently manifested primarily in terms of changes in sea-ice cover, will become more pronounced over coming decades. Increased extreme water levels are expected to drive increased rates of coastal erosion. Diked areas, coastal regions with little relief and coastlines composed of unlithified sediments are more susceptible to erosion than high, rocky coastlines. In the Arctic, increased air and water temperatures will further degrade and thaw permafrost, loosening ice-bonded sediments and also contributing to erosion (Forbes, 2011). In the near term, climate variability, expressed seasonally and through various interannual oscillations, will continue to play a dominant role in determining air and water temperatures, storm strength, wave heights, sea level and other factors pertinent to coastal regions in Canada.

Long-term changes in the frequency and intensity of extreme coastal water levels and flooding in Canada will be primarily driven by changes in mean sea level, although tides, sea ice, storm surges and waves will continue to play prominent roles. Significant rates of historical changes in relative sea level, largely related to glacial isostatic adjustments, are highly variable across Canada (e.g., >3 mm/year of sea-level rise at Halifax, Nova Scotia and >9 mm/year of sea-level fall at Churchill, Manitoba over the past century), making it a challenge to identify the effects of accelerated sea-level rise associated with climate change. These impacts will be more evident in subsequent decades, as rates of global sea-level rise increase further. Regions experiencing increases in mean sea level will see increasingly more frequent water levels that cause flooding today and higher extreme water levels.

In the near term, climate change impacts on Canada's coasts will continue to be most evident in terms of extreme weather events and, in the East and North Coast regions, decreasing sea-ice cover. There are important linkages between the two: when present, sea ice serves to protect coasts from potential wave impacts associated with severe storms and conversely the absence of sea ice can lead to enhanced coastal erosion. Impacts of extreme weather events are not limited to wave erosion and storm-surge flooding, but also include strong winds and heavy precipitation that can damage infrastructure and cause flooding of coastal communities and assets.

BOX 13

FLOOD SIMULATION

A light detection and ranging (LiDAR) technique is used to create high-resolution digital models of terrain surfaces, including buildings and trees where present; from these, digital elevation models can be derived as a basis for flood simulation (Figure 31). This technique, now widespread, was pioneered in Canada about 15 years ago (e.g., Webster et al., 2002; Webster and Forbes, 2006).

In the output produced for public communication, a digital image can be substituted to allow stakeholders to relate to historical and/or projected flood levels through recognition of buildings or other features. In the case of historical flooding in Tuktoyaktuk (Figure 32), the visualization also illustrates the high rates of historical coastal erosion. Mean retreat at the northwestern point from 1935 to 1971, prior to several phases of shore protection, was 3.8 m/year (Rampton and Bouchard, 1975). During a single major storm in September 1970, the same point retreated by more than 13 m in a few hours (Public Works and Government Services Canada, 1971; Rampton and Bouchard, 1975).

It should be noted that most flood simulations utilize still-water models that account for openings through culverts or bridges but do not include the dynamics of flow. In some situations with rough or complex flow patterns, it may be desirable to incorporate a dynamic model and the still-water simulation may overestimate flood extent (Webster et al., 2014).

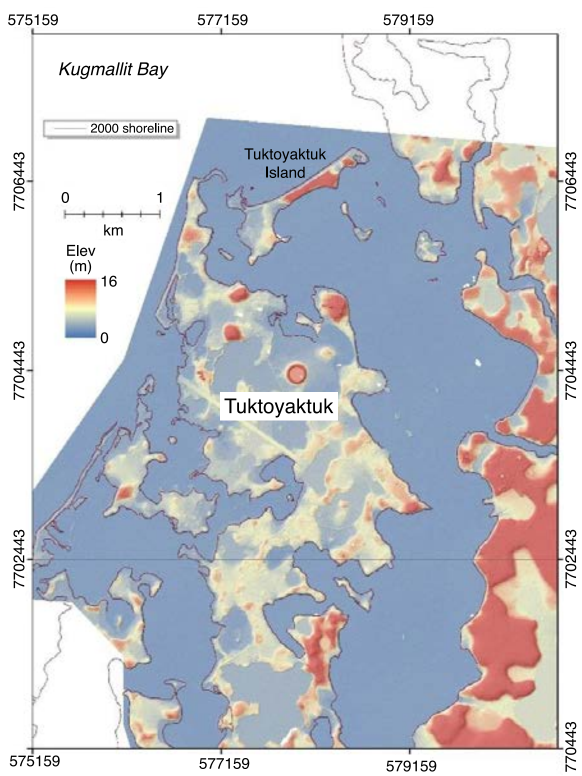

FIGURE 31: LiDAR-derived digital elevation model for Tuktoyaktuk, Northwest Territories. Bare-earth model with vegetation and buildings removed forms the basis for flood simulation (Forbes et al. 2014b).

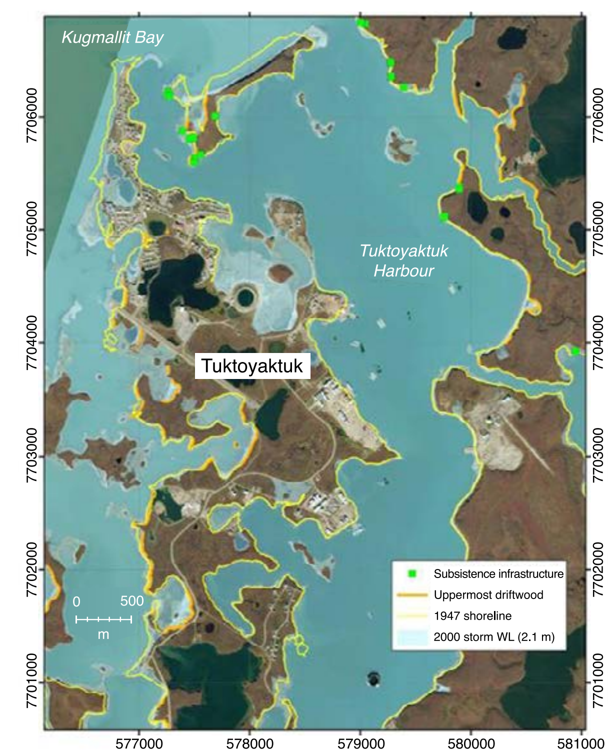

FIGURE 32: Long-term coastal erosion (1947–2010) and visualization of storm flooding in 2000 at Tuktoyaktuk, Northwest Territories. Flood simulation conducted on LiDAR-derived digital elevation model. A high-resolution satellite image taken in 2010 by GeoEye Inc. is inserted as backdrop to facilitate public interpretation (Forbes et al. 2013). *Contains material from* Digital Globe Inc. Abbreviation: WL, water level.

Ecosystem services provided by coastal systems will also be affected by rising sea levels, reduced sea ice and other climate effects such as changes in temperature and precipitation, storminess and wind regimes, teleconnections with regional sea-level anomalies, CO_2 enhancement or acidification of coastal waters. The loss or degradation under climate change of coastal ecosystems (beach-dune complexes, tidal flats, coastal wetlands, seagrass meadows and estuaries) leads to direct and indirect impacts (Carter, 1991). First-order biophysical impacts affect the delivery of ecosystem services; second-order impacts affect coastal protection, water supply, recreation, agriculture and aesthetics; and third-order impacts influence policy and governance, with implications for conservation, habitat protection, protection of property and critical infrastructure, food security and other contributors to sustainable development.

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CHAPTER 3: THE COASTAL CHALLENGE

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1 INTRODUCTION

Canada's coasts, the longest in the world, are a defining element of our national identity. Canadian port cities have been and continue to be gateways to our nation for international trade and immigration, and as our link to the larger world. Coasts are important to Canadians whether or not they live near the shore, for their natural beauty, biodiversity, resources or the contributions made to human society, culture and the economy.

Inuit and First Nations people have throughout history depended on coastal areas for food, and have deep spiritual and cultural ties to the shore. Early Europeans first settled along the Atlantic and Pacific coasts, where they developed farms, fisheries and industries, and built military and mercantile trade cities, before venturing further inland. Historically, Canada's coastal economies were largely based on the processing and distribution of important goods and services (e.g., food, transportation, mineral resources and energy). In recent times, however, coastal communities have become increasingly urban, consumer-driven spaces and centres of research, technology and innovation that provide goods and services to the global marketplace.

As climate and seasonal weather continue to change, coastal environments are being altered over a relatively short period of time (Lane et al., 2013; *see also* Chapter 2). Anticipating the implications of, and understanding the challenges associated with, these changes are first steps toward preparing to respond. Coastal communities in Canada are already taking action to reduce risks associated with changing conditions and to promote the benefits of new or expanding opportunities (*see* Chapters 4–6). Additional information on sectoral impacts and adaptation responses can be found in Warren and Lemmen (2014).

This chapter provides an overview of ongoing and projected changes in climate and other environmental factors that could cumulatively affect the sustainability of coastal environments and coastal societies. The chapter also summarizes key elements in planning approaches to adaptation, and describes how planning for adaptation is being used in some coastal areas to plan for, and respond proactively to, altered weather patterns and a changing climate. More detailed information on each of Canada's coastal regions (East, North and West) is found in Chapters 4–6.

2 CHANGING COASTS

The coastal landscapes of Canada are a diverse array of terrestrial, aquatic and marine environments that link the land to the Atlantic, Arctic and Pacific Oceans (*see* Chapter 1). Human activities have significantly altered terrestrial coastal landscapes and shorelines in all regions of the country. For instance, changes in land cover and land use include replacement of natural land cover with harvested forests, cultivated farmlands, and villages, towns and cities. Rivers, lakes and estuarine areas have been altered by the construction of dams and reservoirs, by water extraction for irrigation and drinking water, and by infilling, dredging and channelization. Intertidal and nearshore areas have been reclaimed (i.e., diked) or infilled for farming or development. Shorelines themselves, which are by nature highly dynamic systems (*see* Chapter 2), have also been reshaped by the construction of dikes and seawalls, breakwaters, causeways and dock facilities, and by dredging and infilling. Even along remote northern coasts, human impacts are increasingly evident as the Arctic becomes more accessible for development (Forbes, 2011; Keeling, 2012; ArcticNet, 2013).

Climate change is putting additional stress on coastal regions, and areas and ecosystems already under pressure from human activities may be impacted the most. The widespread effects of these cumulative stresses on coastal regions throughout the world have been summarized into impact categories that include (Munang et al., 2009; Simpson et al., 2012; Arlington Group et al., 2013; Lane et al., 2013):

- altered ecosystems and landscapes, and loss or reduction in ecosystem services;
- increasingly unstable shorelines;
- inundation of and damage to lands, residences, infrastructure, industries and cultural assets;
- contamination of water supplies;
- increasing costs for protection, maintenance, upgrading, restoration and insurance;
- reduced investment potential and/or emerging new economic opportunities; and
- altered life styles, impacts to health and well-being, and loss of life.

Depending on local factors (e.g., exposure, vulnerability), some or all of these impacts will be observed in coastal environments and communities throughout Canada. This section provides an overview of how different shifts in climate (e.g., increased temperature, sea-level rise, changes in storminess) would affect ecosystem health and social and economic well-being by magnifying the effects of existing trends, and presenting new challenges and opportunities in Canada's coastal regions.

2.1 ECOSYSTEM HEALTH

Throughout the world, coastal ecosystem health has been deteriorating in response to both direct and indirect impacts of human activity (Millennium Ecosystem Assessment, 2005a, b; European Environment Agency, 2006a, b; Lotze et al., 2006; UNEP, 2010). Ecosystems and species can be directly impacted through deforestation, overfishing, introduction of invasive species and development in the nearshore region (e.g., hardening shorelines, diking saltmarshes for agriculture, infilling nearshore waters for waterfront development and constructing bridges and causeways). Chemical and biological pollutants (including nutrients) generated by land-cover changes and land-use activities in the watershed, or as discharges from marine activities, can indirectly impact coastal ecosystems. Damming or channelization of surface water can change the volume and timing of fresh-water flows to marine coasts. In Canada, the magnitude of human impact on coastal systems can be significant, particularly in southern, more populated areas of the country (Ban and Alder, 2008). For example, more than two-thirds of the coastal salt marshes in the Atlantic Provinces have either been drained and converted to agricultural land or diminished by industrial or urban development (Austen and Hanson, 2007).

RESILIENT ECOSYSTEMS

Ecosystems, populations and species are considered healthy if they demonstrate resilience to stress and are capable of managing their structure and functioning over time (Haskell et al., 1992; Costanza and Mageau, 1999). Resilience is a measure of an ecosystem's ability to withstand stress from outside influences, the capacity for recovery from pressures and stress, and the degree to which restoration of pre-stress conditions can be attained (Costanza and Mageau, 1999; Rapport and Whitford, 1999).

Ecosystems are continually adjusting to natural changes in internal and external physical, chemical and biological factors that occur temporally and spatially, and affect ecosystem structure and function. Resilience can determine whether the effects of change are negative, positive or merely different. Changes in ecosystem health can affect the ecosystem services (e.g., food, water, transportation, resources) upon which human society depends.

For much of Canada's coasts, the state of ecosystem health remains poorly documented and/or understood (Mercer Clarke, 2010, 2011). Although data on the environmental effects of industrial operations are collected to meet regulatory requirements, information on broader coastal conditions can be limited even in populated areas of the coast, and is especially sparse for much of northern Canada. Available information is also often outdated, spatially and temporally fragmented, and/or collected using nonstandardized research and reporting methods, making it difficult to render broad conclusions on the current status and trends in the health of coastal ecosystems, population and species (Hutchings et al., 2012). Increased stresses on coastal ecosystems arising from climate change, when added to the pressures of human use, may overwhelm the capacity of natural systems to absorb impacts without potentially being permanently and negatively altered.

2.1.1 ECOSYSTEM SERVICES

Ecosystems provide services and benefits that support the well-being of society through a combination of ecological, chemical and physical processes (Thrush and Dayton, 2010). Ecosystem services can be grouped into four categories (Lotze and Glaser, 2009; Snelgrove et al., 2009; de Groot et al., 2010): 1) provisioning services (e.g., food, energy and transportation); 2) supporting services (e.g., photosynthesis, carbon storage, water and habitat); 3) regulating services (e.g., climate regulation, water purification, waste treatment and protection from physical hazards); and 4) cultural services (e.g., spiritual support, aesthetics, recreation, education). Unsustainable resource use can decrease the quantity, quality and access to ecosystem services, and climate change will likely exacerbate the impacts of other stressors, such as overfishing, disposal of contaminants, nutrient enrichment and loss of habitat to deforestation and urbanization (Figure 1; Mooney et al., 2009; Federal, Provincial and Territorial Governments of Canada, 2010; Hounsell, 2012).

Despite increasing reports of deterioration within oceanic and coastal environments, the value of ecosystem services continues to be largely unrecognized, and there has been little work in Canada to identify the economic contributions of services such as protection from coastal storms, waste reception and filtering, and oxygen production. At the global scale, one study (Costanza et al., 2014) estimated that, in 2011, the total annual worth of ecosystem services to the global economy was US$125 trillion. The impacts of changes in climate on specific ecosystem services, such as food security (Rice and Garcia, 2011) and coastal tourism (Scott et al., 2012), have also been studied. Although Canadian economic studies have reported on the value of ocean services (e.g., fisheries, transportation) to the nation's economy (Gardner Pinfold Consulting Economists Ltd., 2009a, b), it is difficult to extract information on the value of less tangible services, such as waste disposal and protection from weather events.

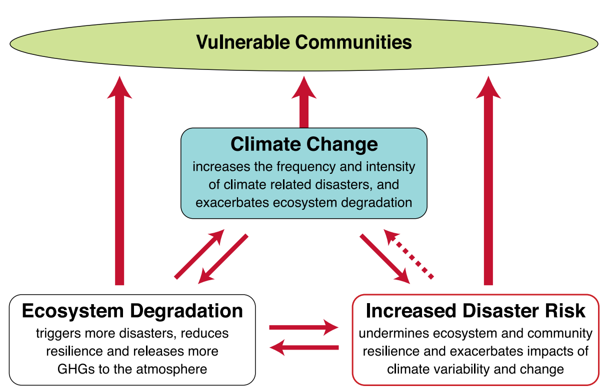
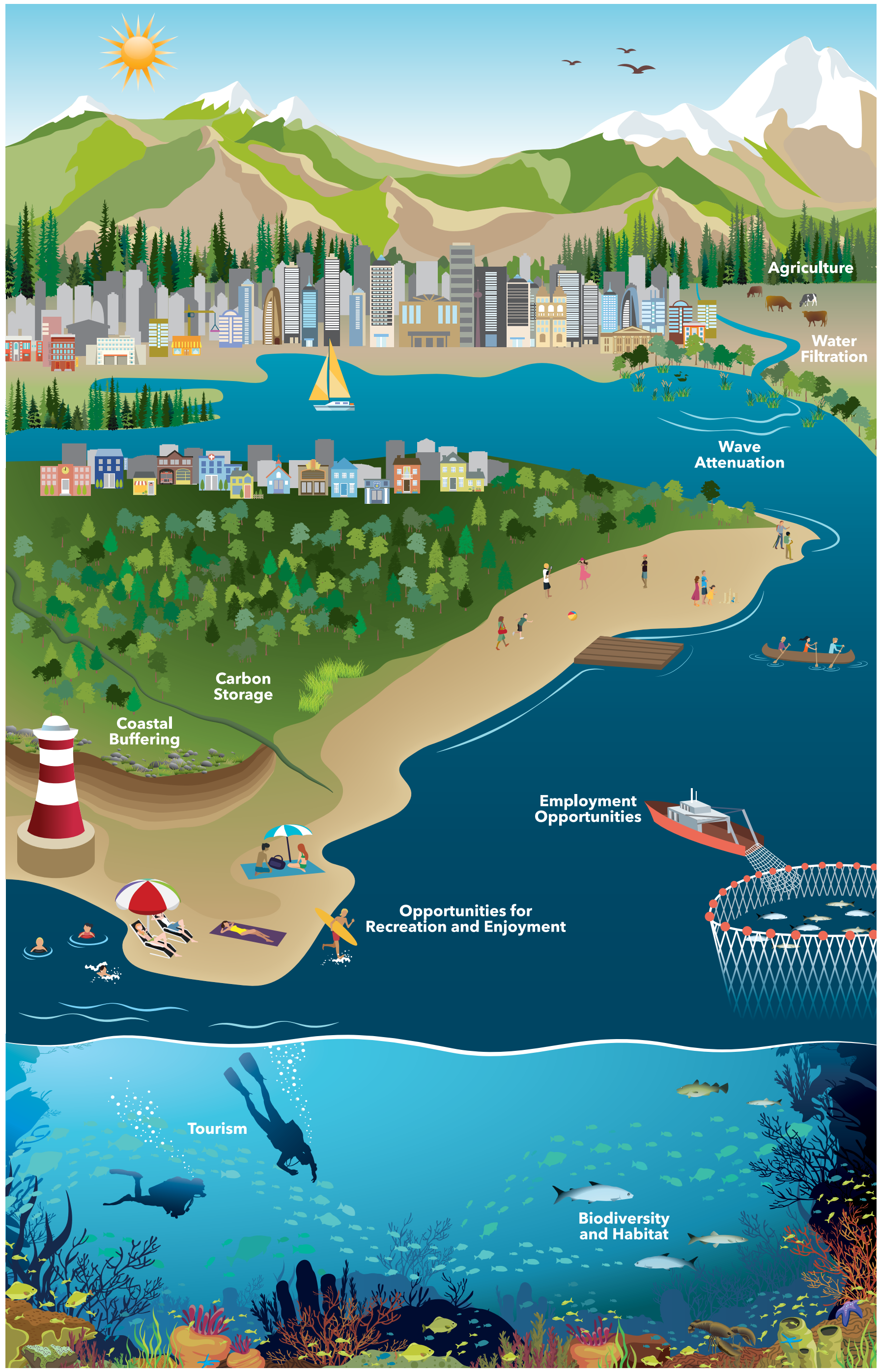


FIGURE 1: Linkages among climate change impacts, ecosystem degradation and increased risk of climate-related disasters (Nantel et al., 2014, *modified from* Munang et al., 2009).

Impacts on Canadian coastal biodiversity resulting from physical and biological changes associated with climate change, when coupled with other anthropogenic pressures, have implications for the sustainability of ecosystem services and ultimately for the social and economic well-being of coastal communities (Berteaux et al., 2010; Hutchings et al., 2012). Conservation of coastal biodiversity can include the management of existing protected areas, as well as the development and implementation of new parks, wildlife reserves and marine protected areas. Guidance for the design of networks of resilient marine protected areas in Canada (Commission for Environmental Cooperation, 2012), and adaptation planning for existing coastal protected areas (Parks Canada, 2007), are examples of early attempts to prepare ecosystems and communities for climate change.

Planned adaptation that uses an ecosystem-based approach employs environmentally sustainable land-planning techniques that focus on maximizing the resilience in both natural and human communities through protection of biodiversity, restoration of ecosystem functioning and sustainable use of resources (Nantel et al., 2014). Nantel et al. (2014) summarized the following core adaptation actions for supporting ecosystem resilience:

- protect intact ecosystems, species diversity and ecosystem function
- link protected areas using sustainably managed landscapes and waterscapes
- restore degraded ecosystems and support species recovery
- maintain or restore natural variability in the ecosystem of interest
- protect and manage range limits
- use active management approaches, such as assisted migration, where appropriate



COASTAL AND MARINE ECOSYSTEM SERVICES (FIGURE 2)

Although often taken for granted, the goods and services provided by coastal and marine ecosystems would be difficult—if not impossible—to replace. These benefits include protection from coastal storm damage, the filtering of toxic substances and nutrients, production of oxygen, and sequestration of carbon dioxide. In addition, fishing, tourism, and recreation provide economic benefit, and support ways of life that contribute to the social and cultural wealth of the nation (Pew Oceans Commission, 2003, p. 7).

FIGURE 2: Coastal ecosystem services (*modified from* Moser et al., 2014).

2.2 COASTAL SOCIETY

In the context of this report, a coastal society comprises communities situated on or near a marine shoreline, as well as the people who have important economic and/or cultural links to the shore. Coastal society in Canada is characterized by complex settlement patterns, population densities and human use of landscapes. Many Canadian coastal communities have demonstrated both resilience to environmental and economic stresses, and a willingness and capacity to adapt. Resilience, as applied to society, refers to the ability of human communities to withstand and recover from stresses or shocks, such as environmental change or social, economic or political upheaval (Adger, 2000; Stockholm Resilience Centre, 2015). Resilience is the capacity of the system to rebuild itself if it is damaged, and can include positive alterations to key elements if those alterations contribute to reducing vulnerability and improving well-being.

Although statistics on Canada's coastal populations can be difficult to obtain, Manson (2005) estimated that more than 13% of Canada's population resides within 20 km of a marine shoreline, on only 2.6% of Canada's total land area. Throughout Atlantic Canada and on much of the coast of British Columbia, population density drops with distance from the shore (Manson, 2005). In Nunavut, all but one of the 25 communities are located on the coast. Aging population is a significant trend in some regions, particularly in parts of British Columbia and rural areas of Atlantic Canada (CBCL Ltd., 2009; Natural Resources Canada, 2014b). In contrast, the population of the North is younger, with only 3.3% of the people in Nunavut being more than 64 years old (Statistics Canada, 2012). Coastal demographics in some areas may also have been affected by restructuring in national and international economics and trade, as well as by economic changes in local primary industries, such as the closure of the Atlantic groundfish fisheries, exploration for and development of offshore deposits of oil and gas, and increased interest and investment in coastal tourism (Dolan et al., 2005).

Since the early 1900s, Canada's coastal populations have, like those throughout much of the rest of the country, been shifting from predominantly rural to predominantly urban. Coastal cities, such as Victoria and Vancouver, BC, Québec, QC, Saint John, NB, Charlottetown, PE, Halifax, NS and St. John's, NL, are hubs of economic and cultural activity. In the North, Inuvik, NT, Iqaluit, NU and Happy Valley–Goose Bay, NL are important regional service centres, as well as essential ports for the import and export of goods. Iqaluit and other northern communities are responding to rapid societal and cultural change resulting, in part, from economic growth and diversification, while also dealing with increasing rates of change in the local environment.

The following sections provide an overview of the potential effects of a changing climate on important elements of coastal society.

2.2.1 INFRASTRUCTURE

Canadian coasts support an array of ports, harbours and marinas located in cities, towns and villages. Larger ports, under the jurisdiction of individual marine Port Authorities, handle more than $160 billion in cargo each year (Association of Canadian Port Authorities, 2007). Small-craft harbours in towns and villages contain more than $2 billion in infrastructure, which is vital to the fishing and transportation sectors, with nearly 90% of all fish landings in the country taking place at a small-craft harbour (DFO, 2014a). In recognition of the potentially significant economic impact that climate change presents to coastal industrial infrastructure, the Province of Nova Scotia commissioned the development of a tool to assess the vulnerability of infrastructure used for fishing and aquaculture activities (CBCL Ltd., 2012).

There are numerous recent examples of damage to coastal transportation infrastructure and transport delays caused by extreme weather events and seasonal conditions (Andrey et al., 2014). Heavy weather has caused damage and delays for ferries and cargo ships, and, in some cases, resulted in periods of isolation (e.g., Îles de la Madeleine ferries were trapped in ice during the 2014–2015 winter; CBC News, 2015). Many coastal roadways were constructed to closely follow shorelines and rivers, and often use bridges and causeways to complete their linkages. These transportation systems are proving to be particularly vulnerable to extreme climate events, especially when higher sea levels and storm surges are coupled with heavy precipitation (Case Study 1).

CASE STUDY 1

HURRICANE IGOR, NEWFOUNDLAND, 2010

(Environment Canada, 2014; Masson, 2014)

In September 2010, Hurricane Igor arrived just off the coast of the Avalon Peninsula on the Island of Newfoundland. When it hit Newfoundland, the system was still classified as a hurricane but was rapidly downgraded to become a post-tropical storm. Nevertheless, hurricane-force winds (120–140 km/h) ripped through parts of Newfoundland, forcing 22 towns and villages to declare states of emergency. As Igor continued its path north, roads and bridges across the island were washed away, isolating more than 150 towns (Figure 3).

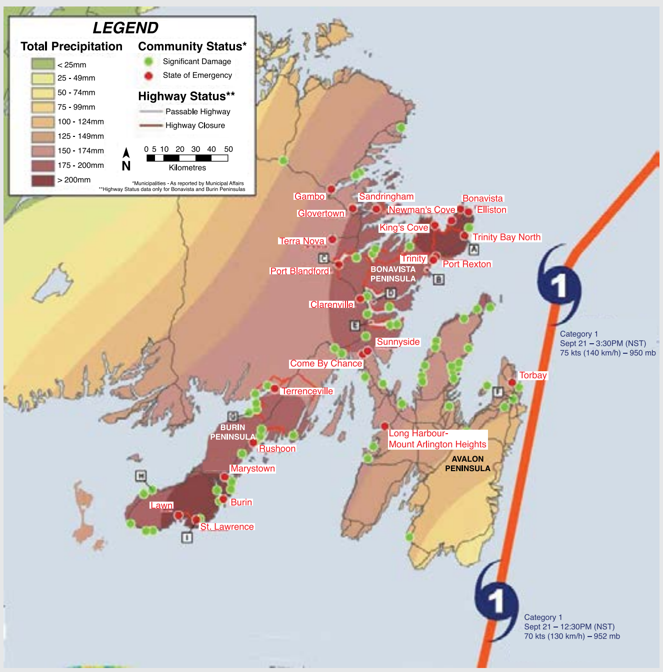


FIGURE 3: Storm track for Hurricane Igor in eastern Newfoundland, September 2010, including areas that suffered significant damage (Government of Newfoundland and Labrador, 2010).

Igor's force was supplemented by a strong upper-air weather front that was tracking west to east across the Island, creating a complex weather system of wind and rain that had a massive circulation and reach. Peak winds reached 172 km/h in some locations. New 100-year records were set for rainfall, including 239 mm that fell in only 2 hours in the community of St. Lawrence on the Burin Peninsula. Approximately 70 000 people lost power, fuel supplies ran short, and there were boil-water advisories across the province. The heavy rains washed out roads, bridges and causeways (Figure 4). The Trans-Canada Highway and main access roads (in some places, the only road access) were closed because of washouts, flooding and damage to asphalt.

FIGURE 4: Washout of highway and bridge near Port Rexton, NL. *Photo courtesy of Fire and Emergency Services, Newfoundland and Labrador.*

In a province famous for its storms, Igor was a destroyer. The storm permanently altered the landscape and changed the lives of many families. Insurance claims exceeded $65 million, the largest weather-related set of claims in the province's history. Uninsured losses have been estimated to be as high as $200 million. Damage to the environment was not calculated. In recognition of the intensity of this weather event, Environment Canada and the World Meteorological Organization have officially retired the name Igor from the rotating list of names for Atlantic hurricanes.

Other public infrastructure in Canada, such as potable water supplies, storm-water management and disposal systems, government buildings and cultural assets, provide needed services upon which communities and industry depend. Recent studies have revealed that much of the public infrastructure in Canada's coastal regions is currently in poor condition and vulnerable to the negative impacts of climate change (Stanton et al., 2010). In their assessment of Canadian municipal infrastructure (drinking-water systems, waste-water and storm-water networks, and municipal roads) for Canada as a whole, Félio (2012) reported that 30% was ranked between 'fair' and 'very poor'. More than half of the roads were determined to be in fair to very poor condition, with an estimated cost to repair of $91.1 billion (2012 dollars; Félio, 2012).

Changing climate exacerbates many risks to existing infrastructure (Andrey et al., 2014). For example, most waste-water treatment systems in coastal areas are located close to the shore to facilitate gravity feed of waste-water to the plant (reducing pumping costs), as well as disposal of the treated effluent into nearby receiving waters (J.D. Clarke, personal communication, 2014). Existing plants in these locations are vulnerable to sea-level rise and to flooding from climate change–enhanced storm surges and wave action. Although spending on public infrastructure in Canada has increased (Figure 5; Infrastructure Canada, 2011), much remains to be done. Future investment in both repairs and new construction would benefit from consideration of existing and anticipated changes in environmental conditions resulting from climate change (e.g., sea-level rise, storminess, increasingly intense precipitation events).

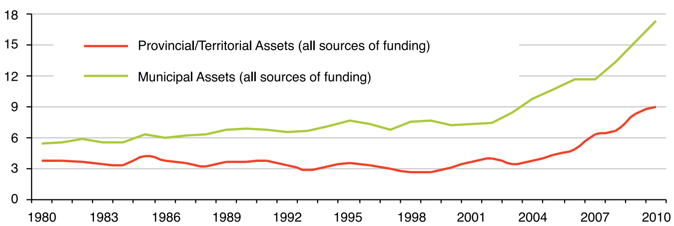


FIGURE 5: Government investments ($ billion) in core public infrastructure (bridges, roads, water, waste-water, transit, and cultural and recreational facilities; Infrastructure Canada, 2011).

Historically in coastal regions, buildings such as homes, businesses, schools and churches were generally constructed short distances inland of the shore on lands that were considered to be reasonably safe from marine hazards (such as high tides and storm surges) and favourable for other reasons (e.g., farming activities and road access). In many communities, early routes for coastal roads followed shorelines and river valleys. Many of these roads have been improved but not relocated to higher ground. Over time, some shorelines have been dramatically altered as a result of coastal dynamics, storm events, rising sea level and human construction (*see* Chapter 2), resulting in loss of land that acted as a natural buffer for communities against wave action, or deterioration of constructed protective measures such as breakwaters and seawalls. Many of the oldest cultural assets and historical sites (e.g., Fortress Louisburg, Cape Breton, NS) are increasingly threatened as a result of sea-level rise.

In recent decades, changing social norms and increasing demands for waterfront living have resulted in considerable alterations to settlement patterns. Many coastal communities are now characterized by significant residential and commercial waterfront development that has replaced traditional docks, wharves and warehouses. These new developments are, in many ways, more vulnerable to rising sea levels and severe weather. Even in areas protected by dikes or seawalls, there is a growing potential for higher waves, tides and/or storm surges to overtop existing structures (*see* Chapter 2). Coastal provinces such as British Columbia have been addressing changes in sea level and have developed new guidelines for maintenance and repair of existing dikes that consider future sea-level rise (*see* Chapter 6; Bornhold, 2008; Ausenco Sandwell, 2011c; Delcan, 2012).

Climate change poses an array of challenges both to aging infrastructure and to the codes and criteria by which new facilities will be sited, designed, constructed and maintained (Box 1; Félio, 2012; Boyle et al., 2013). Most modern infrastructure has been designed and built to standards based on historical climatic conditions. These criteria may no longer be sufficient to withstand expected changes in such parameters as wind and snow loading, or to respond safely to more severe weather events (Auld and MacIver, 2007). Since 2005, there has been a growing body of peer-reviewed literature focused on the process of adapting Canadian infrastructure to climate change (Figure 6). Use of tools such as the engineering-protocol assessments of the Public Infrastructure Engineering Vulnerability Committee (PIEVC) has shown that well-maintained infrastructure is more resilient to a changing climate, as gradual changes in temperature and precipitation patterns can often be addressed through regular maintenance and upgrade cycles, or through adjustments to operation and maintenance policies and procedures (Andrey et al., 2014).

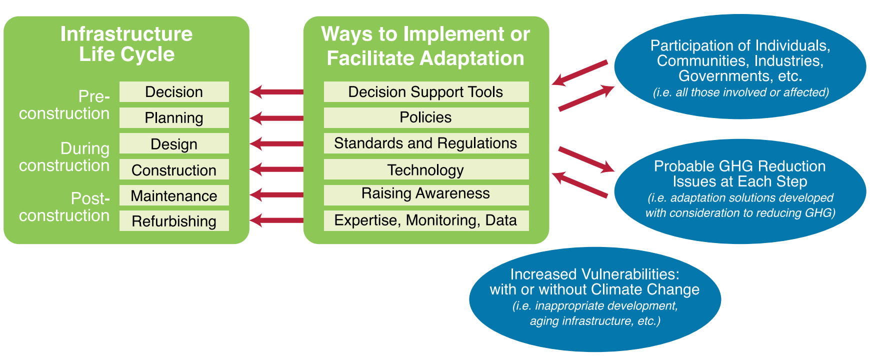


FIGURE 6: Adaptation in the infrastructure life cycle (Larrivée and Simonet, 2007).

BOX 1
CODES, STANDARDS AND RELATED INSTRUMENTS (CSRI)

(Andrey et al., 2014, p. 239)

The Public Infrastructure Engineering Vulnerability Committee (PIEVC), led by Engineers Canada, reviewed its water-resource–infrastructure case studies to identify recommendations for changes to Codes, Standards and Related Instruments (CSRI). Water-resource infrastructure is subject to many types of CSRI, including regulations, codes and standards, local government bylaws and national guidelines. The PIEVC found that the climate information used in the development of CSRI was not always readily available or identified, meaning that updating CSRI is not just a matter of updating the climate information contained within them. Recommendations for action on CSRI reflect the loss of stationarity in climate and the need to enable adaptation, and include 1) improving climate data; 2) addressing incremental options over the life cycle of infrastructure; 3) expanding the scope of CSRI to cover physical, functional and operational performance; and 4) increasing the flexibility in design to adapt to climate change (Public Infrastructure Engineering Vulnerability Committee, 2012).

2.2.2 ECONOMIC CHALLENGES

In general, recent attempts to assess the direct and indirect economic benefits of coastal areas to local and national well-being have been difficult (e.g., Mandale et al., 1998, 2000; Canmac Economics et al., 2002; Roger A. Stacey Consultants Ltd., 2003; Atlantic Provinces Economic Council, 2004; Gardner et al., 2005, 2009; Newfoundland and Labrador Department of Finance, 2005; GSGislason & Associates Ltd., 2007; Heap, 2007; Kildow et al., 2009; Kildow and McIlgorm, 2010). Identification and economic evaluation of coastal sectors are often complicated by conflicting interpretations of coastal boundaries and what constitutes coastal industries. In Newfoundland and Labrador, for example, the mining sector grew from $967 million in 2000 to $4.584 billion in 2010 (Stothart, 2011). A significant proportion of the mining industry ships its product by sea, but the industry is generally not considered 'coastal'.

In British Columbia, an economic assessment of the oceans sector that included forestry, ship-building and ocean recreation estimated the annual GDP value for the sector to be $5.7 billion, generating 84 000 person years in employment (GSGislason & Associates Ltd., 2007; Gardner Pinfold Consulting Economists Ltd., 2009a, b). In 2013, commercial sea fisheries throughout Canada generated in excess of $2.25 billion in total landed value (89% of this from the East Coast region), and aquaculture contributed another $935 million in production (DFO, 2014b).

Throughout Canadian coastal regions, economic sectors have historically faced upswings and downswings in the prosperity of industrial sectors such as forestry, ship-building, fisheries, pulp and paper, and base-metal extraction and smelting. New extractive industries (e.g., oil and gas) have arisen in some areas, and a number of Canada's coastal cities are now hubs for higher education, research and technology development. For some of these endeavours, changes in climate will bring additional challenges to compete in the local, national and global markets.

Fisheries

Some capture fisheries in Canada are highly sensitive to climate variability and change (Barange and Perry, 2009; Rice and Garcia, 2011), whereas marine aquaculture is generally considered to be more adaptable to changing conditions (Campbell et al., 2014). Along southern coasts, many fishing communities have experienced reductions in fishable populations, closure of fisheries and/or shifts to new target species (Campbell et al., 2014). Climate change impacts fish behaviour (e.g., changes in vertical and geographic range, daily migrations), species composition and food chains. For regions where communities are largely dependent on a single fishery, adaptation includes diversification, such as changes in target species and shifting to other industries (e.g., coastal tourism), and/or immigration out of the area, which can affect community demographics and community structure. Along northern coasts, biodiversity shifts and changes in the ranges and distribution of many marine and terrestrial species impact the availability, accessibility and quality of traditional food sources upon which many communities depend (Furgal and Prowse, 2008; Hansen et al., 2008; Wheeler et al., 2010).

In a national-scale assessment of Canadian fisheries and climate change, Campbell et al. (2014) found that continuing climate change could result in significant impacts on the biodiversity and biota that support regional fisheries; that cascading effects of changes in ecosystem production could lead to disruptions in key life-history stages in species that support fisheries; that shifts may take place in the ranges of species and populations; and that there could be increased competition from invasive species. Despite these anticipated challenges, they concluded that Canada will likely remain a net exporter of aquatic foods, with anticipated increases in the total biomass of production from wild-capture fisheries as a result of climate-induced shifts in fish distributions.

Forestry, Mining, Energy

Along the coasts, exploration, development, processing and shipment of both land- and sea-based natural resources are vulnerable to hazardous environmental conditions, which are likely to increase with climate change. Although the biophysical impacts of climate change on many aspects of natural resources are fairly well understood, steps to integrate climate change considerations into business planning and management have thus far been limited (Lemmen et al., 2014).

Forestry, mining and energy contribute significantly to the economy of both the West Coast and East Coast regions of Canada, although information specific to coastal areas is limited. For example, mining in coastal landscapes includes base-metal mines and quarrying operations for structural materials for use in construction and road-building. Coastal landscapes provide easy access to sea transport for operating goods and extracted bulk materials. Climate-related challenges and opportunities identified to date relevant for natural resource sectors in coastal regions (Lemmen et al., 2014) include the following:

- Reductions in Arctic sea ice will open marine-transportation corridors, improving access for exploration and development of new mines and emphasizing the importance of collaboration between mining companies and traditional users of the land and sea (e.g., Lemmen et al., 2014, Case Study 4, p. 79).
- Changes in precipitation may compromise the integrity and viability of tailings ponds and waste-water–treatment facilities, potentially increasing the risk of contaminants polluting rivers and nearshore waters.
- In areas where product is shipped from bulk-loading facilities, changes to onland storage and dock facilities (including loading and/or offloading facilities) may be required to address changing conditions, such as higher winds, heavy precipitation, sea-level rise and storm surges.

Demand for and transmission of energy resources in coastal areas will be affected by climate variability and change (Figure 7), and by sea-level rise. Energy resources, including imported and domestic coal and offshore oil and gas are shipped or offloaded at coastal locations in British Columbia, Quebec, New Brunswick, Nova Scotia, and Newfoundland and Labrador. Within the sector, considerable attention is being given to the siting of proposed major pipeline termini and energy-shipping facilities on both the East and West coasts. Many new renewable energy projects, including hydroelectric, wind and tidal power, could also be located in coastal areas. Large wind farms have already been installed at locations such as the Tantramar Marsh in the upper Bay of Fundy; Lower West Pubnico in southwestern Nova Scotia; and North Cape, the most northwesterly point of Prince Edward Island. Tidal-power development in the Bay of Fundy has been proceeding through early stages of environmental assessment and prototype installation.

Recent extreme weather has wreaked havoc with the transmission of electricity throughout Canada's coastal regions, especially the East Coast (e.g., from Hurricanes Juan and Igor), affecting tens of thousands of people, resulting in costly interruptions in power supplies and requiring major repairs to local and regional transmission infrastructure. The oil-and-gas sector has begun studying the potential risks to offshore exploration and production facilities as a result of increased storminess and changes in ice risk (e.g., National Energy Board, 2011; Lemmen et al., 2014).

Tourism

With the decline of traditional economic sectors (such as fisheries and forestry) in some regions, tourism has emerged as an important industry for many parts of coastal Canada and is the primary industry for many small communities (Table 1; Beshiri, 2005; Scott, 2011; Government of Canada, 2012a, b).

The impact of rising sea levels on tourism resources and infrastructure is a concern in some coastal regions. Some cultural resources (e.g., the Fortress of Louisburg and in Haida Gwaii) are under threat from higher water levels, and beaches in certain regions (e.g., Prince Edward Island National Park) may diminish or disappear. Higher temperatures are also a factor for tourism; a warming climate will affect winter activities such as skiing and snowmobiling (e.g., in Whistler, BC and Gros Morne National Park, NL) and increase the length of the warm-weather tourism season in most areas. Longer summer seasons could result in additional visitation pressures on national and provincial parks, and other protected areas (e.g., visitation could increase 30% by 2050 in the national park system; Jones and Scott, 2006). Where tourism owners and operators are able to anticipate climate impacts and adapt effectively, climate change will present opportunities for economic growth in many areas of Canada. To date, however, the tourism sector in Canada is generally felt to be poorly prepared for changes in climate (Scott et al., 2008, 2012; KPMG, 2010), in part because business planning tends to involve short-term scenarios within which climate change is generally seen to be insignificant relative to climate variability and other factors.

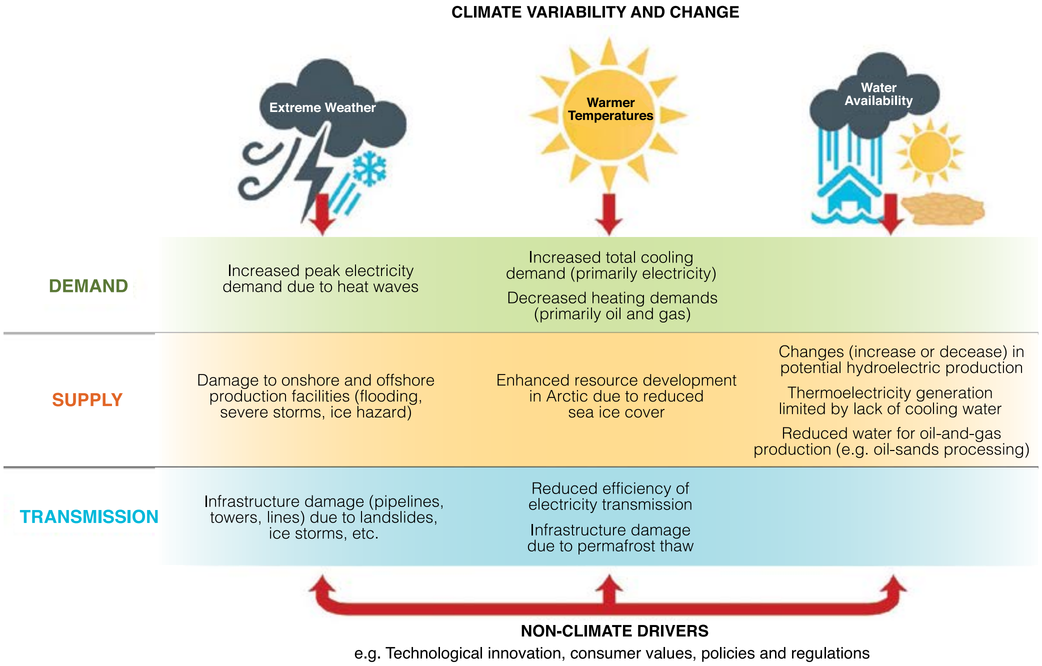


FIGURE 7: Potential climate change impacts on the energy sector, affecting supply, transmission and demand (Lemmen et al., 2014).

TABLE 1: Economic contribution of tourism in Canadian coastal provinces and territories (*adapted from* Tourism Industry Association of Canada, 2012). Data are reported for the entire jurisdiction, not just the coastal component; in a number of the provinces, however, tourism is primarily reliant on coastal landscapes and amenities.

Province and territory	2011 gross domestic product (2002 constant $)	2011 tourism employment (jobs)
Newfoundland and Labrador	$316 million	8 136
Prince Edward Island	$121 million	2 866
Nova Scotia	$683 million	16 636
New Brunswick	$438 million	12 090
Quebec	$5 357 million	130 018
British Columbia	$4 913 million	96 877
Yukon–Northwest Territories–Nunavut	$147 million	Data not available
Total	**$11.975 billion**	**266 623**

Insurance and Investment

In Canada, as elsewhere, the insurance and reinsurance industries are reacting to the rapid increase in losses associated with extreme climate events (Figure 8; Kovacs and Thistlethwaite, 2014; Robinson, 2015). Globally, losses are particularly notable in coastal environments (H. John Heinz III Center for Science, Economics and the Environment, 2000; Keillor, 2003; Heap, 2007; Nicholls et al., 2008; Simpson et al., 2012). In Canada, the risk of catastrophic losses due to storm-surge flooding increases with sea-level rise and increasing severe weather (McBean and Henstra, 2003; Feltmate and Thistlethwaite, 2012). Stanton et al. (2010) estimated that, by the 2020s, annual economic damages to Canada's coasts from sea-level rise and storm surges could be in the range of $2.6 to $5.4 billion, increasing to an estimated $48.1 billion by 2080. Throughout Canada and elsewhere in the world, organizations and institutions responsible for emergency management and disaster-risk reduction are seeking changes to planning and design practices to promote proactive adaptation so they can more effectively manage risks to environments, services and human safety and well-being (H. John Heinz III Center for Science, Economics and the Environment, 2000; McBean and Henstra, 2003; Sussman and Freed, 2008; World Bank, 2008; Yohe et al., 2011; Feltmate and Thistlethwaite, 2012).

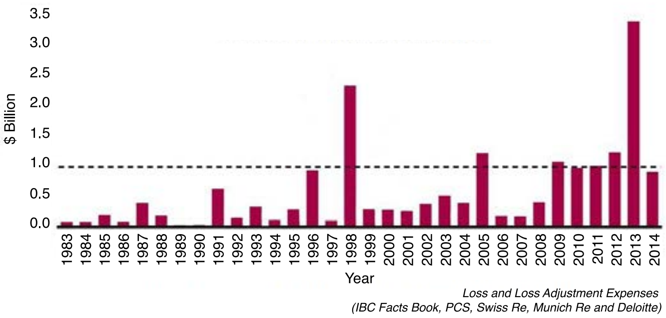


FIGURE 8: Insured losses from natural catastrophic events, 1983–2014. Values in 2014 $ CAD. Dashed line denotes $1 billion in insured losses. Losses in 1998 were the result of ice storms in eastern Canada. Those in 2013 were related to flood events in Alberta and the Greater Toronto Area (*modified from* Robinson, 2015).

2.2.3 HUMAN HEALTH AND WELL-BEING

The threats posed by climate change to human health and well-being are a function of many factors, including exposure to climate hazards, the sensitivity of individuals and populations to environmental changes (with the elderly and persons with pre-existing health conditions generally more sensitive), and the capacity of the individuals or populations to proactively plan for change and/or to respond to disaster (Seguin, 2008; Seguin and Berry, 2008; Costello et al., 2009). Both psychological and physical health can be affected by the stress and anxiety induced by extreme weather events and damaged assets and livelihoods.

There has been limited climate change–related health research specific to coastal Canada (Dolan et al., 2005; Dolan and Walker, 2006). Events such as Hurricane Igor in Newfoundland (Case Study 1) demonstrate how local capacity for emergency response, acute health care and services for displaced families can be stressed by extreme climate events (Public Safety Canada, 2013). Climate change can also affect the quantity and quality of drinking-water supplies, which are impacted by increased temperatures, drought, heavy precipitation events causing contaminated surface runoff, and salinization of groundwater as a result of increasing demand and/or intrusion of seawater due to sea-level rise (Lemmen et al., 2008). Atlantic Canada jurisdictions have been studying the risk of saltwater intrusion, especially in Prince Edward Island, which is entirely dependent upon groundwater to supply potable water. Saltwater intrusion has already been documented in some areas, and the combined pressures of increasing coastal development and projected sea-level rise suggest the problem will only increase in the future (Prince Edward Island Department of Environment, Labour and Justice, 2011). Additionally, in parts of Atlantic Canada, rural coastal populations are aging, which increases their vulnerability to climate change.

3 PREPARING FOR CHANGE

Climate change will affect different regions and communities in different ways, as detailed in the subsequent chapters of this assessment. The magnitude of impact is related to a large number of biophysical and human factors (*see* Chapters 1 and 2), including the capacity of human society to adapt (Boateng, 2008; Simpson et al., 2012). This section discusses factors that affect community response, such as the complexities of coastal governance and the role played by perceptions and values. It also provides an overview of key elements in the adaptation process and discusses adaptation approaches. Adaptation to climate change has been defined by the Intergovernmental Panel on Climate Change (IPCC, 2014, p. 5) as:

> *The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.*

3.1 COASTAL GOVERNANCE

In Canada, governance of coastal areas is often complex, with different aspects managed by a wide array of institutions and organizations, including federal and provincial departments, local governments, nongovernment organizations, and independent corporations and agencies. These institutions operate on specific criteria, with defined roles and responsibilities bounded by jurisdictional authority. Departments and programs from all levels of government address specific goals related to the development, conservation and/or management of coastal assets and activities. In some circumstances, these goals may not align across jurisdictions. For example, federal and provincial regulations can support local government policies and objectives; can, in some situations, pose barriers to local decision-making; or may even require alterations to local development restrictions (Burton, 2008). It can also be challenging for communities to access the data and expertise needed to manage climate risks effectively, as technical information on coastal conditions is often distributed throughout different orders of government, departments and agencies (Savard et al., 2009; Anthony and Sabatier, 2013).

In general, federal, provincial and territorial governments regulate coastal transportation infrastructure, such as ports and harbours, ferries, airports, road networks and railways. They are also responsible for legislated environmental assessment and review processes; for regulating the installation of shoreline protection measures; and for managing such sectors as health, transportation and natural resources, as well as aspects of others, such as fisheries, mining and oil and gas. Local governments and First Nations communities are responsible for managing most of the commercial, retail, institutional and residential land development on coasts through instruments such as master planning, zoning, construction standards, building inspection and occupancy permits (e.g., Richardson and Otero, 2012). Many other organizations are also active on the coast, including port authorities, hospital boards, industrial-park corporations and, increasingly, public-private partnerships that own and/or operate water, waste-water, solid-waste management and energy infrastructure. Environmental conservation and advocacy groups, local service clubs and other volunteer organizations can also have significant impact on local planning and management goals and practice.

The absence of formal coastal management structures to oversee and/or co-ordinate coastal governance in Canada has been noted frequently and, for more than 25 years, a more integrated approach to coastal management has been recommended (Hildebrand, 1989, 1995; Hildebrand and Norrena, 1992; Ricketts and Harrison, 2007). However, little progress has been made toward developing the institutional and regulatory instruments that are likely needed to compel such an approach (Mercer Clarke, 2010).

3.2 PERCEPTIONS AND VALUES

Despite experience with severe weather in coastal areas, people remain attracted to coasts as a highly valued space for living and working (Spalding et al., 2014). The perception of risk, and the value ascribed to a threatened natural or built asset, can vary considerably (Niven and Bardsley, 2013). Although extreme climate events are often expressed in terms of the probabilistic recurrence intervals (e.g., once-in-100-years storm), it is hard for people to conceptualize the severity of such an event, or to understand the ramifications. When Hurricane Juan struck Halifax in September 2003, the Canadian Hurricane Centre warned of hurricane forecasts and high waves. The local CBC News program reported that these warnings of the storm's arrival did not appear to be taken seriously, and even had the adverse effect of attracting a number of people to the coast to view the higher waves (CBC News, 2003). By 2009, attitudes had changed: 82% of Nova Scotians surveyed believed that severe weather had become more frequent and indicated that they checked weather reports daily and took precautions as advised (Silver and Conrad, 2010). Differing perceptions of the risks presented by climate change can influence the choice and the success of adaptation measures (Eyzaguirre and Warren, 2014).

3.3 ADAPTATION GOALS AND OBJECTIVES

The primary goals of adaptation are to reduce the adverse impacts of climate change, and capitalize on emerging opportunities (Box 2 addresses other goals specific to coastal regions). Effective adaptation enhances resilience and sustainability, improves health and well-being, and/or enhances economic value and competitiveness. Establishing goals and objectives helps focus adaptation efforts, so as to prioritize activities, avoid unrealistic expectations and achieve needed support from a wide array of stakeholders.

Broad goals of adaptation can be advanced through targeted objectives that (Simpson et al., 2012):

- use science-based assessment of changing coastal vulnerabilities and risks;
- enhance emergency preparedness and response;
- protect valued public infrastructure and assets of ecological and cultural significance;

BOX 2
ADAPTATION GOALS IN COASTAL REGIONS

The following list of adaptation goals has been adapted from Simpson et al. (2012) and other national and international studies (Ballinger et al., 2000; Field et al., 2001; New Brunswick Department of the Environment and Local Government, 2005; UNEP/GPA, 2005; United Kingdom Department for Environment, Food and Rural Affairs, 2006a, b; Tomlinson and Helman, 2006; International Oceanographic Commission, 2009; Munang et al., 2009; Organization for Economic Co-operation and Development, 2009; United Kingdom Department for Communities and Local Government, 2010; Government of Western Australia, 2012):

- reduce risks to human health and safety
- maintain the health of coastal ecosystems
- reduce vulnerability of, and risks to, the built environment
- secure public access and use of coastal resources
- maintain and diversify livelihood options and opportunities
- strengthen governance frameworks
- avoid shifting the costs of private risks to public resources

- reduce non–climate-related stresses on vulnerable systems and assets;
- zone hazardous lands to prevent new development and constrain use;
- promote development in less vulnerable areas; and
- integrate key stakeholders in adaptation decision-making processes.

Collaboration is fundamental to many adaptation initiatives (Eyzaguirre and Warren, 2014). Experience in coastal areas suggests adaptation is often best pursued as multistakeholder, iterative activities that attempt to work with, rather than in opposition to, natural coastal processes (Lane et al., 2013; Macintosh, 2013; Niven and Bardsley, 2013). There are increasing examples of collaborative efforts in planning at the local level for climate change that cross government, academic, institutional, sectoral and professional boundaries (*see* Chapters 4–6; Bowron and Davidson, 2012; Lane et al., 2013).

Two emerging concepts in the academic discussions on adaptation to climate change are 'transformational change' and 'limits to adaptation'. At present, most adaptation action in Canada and elsewhere consists of incremental changes to existing systems (Eyzaguirre and Warren, 2014). Transformational change refers to changes in the fundamental attributes of a system, and may be necessary where limits to adaptation are encountered. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007, p. 733) defined limits to adaptation as:

> *…the conditions or factors that render adaptation ineffective as a response to climate change and are largely insurmountable.*

The concepts of adaptation limits and transformational change have received only limited attention in Canadian research to date (Warren and Lemmen, 2014) but may be particularly applicable to some coastal issues.

3.4 REDUCING VULNERABILITY AND MANAGING RISK

The management of risk is a process by which communities, organizations and/or individuals assess their vulnerabilities; identify their options; and prioritize the implementation of both short and long-term actions for avoiding, reducing or eliminating those vulnerabilities (Noble et al., 2005; Simpson et al., 2012). Assessing risk involves considering both the likelihood of the impact occurring (probability) and the magnitude of the impact (consequence). Finding an effective adaptation response strategy requires consideration of both desired and undesired consequences (Lane and Stephenson, 1998). The choices made in adaptation planning may be a reflection of risk tolerance: the level of risk that an individual or society is willing (and able) to accept. Adaptation planning must also consider the impact of time on planning processes, recognizing that, as conditions and available knowledge change, adaptation options may also change. Iterative planning processes that address these realities in a time-based context may have the greatest potential to provide communities with cost-effective alternatives for managing their risks. For example, when designing barriers to protect against high water levels, it is often appropriate to build flexibility into the structures so as to allow for adjustments over time as sea level rises (Aerts and Botzen, 2013).

One of the considerations for managing risk is the clear assignment of costs (as well as benefits) of nearshore development to the individuals and organizations making the decision to develop in those areas (Titus, 1998; United States Climate Change Science Program, 2009; Titus et al., 2009). As Simpson et al. (2012, p. 89) concluded, there is a need for "[p]olicies and practices that specifically warn property owners that protection will neither be provided nor permitted and that no restitution will be made for damages or losses incurred…" should they be determined to develop and/or to occupy hazardous areas. While humanitarian assistance will always be provided during times of crisis, risk management involves asking why public funds should be used to compensate for damages incurred when individuals defy known hazards to enjoy the benefits of development on shores that are at risk from current or anticipated threats (e.g., storm surge and high winds; Titus, 1998; United States Climate Change Science Program, 2009; Grannis, 2011). Decisions not to build, or to relocate existing structures and uses, in areas now determined to be hazardous can be difficult and contentious, whether they are made privately or required through changes in zoning and/or occupancy requirements.

3.5 ADAPTATION PLANNING

Planning for adaptation to coastal climate change involves monitoring changing conditions (trends and projections); assessing new science and knowledge; and applying the insights to benefit policy, decision-making and practice (Lane et al., 2013; Macintosh, 2013; Niven and Bardsley, 2013; Eyzaguirre and Warren, 2014). Adaptation planning focuses on assessing vulnerabilities, advancing risk management and identifying approaches and instruments that can best promote sustainability and resilience (Burby et al., 1999, 2000; Simpson et al., 2012).

Adaptation-planning efforts are generally iterative processes that can take many different pathways and may include elements such as updating policy, legislation and regulations; modifying operational practices; applying new tools and technologies; revising investment and insurance practice; and altering social behaviour and expectations (Figure 9; Eyzaguirre and Warren, 2014). In many cases, adaptation is most effectively undertaken as part of existing policy and planning processes, which is known as the mainstreaming of climate change adaptation into the broader planning process.

Changes will occur across a range of spatial and temporal scales, and often require flexible strategies that prepare communities to better address new realities related to increased hazards and shortened building lifespans (Figure 10). Proactive approaches to planning recognize that it is generally more effective and economical to avoid or prevent damage from severe weather and a changing climate than to respond to adverse, and sometimes catastrophic, impacts (Nicholls et al., 2007; Stern, 2007; Tescult Inc., 2008; Anthoff et al., 2010; Stanton et al., 2010; Brown et al., 2011; Doiron, 2012; IPCC, 2014).

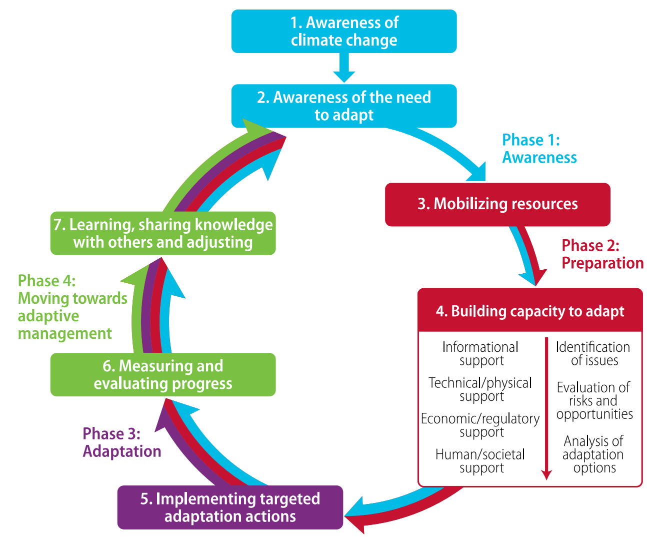


FIGURE 9: Steps in the adaptation planning process (Eyzaguirre and Warren, 2014).

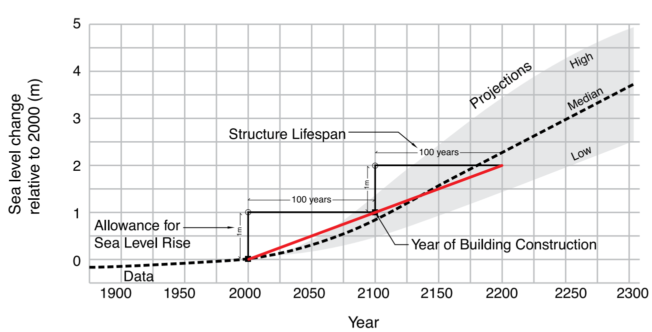


FIGURE 10: Incremental effects of sea-level rise on planning for structures within a 100-year projected life span (*modified from* Ausenco Sandwell, 2011b). The allowance for sea-level rise depends on when a structure is built and the projected sea-level change during the expected lifetime of the structure, and is the baseline for considering other effects, such as storm surge and wave run-up, that contribute to extreme water levels.

To address current and future well-being effectively, adaptation planning should also consider a wide spectrum of linked and often cascading effects on regions, communities and individuals (e.g., economic impacts to primary industries, unemployment, damage to parks, and changes to human health and well-being). Identification and analysis of trickle-down impacts on the four pillars for sustainability (environment, economy, society, culture) will help ensure that issues affecting sustainability are understood by all sectors of society, and that appropriate and timely efforts minimize negative effects and maximize emerging economic opportunities.

When adaptation processes are not well informed, or where insufficient attention has been paid to planning and design, they can lead to maladaptation—actions that can be expensive and inadequate in the longer term and ultimately increase vulnerabilities to environmental change (e.g., poorly designed seawalls; Bernatchez et al., 2008; Brown et al., 2011; Bernatchez and Fraser, 2012; IPCC, 2013, 2014). Maladaptive short-term measures can also prevent future implementation of more appropriate activities by consuming available financial resources and occupying valuable lands.

There is an expanding number of examples of practical experience with adaptation planning in Canada, particularly at the community scale (e.g., Forbes et al., 2009; Vasseur, 2012; Lane et al., 2013; Natural Resources Canada, 2014a). Further examples are provided in the regional chapters of this assessment (*see* Chapters 4–6).

3.5.1 LOCAL DEVELOPMENT POLICY, PLANNING AND DESIGN

In Canada, planning and managing land development and use occurs across a range of governments and sectors but is often the responsibility of local governments. Governing instruments can include formal regional and town plans, bylaws, zoning and protective easements, and local building codes (e.g., Richardson and Otero, 2012). In working with these instruments, there are many opportunities to better address risks associated with climate change. Communities may have the authority to adjust their planning (e.g., to designate areas such as flood plains as not appropriate for development) and to establish guidelines for development and design. They often must also meet provincial/territorial and/or federal regulations and guidelines.

The risk of legal liability and the potential for associated financial impacts can be factors in the selection of adaptation options (*see* Chapter 6). Liabilities could potentially be associated with existing zoning approvals of new development in areas anticipated to be affected by sea-level rise, as well as with the development of more restrictive zoning regulations aimed at limiting development in areas at risk of inundation or damage from storm surges or other weather-related hazards. Because of the long lifespan and cost of many infrastructure investments, good technical information about climate vulnerability is important for allocating resources for expansions and upgrades appropriately. Updating of building codes and best-practice guidelines to reflect changing environmental conditions can assist in establishing proactive design criteria.

3.5.2 PLANNING FOR SEA-LEVEL CHANGE

For coastal communities in Canada's East Coast and West Coast regions, and the Beaufort coastline of the North Coast region, rising sea level is a significant challenge for adaptation planning. As mean sea level rises, the risk of flooding increases (Hinkel et al., 2014) and, as nearshore waters deepen, larger and more damaging waves will reach exposed areas of the coast (*see* Chapter 2). Risks include degradation and loss of coastal ecosystems, damage to infrastructure (e.g., roads, buildings, ports) and associated threats to human health and safety (*see* Chapters 4–6). In general, the more sea level rises, the greater the risks.

Assessing vulnerability to sea-level rise and developing effective adaptation strategies is directed by, among other things, the risk tolerance for damage a decision maker (i.e., community, industry, government) is willing to accept. Risk tolerance is an informed assessment, which can be subjective and is generally based on numerous factors, including the value and lifetime of assets at risk; the economic, social and environmental consequences of negative impacts (e.g., flooding); and the capacity of a system to adjust to, or to recover from, the impacts. Jurisdictions in coastal areas with irreplaceable or vital assets, or structures with long life spans, would have a low tolerance for risk from flooding. In contrast, jurisdictions where little coastal infrastructure is present or planned would have a higher risk tolerance (Box 3; Parris et al, 2012).

Climate change scenarios provide a range of plausible projections of sea-level rise. Knowing the level of tolerance for risk determines which projection of sea-level rise (as determined by climate change scenarios) to plan for. For example, the likely range of mean global sea-level rise by 2100, as presented in the IPCC Fifth Assessment Report and used in this report and by James et al. (2014, 2015) to project relative sea-level changes in Canada (*see* Chapter 2, Box 8 for detailed discussion), is 28 to 98 cm by 2100 (Table 2). An additional scenario considered in this report and by James et al. (2014, 2015), the 'high-emissions plus Antarctic ice-sheet reduction' scenario, projects an even greater sea-level rise (Table 2). Even larger amounts of sea-level rise are possible, although the IPCC Fifth Assessment Report placed *low confidence* in 'semi-empirical' sea-level projections (*see* Chapter 2; IPCC, 2013). This relationship between risk tolerance and sea-level scenarios is well described in Parris et al. (2012).

Although there is a fairly large spread in the anticipated changes in sea level by 2100 among the scenarios, most of the divergence takes place in the latter half of the 21st century (*see* Chapter 2, Figure 21). The choice of sea-level–rise projections does not greatly affect the risk tolerance for impact in short- to medium-term planning horizons (e.g., one to three decades). However, since global sea levels are projected to rise throughout this century and well beyond 2100 (*see* Chapter 2; IPCC, 2013), planning efforts will generally want to consider the longer term implications.

BOX 3

SEA-LEVEL RISE SCENARIOS AND THE UNITED STATES NATIONAL CLIMATE ASSESSMENT

Scenarios for global sea-level rise were developed for the United States National Climate Assessment by the United States National Oceanic and Atmospheric Administration (Parris et al., 2012). The scenarios are to be used "to consider multiple future conditions and devise multiple response options" to "initiate actions that may reduce future impacts." Thus, no specific probabilities or likelihoods are assigned to individual scenarios, and the report emphasizes that no scenario is to be used in isolation. The four scenarios, which range from 20 to 200 cm above mean 1992 sea level, are intended to encompass the full range of plausible future sea-level change by 2100, with the probability of sea level rising by at least 20 cm, and by no more than 200 cm, assessed at greater than 90% (Parris et al., 2012).

In decision-making, the lowest projections of sea-level rise (least amount of increase in global mean sea level) are appropriate for use where the tolerance to risk is high, and the highest projections (highest amount of increase in global mean sea level) are appropriate for use where the tolerance to risk is low. For example, a situation with very low tolerance to risk could be planning for new infrastructure with a long anticipated life cycle, such as a power plant (Parris et al., 2012).

TABLE 2: Relationship between tolerance of risk and projected sea level changes by 2100.

Tolerance to risk of sea-level rise	Climate change scenarios*	Global sea-level rise** by 2050 (cm)	Global sea-level rise by 2100 (cm)	Comments	Range of projected changes in relative sea level across Canada at 2100*** (cm)
Higher	Low emissions (RCP2.6)	Median: 22 cm Range: 16–28 cm	Median: 44 cm Range: 28–61 cm	28 cm is the lower end of the likely**** range defined by the IPCC Fifth Assessment Report	–109 to 62
High	Intermediate emissions (RCP4.5)	Median: 23 cm Range: 17–29 cm	Median: 53 cm Range: 36–71 cm	—	–100 to 71
Low	High emissions (RCP8.5)	Median:25 cm Range: 19–32 cm	Median: 74 cm Range: 52–98 cm	98 cm is the upper end of the likely range defined by the IPCC Fifth Assessment Report	–84 to 93
Lower	High emissions plus Antarctic ice-sheet reduction	Not specified	139 cm	Includes additional contribution from the West Antarctic Ice Sheet	–13 to 168

* *See* Chapter 2, Box 7 for description of scenarios

** Climate and sea-level projections in the IPCC Fifth Assessment Report are synthesized from computer-model results from a number of climate-modelling centres. The combined, or ensemble, results are frequently presented in terms of the average (median) and a confidence range given as percentiles. The range presented here refers to the 90% confidence range [5th percentile to 95th percentile]. The 5th percentile is the level where 5% of the model runs were smaller, and the 95th percentile is the level where 95% of the model runs were smaller. Although not true bounds, the 5th and 95th percentiles are often treated as effective lower and upper bounds of projections for a scenario.

*** Based on projections at 59 locations on Canada's three coasts. Values are the range in median projections for each scenario and illustrate the strong influence of vertical land motion on projections of relative sea-level change in Canada.

**** The likely range is defined in the IPCC Fifth Assessment Report as having a 66–100% probability. Hence there is up to a 33% chance that the actual change observed will lie outside of this range. For global sea-level rise, most of this uncertainty is associated with the upper limit.

Cost is often a key factor in adaptation decision-making. In many cases, selecting higher planning levels (i.e., assuming a larger amount of sea-level rise) would increase the costs associated with adaptation options. For example, at the global scale, Hinkel et al. (2014) found that the 'dike costs' (which include building, upgrading and maintaining newer dikes) in 2100 varied with the climate scenarios applied, with an estimate of US$12–31 billion under the low-emissions scenario (RCP2.6) and US$27–71 billion under the high-emissions scenario (RCP8.5). Iterative and flexible planning, which involves selecting and implementing options that can be revisited and updated over time, is a way to reduce current costs and allow for future changes in scientific understanding of projected sea level and other changes in circumstances to be integrated into decision-making processes when available. An example of the iterative nature of planning for sea-level rise, and the time that it can take to make informed policy changes, is the experience of the Province of British Columbia (Case Study 2; *see* Chapter 6).

CASE STUDY 2

PLANNING FOR SEA-LEVEL RISE IN BRITISH COLUMBIA

(from BC Ministry of Environment, 2013; Andrey et al., 2014)

During the past several years, a series of actions in British Columbia have facilitated the incorporation of new scientific information about changes in sea level into policy and planning processes (Figure 11; *see* Chapter 6). Analysis of regional vertical land motion and global projections of sea-level rise produced new estimates of future sea-level changes (Bornhold, 2008; Thomson et al., 2008), with significant implications for the current system of sea dikes that protect important infrastructure and property (Figure 12). Subsequent analyses, undertaken by the BC Government, the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) and others, were intended to assist policymakers and planners to incorporate sea-level rise into flood-risk assessment, coastal-floodplain mapping, sea-dike design and land-use planning (e.g., Delcan, 2012). The work to develop guidelines for planning was undertaken with an explicit recognition that they would need to be revisited periodically, in response to new information and practical experience.

Some of the outputs from the various analyses undertaken to date include:

- a recommendation that coastal development should plan for sea-level rise of 0.5 m by 2050, 1.0 m by 2100 and 2.0 m by 2200, adjusted for local vertical land motion;
- technical reports to guide calculation of sea-dike–crest elevation and flood construction levels, considering sea-level rise, wind set-up, storm surge and wave run-up;
- guidance for sea-level–rise planning, including designation of 'sea-level–rise planning areas' by local governments;
- a report on simulations of the effects of sea-level rise and climate change on Fraser River flood scenarios (BC Ministry of Forests, Lands and Natural Resource Operations, 2014);
- a report comparing the costs of a variety of adaptation options, ranging from dike construction to flood proofing and managed retreat (Delcan, 2012); the study estimated that the cost of upgrading infrastructure works required along 250 km of diked shorelines and low-lying areas in Metro Vancouver to accommodate a 1 m rise in sea level, including necessary seismic upgrades, would be about $9.5 billion;
- professional-practice guidelines for engineers and geoscientists to incorporate climate change in flood-risk assessments; and
- seismic design guidelines for dikes, focusing on factors to be considered in the seismic design of high-consequence dikes located in southwestern BC.

These analyses have spurred municipal action. For example, the City of Vancouver offered workshops to

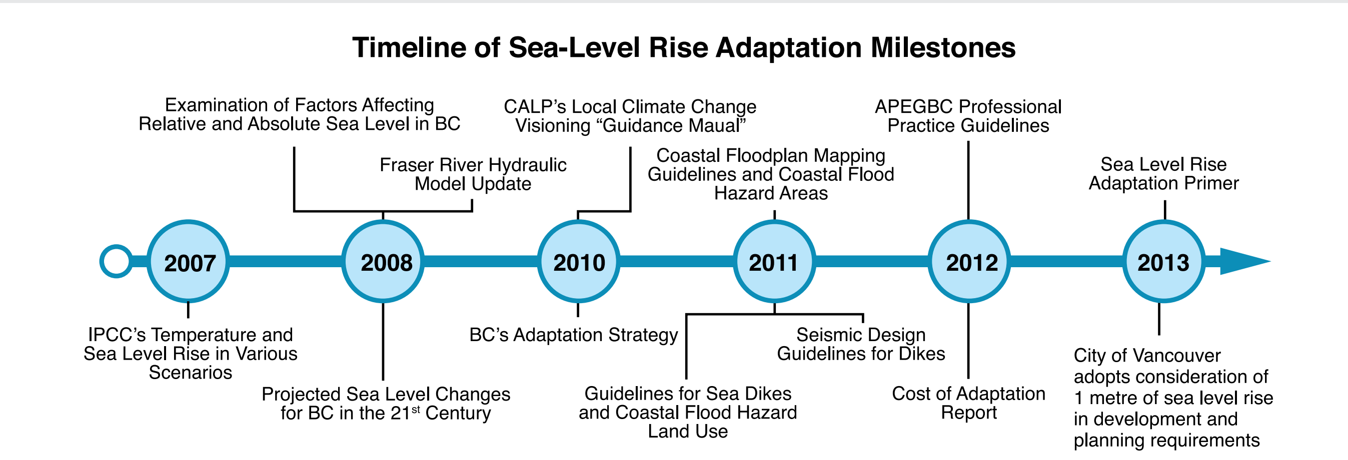


FIGURE 11: Timeline of milestones for adaptation to sea-level rise in British Columbia (*modified from* Sustainability Solutions Group and MC3, 2013). Abbreviations: APEGBC, Association of Professional Engineers and Geoscientists of British Columbia; CALP, Collaborative for Advanced Landscape Planning.

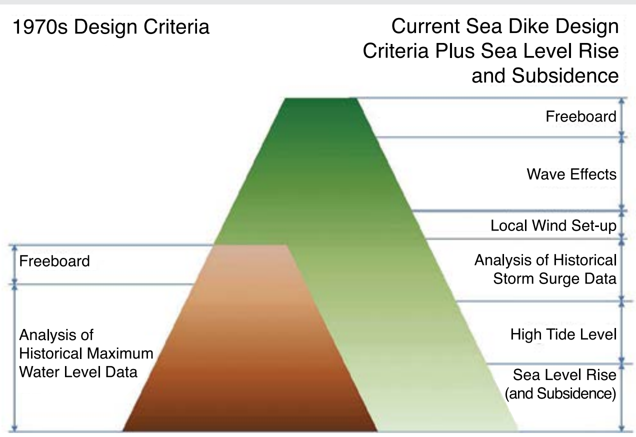


FIGURE 12: Conceptual differences between old and new approaches to sea-dike design (Delcan, 2012).

engineers, developers and municipal staff on adapting coastal infrastructure. In turn, these workshops led the city to review their flood-proofing policies and, in 2013, Vancouver became the first city in BC to adopt formal consideration of 1 m of sea-level rise in development and planning requirements. The city is currently considering a number of other development-planning options.

To allow others to benefit from the many years of work and outputs developed for BC, a working group that included local, provincial and federal government representatives, industry, academia and practitioners worked together to develop a national Sea Level Rise Primer (http://www2.gov.bc.ca/assets/gov/environment/climate-change/policy-legislation-and-responses/adaptation/sea-level-rise/slr-primer.pdf), with examples from BC, Quebec and the Atlantic Provinces. The primer helps communities to identify, evaluate and compare adaptation options, and showcases planning and regulatory tools, land-use change or restriction tools, and structural and nonstructural tools.

An emerging concept relevant to risk tolerance and sea-level change and flooding involves determining the change in elevation at which future storm-surge flooding will occur with the same frequency as present flooding. This information can inform planning elevations for developments or projects. Recent research has developed methods to determine these elevation values (e.g., Thompson et al., 2009; Hunter, 2010; Hunter et al., 2013; Zhai et al., 2013, 2014). These values are larger than the simple projected change in mean sea level, due to uncertainties in projected relative sea-level rise combined with the recurrence properties of storm surges.

3.5.3 TOOLS TO ASSIST ADAPTATION

The suite of instruments and tools available to assist adaptation planning and action along coasts has increased in recent years. Research involving academia and professional practice is increasingly providing more tools to aid decision-making. Recent Canadian examples include the Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol (Box 4); the *Sea Level Rise Primer* (Case Study 2; Arlington Group et al., 2013); climate change adaptation guidelines for sea dikes and coastal–flood-hazard land use in British Columbia (Ausenco Sandwell, 2011a–c); and risk-management guidelines for nearshore development in Halifax, NS (Halifax Regional Municipality, 2007). In addition, there are increasing examples of coastal communities (e.g., Gibsons, BC and Charlottetown, PE) that have used the outputs of new research on anticipated changes in sea level and storm surges to inform their harbour- and waterfront-planning processes (*see* Chapters 4–6).

BOX 4

USING THE PIEVC PROTOCOL TO ASSESS VULNERABILITY OF INFRASTRUCTURE

The Public Infrastructure Engineering Vulnerability Committee (PIEVC) protocol is an important tool to help evaluate the vulnerability of infrastructure. The goals of the PIEVC, which comprises governments, engineering professionals and nongovernmental organizations, include ensuring the integration of climate change into the planning, design, construction, operation, maintenance and rehabilitation of public infrastructure in Canada (Public Infrastructure Engineering Vulnerability Committee, 2014). Their protocol is a formalized process that can be applied to any type of infrastructure (e.g., buildings, roads, water systems) to assess engineering vulnerability to, and risk from, current and future climate impacts. Of the case studies completed to date, coastalrelevant examples include studies on:

- sewage infrastructure in the Vancouver, BC area (Kerr Wood Leidal Associates Ltd., 2008);
- water-resources infrastructure in Placentia, NL (Catto, 2008); and
- the sewage-treatment plant in Shelburne NS (ABL Environmental Consultants Limited, 2011).

The use of incentives and disincentives to encourage adaptation planning and/or discourage development and human use in areas at risk are also useful tools for governments and for the insurance and financial sectors, who can assign higher costs for insurance or not provide insurance for properties considered to be at higher risk (Aid Environment, 2004; Grannis, 2011; Simpson et al., 2012). Types of incentives include:

- **positive incentives** that encourage beneficial activities (e.g., lower taxes on the development of property inland of coastal setbacks);
- **disincentives** that penalize developers for activities considered as unsustainable (e.g., fines for infilling coastal marshes or mining sand from beaches); and
- **indirect incentives** to effect positive change through application of progressive planning and design (e.g., treating waste water to ensure sustainability of coastal vegetation and using beach nourishment as opposed to groins and seawalls).

Incentives can also be unintentional, such as perverse incentives that reward unsustainable behaviour (e.g., inadequate land-use zoning, or inadequate enforcement of zoning, leading to uncontrolled coastal development; agricultural benefits for draining marshlands; and funding for replacing but not enlarging damaged storm-water infrastructure).

The Government of Nova Scotia has used positive incentives to encourage communities to develop Municipal Climate Change Action Plans (MCCAPs) that document efforts toward mitigation and adaptation. As part of the Municipal Funding Agreement and the extension to the 2010–2014 Federal Gas Tax Fund agreement, the province required communities seeking access to gas tax revenues to prepare an MCCAP as an amendment to their Integrated Community Sustainability Plan (*see* Chapter 4; County of Richmond, 2013).

3.6 ADAPTATION APPROACHES

The available suite of options for coastal adaptation are often grouped into four broad categories: 1) no active intervention, 2) accommodation, 3) protection, and 4) avoidance/retreat (Boateng, 2008; Chouinard et al., 2008; Vasseur and Catto, 2008; Intergovernmental Oceanographic Commission, 2009; Linham and Nicholls, 2010; Nicholls, 2011; Simpson et al., 2012; Arlington Group et al, 2013; Niven and Bardsley, 2013). Although these categories are used predominantly in discussions related to anticipated coastal impacts of sea-level rise and storm surge (Figure 13), they can also apply to a broader range of hazards and risks associated with severe weather events and environmental change (e.g., more intense precipitation events or droughts; extreme heat or cold events; landslides).

Most adaptation plans will involve a number of initiatives from one or more of these response categories, selected to respond to a range of local vulnerabilities and risks that will change over time. For example, beach nourishment combined with coastal-protection structures can be a reliable and cost-effective option in some situations but often only for a limited period of time.

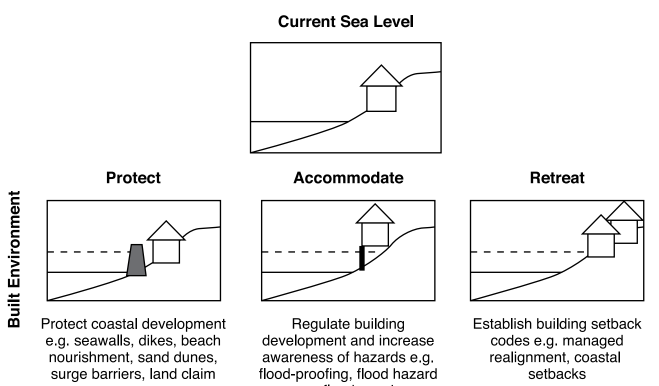


FIGURE 13: Schematic representation of protection, accommodation and retreat responses to sea-level rise (*modified from* Linham and Nicholls, 2010, based on IPCC, 1990)

3.6.1 NO ACTIVE INTERVENTION

'No active intervention' refers to conscious decisions by decision makers to take no action at this time, based on a thorough understanding of the risks involved. No active intervention responses are appropriately employed when there is no significant risk, where little can practically be done to avoid or reduce coastal hazards, or when action taken now is an inappropriate allocation of resources against the potential of a future threat. They are inappropriate when they are the result of apathy, but can be applied where communities are constrained by limited resources. Uncertainty is generally not a good justification for delaying efforts on adaptation (e.g., Lemmen et al., 2008; Macintosh, 2013; Niven and Bardsley, 2013).

3.6.2 ACCOMMODATION

Accommodation responses seek to lower the risks of hazards on continued human use of infrastructure, lands and waters. Generally, accommodation allows for occasional, short-term impacts (e.g., impacts from storm events or seasonal flooding) and is an appropriate response when the practicality of protecting coastal assets is outweighed by the costs, and/or the effectiveness would be limited to a relatively short period of time. Accommodation responses may include modifications to planning and design guidelines and standards to better prepare for extremes of heat and cold; to improve flood resistance (e.g., elevating buildings, ensuring alternative transportation links); and to augment design and construction standards through improved codes and regulations, as well as restrictions imposed through insurance and financial institutions (Arlington Group et al., 2013).

Examples of accommodation responses include flood-proofing buildings and improving storm-water management (e.g., installing larger diameter piping in storm-water collection and disposal systems to reduce the risk of flooding, and implementing low-impact development to reduce runoff into storm-water systems and improve groundwater regeneration). Accepting temporary flooding of nonessential areas (e.g., parking areas, recreational fields) is another example. Accommodation responses on the coast often utilize a range of no-cost/no-regret actions, such as protection of local salt marshes, or low-cost/low-regret actions, such as restrictive use of designated areas (Füssel, 2007).

3.6.3 PROTECTION

Protection responses have been used for centuries to reduce risk and improve security in nearshore environments, and have traditionally been the preferred method for dealing with shoreline erosion throughout most of Canada's coasts. Protection responses include both hard-armouring and soft-armouring measures.

Hard-armouring measures can reduce vulnerabilities and risks by protecting coastal infrastructure in its existing location, by ensuring that the shoreline does not move from its current position, and/or by maintaining current uses (Bijlsma et al., 1996). Hard-armouring measures include:

- shoreline armouring, such as seawalls or bulkheads built of armour stone, concrete or sheet piling; and
- flood protection, such as dikes, tide gates and storm-surge barriers, to prevent flood waters from entering the upper reaches of an estuary or river.

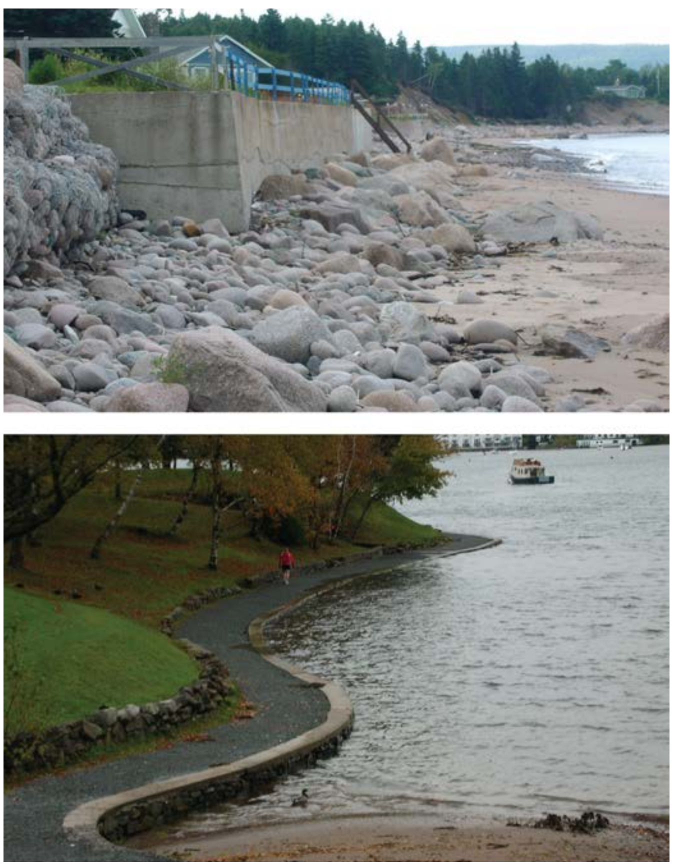


FIGURE 14: Hard armouring of the shoreline, Nova Scotia. *Photo courtesy of M. Davies.*

Hard armouring has historically been a common feature of settled coasts throughout Canada (Figure 14). Examples of shoreline armouring include the dike systems of the British Columbia coast, the seawalls along the Northwest Arm of Halifax Harbour, NS and the Stanley Park seawall in Vancouver, BC. Where hard armouring has been used to extend usable land, it can increase nearshore water depths and vulnerability to wave action and interfere with established coastal erosion cells and longshore current patterns. Most efforts to place hard-armouring measures require professional expertise to examine alternatives, obtain the necessary regulatory approvals and ensure that measures are adequately and expertly designed and constructed to prevent unanticipated negative effects on local natural and built environments (Case Study 3).

CASE STUDY 3

COW BAY CAUSEWAY, HALIFAX REGIONAL MUNICIPALITY, NOVA SCOTIA

(Davies et al., 2010b)

North of Halifax, NS, along the eastern shore, the Cow Bay Road runs on top of a 500 m causeway built over a cobble barrier beach. Protected by an armour stone revetment, this causeway has experienced maintenance problems in the last decade. Storm waves overwash the road, carrying large stones and debris (Figure 15). The asphalt road surface is now more frequently being damaged by waves. Rising relative sea levels have reduced the causeway's freeboard, increasing the frequency and severity of damage, while intensifying offshore storms have resulted in larger waves reaching the shoreline in this area.

FIGURE 15: Effects of storm-wave overwash on Cow Bay Road, Halifax Regional Municipality, NS. *Photo courtesy of R.B. Taylor.*

An analysis was undertaken to evaluate the relative merits of building a more effective armour stone barrier or raising the roadbed. Using a life-cycle costing approach (Davies et al., 2010a), a design was developed for the causeway that minimizes total costs (combined capital and maintenance costs) during the next 30 years. In the longer term, it is likely that the causeway will have to be abandoned and the road routed further inland. However, the most cost effective approach for the next 30 years was determined to be rebuilding the protective barrier to withstand higher water levels and larger waves.

Soft-armouring measures for eroding shorelines include approaches that lessen the damaging effects of tides, currents, waves and storms, while improving nearshore sediment stability. Examples include maintaining and/or restoring beaches and marshes, and the protection and/or restoration of coastal vegetation. When soft armouring is properly designed and implemented, it supports the continuation of existing coastal processes, such as the replenishment of beach and dune sand and the stabilization of salt marshes.

Beach replenishment can be a component of soft-armouring initiatives, used in conjunction with other protection measures (Figure 16). Sources for replenishment sand can be either offshore or land-based deposits. The longevity and effectiveness of replenishment measures are directly related to ongoing coastal geomorphological processes and the impact of storm events.

FIGURE 16: Hybrid protection at Basin Head, PE. Buried revetment covered with sand dune and marram grass. *Photo courtesy of M. Davies.*

In areas where historical dikes created agricultural land that is no longer used for farming, breaching the dikes to allow restoration of the original salt marshes is a soft-armouring response that can improve the capacity of the local shoreline to resist erosion (Bowron et al., 2012; van Proosdij et al., 2014). Establishment of salt marshes seaward of dikes and other hard-armouring projects can also assist in reducing wave energy. Although the effectiveness of such approaches is promoted by technical experts (e.g., Lamont et al., 2014), the measures appear to be largely invisible and poorly understood by the general public. In British Columbia, the Green Shores Program (Lamont et al., 2014) promotes policy and practice for the use of soft armouring as a means to protect against sea-level rise and floods. On Quebec's North Shore, local perceptions of the benefits of hard-armouring measures affected decision-making such that a soft-armouring proposal of beach nourishment was only acceptable to residents if it was combined with a seawall (Bernatchez et al., 2008).

Hard armouring (e.g., seawalls and dikes) can result in a heightened, and sometimes false, sense of protection from coastal flooding. In the past, when weather patterns were established over decades, well-designed and constructed hard armouring could provide a high degree of security from waves and storm surges. As the climate changes and sea level rises, there is less surety in the degree of protection provided by hard armouring, especially as time advances. Some forms of hard armouring can also (at times) increase flooding risks, if structures are breached during high-water events and flood waters become trapped behind them (Mercier and Chadenas, 2012).

3.6.4 AVOIDANCE AND RETREAT

Avoidance and retreat responses are appropriate where the risks to infrastructure or to human health and safety are determined to be unacceptably high, and where protection or accommodation responses are considered impractical. Avoidance is practiced when no new development is allowed in an area, especially in low-lying or exposed areas where construction is traditionally avoided. Retreat responses encompass situations where existing assets are either abandoned or removed from areas under threat (short or longer term) and human activities and uses are constrained. Managed retreat (Titus, 1998; Tomlinson and Helman, 2006; Turner et al., 2007; Forsythe, 2009) seeks to respond to climate-induced coastal risks through planned abandonment and gradual relocation.

Retreat responses can have considerable economic and cultural costs to society and to individuals. Along built shorelines, assets often form the oldest features of a community or have considerable commercial value. Whether the asset is a feature of historical, cultural or environmental value, or individual homes, the trauma of abandonment can be severely felt throughout a community. As a result, retreat responses are generally one of the last options considered in adaptation planning. The unpopularity of retreat as a response to coastal risks often results in action being delayed until the threats materialize (Macintosh, 2013; Muir et al., 2013). Resulting damages can provoke decision makers to take immediate and potentially costly actions without the appropriate science and professional advice, resulting in ineffective solutions (Cooper and Pile, 2014).

Managed retreat is being used in a number of communities throughout Canada whose adaptation-planning efforts are based on avoidance of impacts associated with higher sea levels and severe weather. Harbour and waterfront plans developed for Gibsons, BC (Town of Gibsons, 2012) and Charlottetown, PE (Ekistics Planning and Design, 2012) have included provisions for new development that address predictions for sea-level rise and for increased storm surges. In Halifax, NS, a guideline for coastal development requires new structures to avoid low-lying areas with a potential for flooding from sea-level rise and severe weather (Halifax Regional Municipality, 2007).

3.7 EMERGENCY PREPAREDNESS

Another element of preparing for climate change is improving emergency preparedness. As the frequency and/or intensity of extreme-weather events increase as a result of climate change, there is greater need to undertake procedural changes to improve preparedness for disaster response. 'Preparedness' refers to any pre-disaster activity undertaken to enhance a community's ability to respond to, and cope with, storm conditions (UN/ISDR and UN/OCHA, 2008). In Canada, local, provincial and federal emergency measures organizations co-ordinate with police, fire and emergency medical responders, and other organizations (e.g., Canadian Red Cross), to collaborate and share operations and resources.

Within communities, emergency measures organizations have important roles in planning for adaptation. As environmental conditions change, protocols for emergency response, evacuation routes and storage of disaster-relief supplies may need to be revisited to ensure that they remain adequate. As the prediction of severe-weather events improves, communities can reduce risks through improved preparedness for disaster response, early evacuation of populations at risk and provision of temporary protection for buildings, property and natural resources (Case Study 4).

CASE STUDY 4

LITTLE ANSE, ISLE MADAME, CAPE BRETON, NOVA SCOTIA

(Chung, 2014a)

Little Anse is a small coastal village of approximately 125 inhabitants located on the eastern coast of Petit-de-Grat Island of the Isle Madame archipelago in Cape Breton, NS (Figure 17). In recent years, fishing activity that was once based in the village has moved to the larger harbour of Petit-de-Grat. The road that connects the village to the larger community is subject to flooding during storm events, isolating local residents, many of whom are elderly. The breakwater at Little Anse, which once protected the cove and the low-lying road from storm effects, has been damaged and has fallen into disrepair.

FIGURE 17: Aerial photo of Little Anse, Nova Scotia (*modified from* Digital Globe and Google, 2016).

Repair or replacement of the damaged breakwater (estimated at roughly $1–5 million) or construction of an alternative road are expensive responses that would pose significant, and potentially prohibitive, financial burdens on the municipality and the province (Camare, 2011). To alleviate the threats to human health and safety that occur when the road access is flooded, participants in an International Community–University Research Alliance (ICURA) project (C-Change: Managing Adaptation to Environmental Change in Coastal Communities, Canada and the Caribbean) have been working with emergency responders, community leaders and the Canadian Red Cross to identify and locate those individuals at greatest risk, to ensure that emergency preparedness and response procedures are adequate and to identify alternative measures to ensure the safety and well-being of the residents during storm periods (Lane et al., 2013; Chung, 2014a, b).

Plans are underway to develop short-term evacuation options for those most at risk. When severe weather forecasts anticipate a storm surge that could flood the road, residents would voluntarily be moved to a safe location (community centre) to ride out the storm in safety. Planning for this accommodation operation will engage public-health workers, emergency services, local pharmacists, and service and faith-based groups to provide assistance, meals and comfort during their stay.

4 CONCLUDING THOUGHTS

Rockström and Klum (2015) have stated that humanity is struggling against four main pressures: population growth and affluence, ecosystem degradation, climate change and surprise. Surprise is the product of catastrophic or creeping changes that occur when thresholds are crossed and wide-ranging impacts are felt throughout environments and societies. They have also noted that society has tremendous ability, through creativity and innovation, to adjust and adapt to these stresses and to thrive in a rapidly changing world. While this chapter presented a high-level overview of the challenges that climate change presents for Canada's coastal regions and the approaches for adaptation, the following regional chapters provide more detailed discussions of innovation at work across the country.

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CHAPTER 4: PERSPECTIVES ON CANADA'S EAST COAST REGION

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KEY FINDINGS

Canada's East Coast region is geographically, ecologically and socially diverse, resulting in a wide range of climate change effects and responses. Analysis of existing literature and ongoing adaptation initiatives leads to the following key findings:

- **Air temperatures, sea-surface temperatures and ocean acidity have all increased in the region during the past century, while sea-ice cover has decreased.** Projected climate changes through the 21st century include continued warming of air and water temperatures, and increased precipitation, acidification and water stratification. Sea level will rise, with significant regional variability. Sea ice will decrease in area, thickness, concentration and duration, with volume likely to be reduced by more than 95% by the end of the 21st century.
- **Sea-ice cover and sea-level rise are key determinants of coastal erosion rates.** Increases in coastal erosion have been documented along many coasts in the region during years characterized by mild winters and low ice coverage. Future coastal-erosion rates will likely increase in most areas.
- **There are many adaptation measures that promote the resilience of coastal areas.** These include protection, revegetation and stabilization of dunes; maintenance of sediment supply; and provision of buffer zones, rolling easements or setbacks that allow the landward migration of the coastline.
- **Although hard coastal defence structures may be necessary to address sea-level rise and coastal flooding in some situations, particularly in urban areas, such structures disrupt coastal processes** and can exacerbate erosion, sedimentation and coastal squeeze, leading to degradation and loss of coastal habitats and ecosystem services. Retreat, sand nourishment and managed realignment represent alternatives to hard coastal-defence structures.
- **Experience in the East Coast region has shown that mechanisms such as setbacks, which control or prohibit coastal development, can be challenging to implement.** However, it is often even more difficult to remove and relocate buildings from an eroding coastline or flood-susceptible area. Selection of appropriate adaptation options may be particularly challenging in unincorporated areas where summer cottages, secondary homes or principal dwellings are established parallel to the shore in a ribbon fashion.
- **Provinces and communities across the region have made advances in identifying vulnerabilities to climate change impacts through collaboration with academia, the private sector and nongovernmental organizations.** Many have begun planning for adaptation, while others have moved from planning to implementation of adaptation strategies, although this remains a challenge for many. Few are engaged in ongoing monitoring of the effectiveness of implemented adaptation strategies.

1 INTRODUCTION

For this report, Canada's East Coast region includes the marine coasts of the Atlantic Provinces (New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador) as far north as Hamilton Inlet, Labrador, as well as the marine coasts of Quebec along the estuary and Gulf of St. Lawrence up to the city of Québec (Figure 1). The region has been inhabited by aboriginal populations for at least 9000 years (Chapdelaine, 1996), with European colonization beginning in the early 17th century. Today, more than 70 ethno-linguistic communities are represented on the coast, including the First Nations peoples. The current coastal population of the region, about 3 million people, resides in a few large cities and many small towns and tiny hamlets. Population density is lowest along Quebec's North Shore and the coast of Labrador.

The East Coast region features a great variety of landscapes consisting of rich and diversified ecosystems. Coastal communities benefit from the services provided by these ecosystems (e.g., food supply and protection against wave erosion), which contribute to both regional and national economic prosperity. Resource sectors, such as fisheries, aquaculture, transportation, tourism, mining and industrial development, rely either on marine resources or on the transportation services facilitated by the marine environment.

Climate change will affect many coastal processes, as well as adjacent terrestrial and oceanic environments, in the East Coast region. Changes in sea level, storm surges and heavy precipitation events can result in failure of coastal infrastructure, shoreline erosion, coastal and inland flooding, ice pile-ups, and saltwater intrusion into surface water and groundwater. Climate change impacts also include increasing water temperature, changes in duration of ice cover, acidification and oxygen depletion that, in turn, impact marine resources and ecosystems. If severe storms (e.g., tropical or extra-tropical storms, hurricanes) increase as a result of climate warming, the potential for wind, wave and water damage will also increase. These impacts would be further exacerbated by rising sea level. Although it is widely recognized that many natural hazards related to climatic events will increase on a global scale as a result of climate warming, there is less confidence about projected changes at the regional scale (*see* Chapter 2; IPCC, 2012).

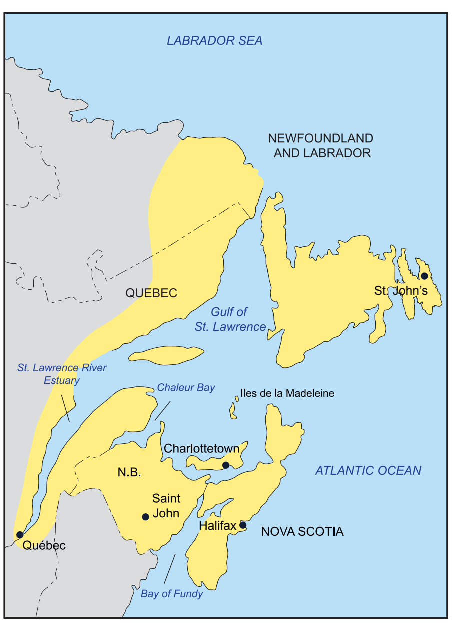

FIGURE 1: Geographic extent of the East Coast region.

Climate change will result in long-term and permanent changes in coastal regions. The impacts of climate change on marine, terrestrial and coastal ecosystems affect human communities located close to the shore, as well as those that depend on coastal ecosystems. The vulnerability of a coastal community to climate risks depends on the physical characteristics of the coast and on the management of human activities within this changing environment. These changes will impact the lifestyles, economies and sustainability of coastal communities, presenting both risks and opportunities for economic activities. Coastal communities can reduce risks and take advantage of opportunities by adapting to these evolving conditions.

This chapter begins with an overview of observed and projected changes in climate and physical and biological coastal processes in the East Coast region (Sections 2–4). This provides a foundation for understanding climate change impacts on, and vulnerability of, coastal communities and key economic sectors, which are discussed in Section 5. It concludes with a discussion of the process of adaptation and our capacity to undertake actions that reduce climate impacts and benefit from possible opportunities (Section 6). Adaptation is framed in the context of multiple drivers of change, recognizing that communities, ecosystems and industry are continually evolving in response to a wide range of pressures, most of which are unrelated to climate. Adapting to climate change is a challenge that requires leadership, imagination and inclusion of a wide variety of participants, including communities, governments, industry, academia, coastal scientists, engineers, planners and civil society.

2 OBSERVED AND PROJECTED CLIMATE CHANGES

Canada's East Coast region is already affected by the changing climate (Vasseur and Catto, 2008). The strongest climate trend relates to increased air temperatures during the last century, a trend that climate models project to continue or accelerate for the coming century (Bush et al., 2014). Other climate variables, such as precipitation, evaporation, fog, winds and snow, may also be changing, but the trends are less strong than those for temperature.

This section reviews trends and projected changes in selected key climate parameters for the East Coast region: air temperature, precipitation and ocean-water temperature, because of their global application as indicators of long-term climate change; and wind and storms, due to their strong influence on climate impacts along coasts. Further information on observed and projected climate change in Canadian coastal areas is provided in Chapter 2 (at a national scale) and in the Atlantic Large Aquatic Basin assessment (DFO, 2012b). Changes in sea level, sea ice and wave climate are discussed in Section 3 in the context of their impacts on physical coastal processes.

2.1 AIR TEMPERATURE AND PRECIPITATION

A statistically significant increase in mean annual air temperature for the period 1900–2010 is evident throughout the East Coast region (Figure 2). The data demonstrate a general warming trend with high interannual and interdecadal variability (*see* Chapter 2 for discussion of climate variability). The average warming for the East Coast region as a whole during the 110-year period of record was 0.90 ±0.37°C (Figure 2a). Stations located along the Atlantic Ocean warmed 0.75 ±0.34°C (Figure 2b), whereas those located along the Gulf of St. Lawrence coast warmed 1.12 ±0.43°C (Figure 2c). Other studies (Finnis, 2013; Galbraith and Larouche, 2013) similarly denote an increasing spatial temperature-change gradient from the southeast to the northwest across the East Coast region. Temperature increases in the region are similar to, or greater than, global average warming during this same period (e.g., IPCC, 2013).

Climate-model projections indicate that historical trends of change in near-surface air temperature are expected to continue and become more pronounced (Table 1). Average precipitation, which does not show a clear historical trend, is expected to increase in winter and spring, and remain stable or decrease slightly in summer and fall. Seasonal changes in both mean near-surface air temperature and precipitation for the East Coast region are projected to be greatest in winter (Ouranos, 2010).

2.2 OCEAN-WATER TEMPERATURE

The main ocean-water bodies in the East Coast region are made up of three distinct layers: the surface layer, a cold intermediate layer and a deeper layer (Galbraith and Larouche, 2013). Local variations are observed in many areas, especially in fiord embayments, such as Smith Sound, NL and Fjord du Saguenay, QC. Rising air temperature (Section 2.1) has changed the temperature of surface marine and coastal waters (Han et al., 2013). During the period 1945–2010, the surface-water temperature of the northwest Atlantic Ocean increased 0.32°C, with the largest increase occurring in the Labrador Sea (Han et al., 2013). Increases in surface-water temperature in the Gulf of St. Lawrence are similar to those in air temperature over the same region (Galbraith et al., 2012). On the Atlantic coast, increases of +1.04°C and +0.89°C in surface-water temperature were observed for the Labrador Sea and the Scotian Shelf, respectively, during the period 1982–2006 (Sherman et al., 2009), with a similar warming trend (+0.38°C/decade) observed for the Labrador Sea during the period 1981–2010 (Han et al., 2013).

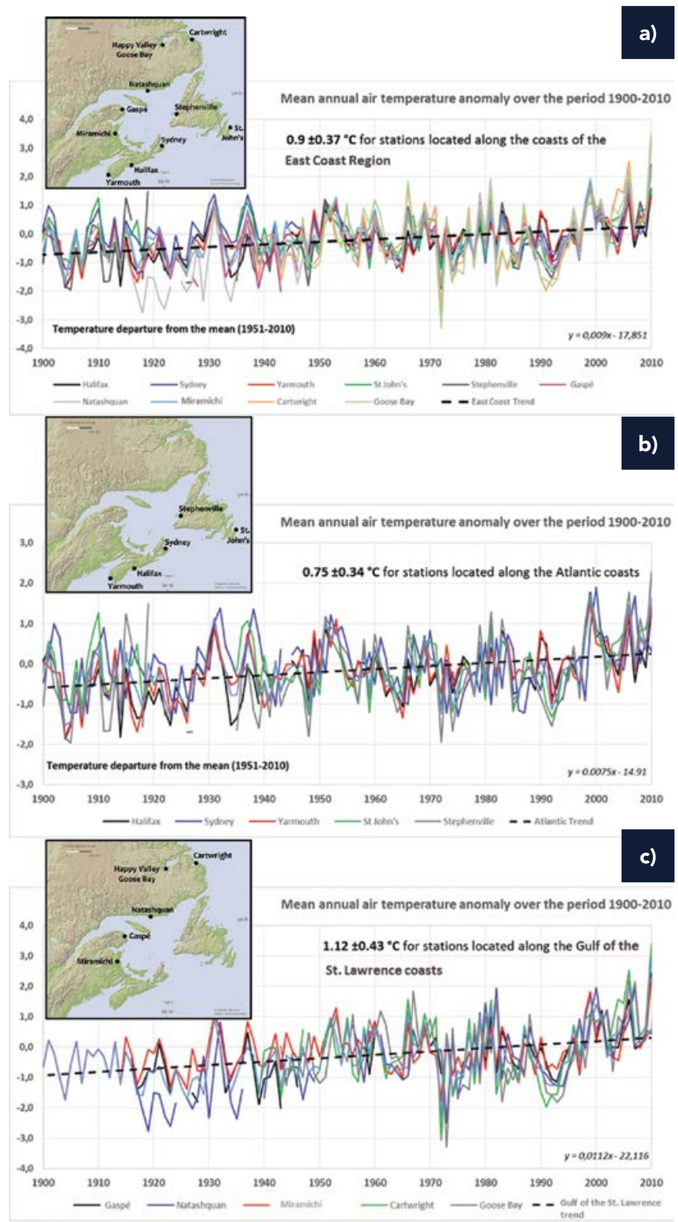

FIGURE 2: Mean annual air temperature anomaly (departure from the 1951–2010 mean) at **a)** meteorological stations in the East Coast region as a whole, **b)** stations located along the Atlantic Ocean, and **c)** stations located along the Gulf of St. Lawrence coast. The confidence interval is 95% for all plots. Positive values indicate that mean annual temperature is higher than the average temperature for the 1951–2010 time period. The 1951–2010 period was chosen as a reference period because of the availability of homogenized data (Vincent et al., 2012). Source: Ouranos (*modified from* Savard et al., 2008).

TABLE 1: Anticipated change of near-surface air temperature and precipitation in the East Coast region for 30-year periods, centred on 2020, 2050 and 2080, relative to the 1970–2000 period, based on results of the Coupled Model Intercomparison Project (CMIP 3) using *Special Report on Emissions Scenarios* (SRES) scenarios (IPCC, 2007). See Ouranos (2010) for details on methodology.

Season	Climate Parameters	Change by 2020	Change by 2050	Change by 2080
Winter	Temperature Precipitation	1.4 to 2.2°C 2.8 to 9.7%	2.5 to 3.8°C 6.5 to 15.4%	3.4 to 5.0°C 12.6 to 22.9%
Spring	Temperature Precipitation	0.8 to 1.5°C 0.3 to 8.1%	1.6 to 2.7°C 3.1 to 11.5%	2.2 to 4.1°C 8.8 to 18.5%
Summer	Temperature Precipitation	0.9 to 1.6°C –1.9 to 5.2%	1.7 to 2.7°C –1.4 to 5.7%	2.2 to 3.8°C –4.0 to 7.1%
Autumn	Temperature Precipitation	1.1 to 1.6°C –2.8 to 3.6%	1.9 to 2.8°C –2.0 to 7.1%	2.3 to 4.1°C –0.9 to 10.1%

Global-climate projections generally indicate widespread warming (1 to 3°C by 2100 under an intermediate-emissions scenario) of the upper ocean around Canada during the 21st century, with substantial seasonal and spatial variability (Meehl et al., 2007; Capotondi et al., 2012). Warming is expected to be more limited in the North Atlantic south of Greenland, due to a likely reduction in the northward ocean transport of heat by the Atlantic Meridional Overturning Circulation (Drijfhout et al., 2012; Hutchings et al., 2012). It is unclear whether this projected ocean-temperature anomaly will extend westward into the Labrador and Newfoundland coastal waters, as global models have difficulty resolving ice-ocean variability in the Labrador Sea (de Jong et al., 2009).

2.3 WIND AND STORMS

Trends in wind velocity and direction, and in storms during the 20th century, are difficult to determine conclusively, in part because datasets are not as complete as for air temperature. Wind is very sensitive to local topography, and any relocation of wind stations (even if moved a short distance) or replacement of instrumentation or equipment can introduce significant changes in a time series that are not related to climate change. The most reliable databases start only in 1961 or 1979 (when satellite observation data became available). Analysis of the density of intense storm centres over North America for the period 1961–2000 indicates that the northwestern Atlantic Ocean, the Labrador Sea and the Gulf of St. Lawrence are some of the stormiest areas in North America (Figure 3; Savard et al., 2014).

Climate projections indicate that significant changes in wind speed are unlikely as a result of climate warming, but there is likely to be a northward shift in storm tracks that will affect storm frequency in the East Coast region (Loder et al., 2013).

3 CHANGES IN PHYSICAL PROCESSES AND COASTAL GEOMORPHOLOGY

Coasts are a naturally dynamic environment (*see* Chapter 2). They are in a state of constant flux that involves sediment movement, changes in coastal morphology and shifts in the organisms that inhabit these systems. Although coastal systems may be considered as being in dynamic equilibrium, this depends on the ability of the system to transport sediment alongshore by longshore currents, or seasonally onshore and offshore through wave action. In normal conditions (excluding storms), sediment is transported alongshore through the process of littoral drift, generally within the boundaries of a littoral cell (*see* Chapter 2). Erosion or deposition rates depend on a range of natural (e.g., riverine sediment supply and formation of ice foot [ice along the shoreline]) and anthropogenic processes (e.g., dredging and shore protection).

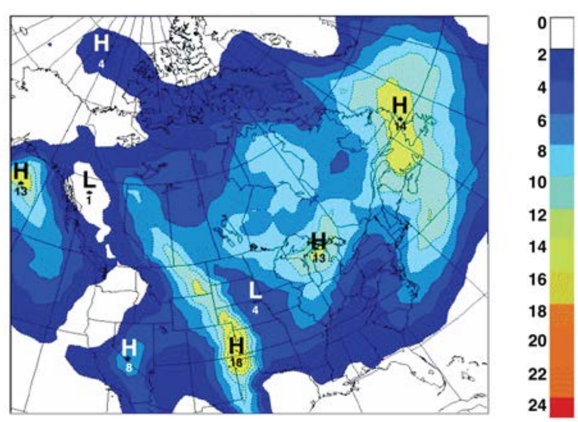

FIGURE 3: Spatial distribution of the annual average density of storm tracks for the 1961–2000 time period from ERA-40 reanalysis (a reanalysis of the global atmosphere and surface conditions for a period of 45 years, extending from September 1957 through August 2002, by the European Centre for Medium-Range Weather Forecasts; *modified from* Savard et al., 2014)

Rising air and sea-surface temperatures will lead to shorter sea-ice seasons, which in turn cause an increase in total wave energy dissipated on the coast (Neumeier et al., 2013). Combined with rising sea levels, this will affect the risk of storm-surge flooding and will exacerbate coastal erosion and sedimentation in areas already sensitive to these processes. Climate change will also affect processes, such as freeze-thaw cycles, input from inflowing rivers and ice scouring, that influence sediment balance and contribute to the changing nature of the coastal landscape.

In the following sections, the main climate change–related drivers of change in coastal geomorphology are discussed in more detail. These include the changes in sea level, storms and ice conditions that affect extreme water levels and waves.

3.1 CHANGES IN RELATIVE SEA LEVEL

Recent findings on sea-level rise (SLR) are given in global assessments, such as the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Church et al., 2013; IPCC, 2013). Global sea-level change is the vertical change of the sea surface relative to the Earth's centre, averaged for all oceans on the planet. In contrast, 'relative' sea-level change is the change in mean sea level relative to solid ground at any specific point on the coast (*see* Chapter 2).

During the 20th century and the first decade of the 21st century (i.e., 1900–2009), the trend of global sea-level rise was 1.7 ±0.2 mm/year. The rate of global sea-level rise between 1993 and 2009 increased to 3.2 ±0.4 mm/year (from satellite altimetry) or 2.8 ±0.8 mm/year (from tide-gauge records; Church and White, 2011). The IPCC (2013) projects a range of global sea-level rise of 26–98 cm by the year 2100, based on the representative concentration pathway (RCP) emissions scenarios (*see* Chapter 2). Collapse of a sector of the West Antarctic Ice Sheet has the potential to add another few tens of centimetres of global sea-level rise, but its probability of occurrence is uncertain (Church et al., 2013).

In Canada's East Coast region, spatial differences in vertical land motion, largely associated with glacial isostatic adjustment, produce regional differences in relative sea-level change (*see* Chapter 2). Glacial isostatic adjustment is the delayed response of the solid Earth to the surface unloading that occurred at the end of the last ice age. Vertical land motion measured at GPS stations in the East Coast region (*see* Chapter 2) shows sinking land across the southeastern part of the region. Sinking land contributes to relative sea-level rise. In the northwestern part of the region, the land is rising and relative sea-level change is reduced compared to global values.

Recent projections of relative sea-level change on Canadian coasts (James et al., 2014), based on the results of the IPCC Fifth Assessment Report, are described in Chapter 2. The projections include the steric effect (thermal expansion of the surface layer of the ocean); meltwater from mountain glaciers and ice caps, and the Greenland and Antarctic ice sheets; projected changes in dynamic oceanography; and other smaller sources (*see* Chapter 2). For much of the East Coast region, a projected reduction in the strength of the Gulf Stream contributes 10–20 cm to sea-level rise by 2100, due to dynamic oceanographic effects (Yin, 2012).

Projections for the East Coast region are presented in Figures 4 and 5. For the high-emissions scenario, James et al. (2014) projected the mean elevation of sea level to be 80–100 cm higher at 2100, relative to 1986–2005, in the southeastern part of the region (Atlantic coast of Nova Scotia and New Brunswick) and on the southern side of the Gulf of St. Lawrence (Figure 4). In the northwestern part of the East Coast region (i.e., on the North Shore of the Gulf of St. Lawrence in Quebec), sea level is projected to be about 20–40 cm above its current position by the year 2100. In Newfoundland, projections indicate sea-level will rise 60–80 cm by 2100. This variability is due largely to differences in vertical land motion, which range from nearly 2 mm/year of subsidence for some locations in Nova Scotia to nearly 5 mm/year of uplift on the North Shore of the Gulf of St. Lawrence. Other factors also play a role. Based on the range of estimated maximum contributions presented in the literature and summarized by Church et al.

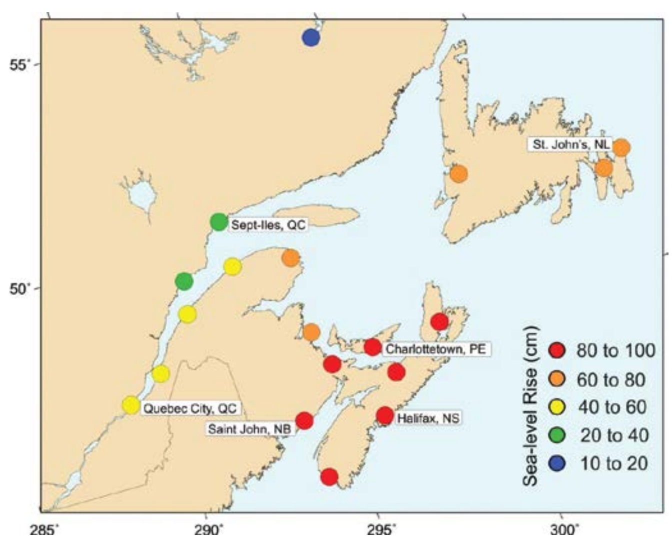

FIGURE 4: Projections of relative sea-level rise by the year 2100 for the median value of the high-emissions scenario (RCP8.5; after James et al., 2014). *See* Chapter 2 for additional information on sea-level projections. Sea-level projections through the 21st century are given in Figure 5 for the six labelled communities.

(2013), James et al. (2014) estimated additional sea-level rise associated with potential collapse of a portion of the West Antarctic Ice Sheet could contribute up to an additional 65 cm of global sea-level rise. This additional contribution has the potential to increase relative sea-level rise to more than 1.5 m by 2100 for some locations in the East Coast region (Figure 5).

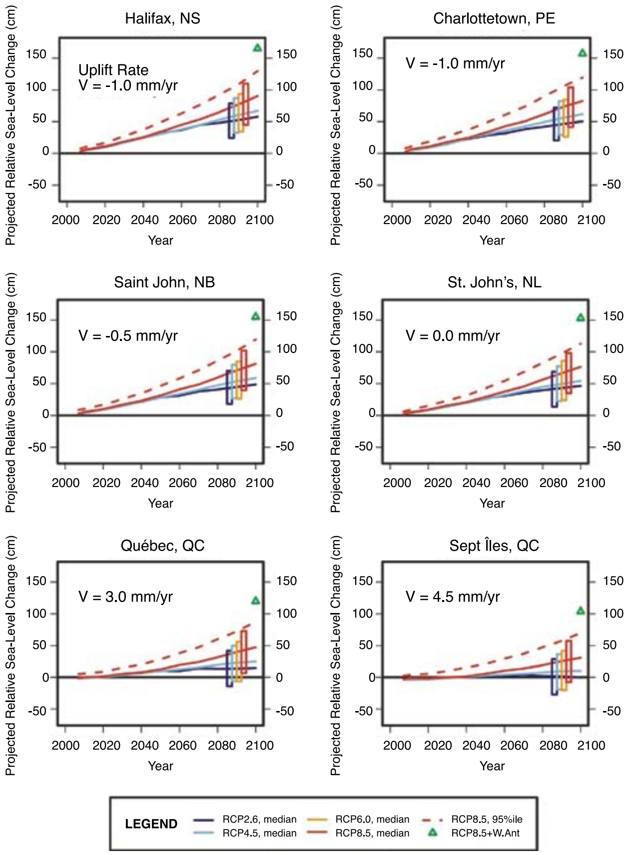

FIGURE 5: Projected sea-level change through the 21st century for selected communities in the East Coast region (after James et al., 2014, 2015). RCP2.6 is a low-emissions scenario, RCP4.5 and 6.0 are intermediate-emissions scenarios and RCP8.5 is a high-emissions scenario. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario, an augmented scenario in which the West Antarctic Ice Sheet 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 dashed red line gives the 95th percentile value for the high-emissions scenario. Vertical land motion (V) is given to nearest 0.5 mm/year in each panel. *See* Chapter 2 for further explanation of scenarios. Projections for additional sites are given in Appendix A.

3.2 STORM SURGE AND EXTREME WATER LEVELS

Storm-surge elevation is the difference between the observed water level during the surge and the level that the tide would normally rise to in the absence of storm activity. Storm surges result from variations in atmospheric pressure and wind (*see* Chapter 2; Forbes et al., 2004; Thompson et al., 2009). Storm surges can occur over one or several tidal cycles (Figure 6), depending on the speed of the low-pressure system moving through an area. When a surge occurs at the same time as a high tide, lands and infrastructure located in low-lying areas can be flooded (Case Study 1).

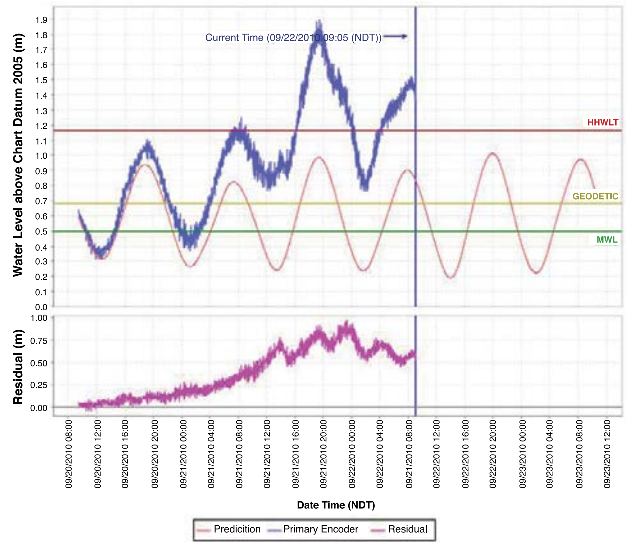

FIGURE 6: Example of surge caused by Hurricane Igor (October 2010) over several high-tide cycles in St. John's, NL. The higher high water large tide (HHWLT) was exceeded on at least three occasions (Canadian Hydrographic Service, Atlantic Region). Abbreviations: MWL, mean water level; NDT, Newfoundland Daylight Time.

CASE STUDY 1

THE GROUNDHOG DAY STORM

The 'Groundhog Day' storm of February 2, 1976 is a classic example of the impact of a storm occurring coincident with high tides to produce a large surge. Significant damage (representing more than $10 million at the time) and coastal flooding were reported in southwestern Nova Scotia and southern New Brunswick, where water levels rose more than 2.5 m above the predicted tides, heavily eroding shorelines (Parkes et al., 1997; Desplanque and Mossman, 2004). Strong south-southeast winds blowing for 5–6 hours resulted in a large storm surge in areas of the Bay of Fundy. Water levels rose to 3.2 m above predicted tides in 15 minutes (Desplanque and Mossman, 2004), and new tide-height records were set at Yarmouth, NS and Saint John, NB harbours (Amirault and Gates, 1976). Fortunately for those farther up the Bay of Fundy, the tide was an apogean spring tide (lower than average tide because the moon was most distant from Earth in its monthly orbit). Therefore, although a surge of 1.46 m was recorded and dikes were overtopped, the damage was limited. Had the storm occurred 16 days later during the perigean spring tide (higher than average tide because the moon is closest to Earth in its monthly orbit), the damage would have been much greater (Desplanque and Mossman, 2004). It is estimated that, if the Groundhog Day storm had occurred on April 16, 1976, it "would have had the potential of causing calamity on the scale of the Saxby Tide" (Desplanque and Mossman, 2004; *see* Chapter 2).

In Charlottetown, PE, the two largest recorded storm surges between 1911 and 2000 (1.43 m on December 19, 1963 and 1.41 m on March 12, 1991) did not flood the historical waterfront properties of the city, as both storm surges occurred during low tide. However, during the same time period, six smaller storm surges were sufficiently high, when combined with the tide height, to flood the waterfront area of the city, registering a maximum water level of 3.6 m or more above chart datum (Parkes and Ketch, 2002). Historically, relative sea level has been rising in Charlottetown at the rate of 3.2 mm/year since 1911 (Parkes et al., 2002). If sea levels had been at today's height, both the 1963 and 1991 storm surges would have resulted in flooding of the historical waterfront.

Using long-term tide-gauge data, Xu et al. (2012) studied the recurrence frequencies of extreme storm surges for five sites in the estuary and Gulf of St. Lawrence, and on the Atlantic coast: Lauzon, QC; Rimouski, QC; Charlottetown, PE; Halifax, NS; and St. John's, NL. Although the study concluded that there was no observed trend in storm-surge heights (i.e., no net increase or decrease) for the entire East Coast region, there were site-specific increases in storm-surge recurrences at St. John's and Rimouski during the 1922–1951 to 1981–2011 periods (Xu et al., 2012). The relative degree of negative impact on a coastal community from storm surge is also associated with the frequency of occurrence of a storm of that magnitude. Communities and coastal ecosystems that are frequently impacted by surge events are more likely to have evolved coping responses. For example, a 1 m storm surge is a relatively rare event in the Placentia, NL and Ferryland, NL areas, and could therefore pose a threat to coastal communities, whereas a 1 m storm surge in Lauzon, QC is a yearly event that may have little effect on the well-being of coastal residents.

On Quebec coasts, Bernatchez et al. (2012a) identified 30 storm-surge events that caused significant damage at a regional scale between 1950 and 2010, including 14 events that caused flooding. In the Bas-Saint-Laurent area, run-up during the storm of December 6, 2010 caused water levels to reach a little more than 2 m above the high tide (Quintin et al., 2013), corresponding to a once-in-150-years event (Bernatchez et al., 2012a). The average amount of erosion of low-lying sandy coasts as a result of this storm was 3.7 m, with a maximum erosion of 15 m measured at one site (Quintin et al., 2013).

Climate change affects storm surge and associated flooding as a result of sea-level rise, possible changes in storm frequency and intensity, and other ocean-dynamics factors. For example, tidal resonance in the Bay of Fundy is projected to increase the tidal range and lead to greater water-level extremes, although it will not affect mean sea levels (Greenberg et al., 2012). This contribution to water-level extremes has been estimated to be on the range of 5–20 cm by 2100 in the Bay of Fundy, compared with close to zero in Halifax, NS. The magnitude of changes in sea level is fairly well understood, but less is known about potential changes in other factors. Modelling allows analysis of potential storm-surge impacts under future climate conditions (e.g., Bernier et al., 2006).

3.3 WAVE CLIMATE AND SEA ICE

Wave-climate modelling (e.g., Swail et al., 2006) is used in coastal vulnerability assessments and in the planning and design of offshore and coastal infrastructure (e.g., drilling platforms, wharves, jetties, breakwaters, and offloading and loading structures). It has also contributed to an improved understanding of coastal evolution (i.e., sediment dynamics and water currents), changes in wave characteristics over time (i.e., period, height and wavelength) and possible future wave conditions in a changing climate.

Modelling of the wave climate of the estuary and Gulf of St. Lawrence for the period 2071 to 2100 indicates an increase in wave height of between 5 cm and 1 m, for a return period of 50 years, and a slight increase in overall mean wave energy due to decreasing sea-ice cover (Neumeier et al., 2013).

The East Coast region includes the most southward extent of winter sea ice in Canada's coastal waters. The average annual sea-ice cover in the East Coast region has decreased by 0.27% per year since the Canadian Ice Service began collecting data in 1968–1969 (*see* Figure 7 for trend since 1980–1981; Senneville et al., 2014). For the period 1998–2013, the average decrease was 1.53% per year (Senneville et al., 2014; note that both 2014 and 2015 had ice cover exceeding the 1980–2010 median). Warmer average winter temperatures have reduced the percentage of ice cover, shortened the duration of the ice season and decreased ice thickness. These trends are projected to continue, with modelling indicating that sea ice will be almost completely absent in most of the Gulf of St. Lawrence by 2100 (Senneville et al., 2014).

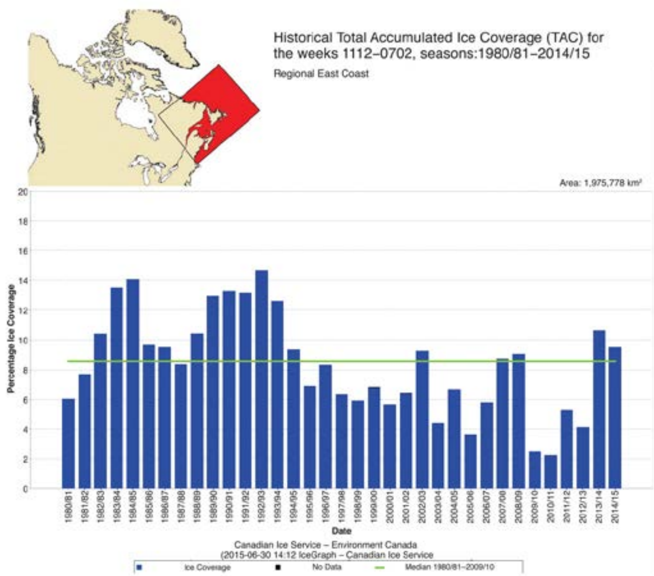

FIGURE 7: Historical total accumulated ice coverage for the weeks December 11 to February 7 from 1980 to 2015 in the East Coast region (Environment Canada, 2015).

Since ice cover impedes wave formation, the shortening of the ice season increases the total energy of storm waves developing in an ice-free water body, such as the Gulf of St. Lawrence (Neumeier et al., 2013). This, in turn, will modify the coastal sediment balance, activating shore erosion in some areas while reducing erosion in others as material is redistributed (Jones et al., 2009; Overeem et al., 2011).

In the Gulf of St. Lawrence, the period of wave inhibition by sea-ice decreased by 30% for the period 1995–2007 (average ice-covered period of 55 days/year) relative to the period 1960–1995 (average ice-covered period of 80 days/year; Savard et al., 2008). In comparing future conditions (2041–2070) to the recent past (1982–2011), modelled simulations suggest that the period of sea-ice cover will decrease by 36 days and the number of days that the ice foot completely protects the coast will decrease by an average of 33.4 days (Senneville et al., 2014). Ice-foot development currently occurs during some winters along coastlines in the southern Gulf of St. Lawrence and around the Avalon Peninsula, NL, and more frequently along the Quebec North Shore, in northeastern Newfoundland and in Labrador.

3.4 GEOMORPHOLOGY, SEDIMENT SUPPLY AND COASTAL DYNAMICS

The East Coast region has a diverse geomorphology. Mountain and fiord coastal areas are common in parts of Newfoundland and Labrador, while topographically low to moderately high, resistant bedrock cliffs, occasionally interrupted by unconsolidated coasts, are found along the northern and eastern shores of the Gulf of St. Lawrence, the Bay of Fundy coast of New Brunswick, and the exposed Atlantic shores of Nova Scotia and Newfoundland. Soft erodible cliffs are widespread along the southern and western shores of the Gulf of St. Lawrence (Prince Edward Island, New Brunswick and the Îles de la Madeleine). Resistant cliffs in the region retreat slowly, at annual rates of less than a centimetre per year (e.g., Davidson-Arnott and Ollerhead, 2011). Coastal cliffs in unconsolidated materials and in soft, nonresistant rocks are more dynamic (Bezerra et al., 2011) and therefore more sensitive to climate change. Unconsolidated, low-lying coasts consisting of salt marshes, sandy barrier islands and beaches occur mainly along the St. Lawrence estuary and western shores of the Gulf of St. Lawrence (Quebec, Prince Edward Island and New Brunswick) and on the Îles de la Madeleine, as well as along the Bay of Fundy, especially at its head. Extensive, fine-grained tidal flats and salt marshes are exposed at low tide in the upper Bay of Fundy, where tides may exceed 14 m.

During the last glaciation, large quantities of sediment were deposited offshore because sea level was substantially lower than at present (Shaw et al., 2002). Subsequent glacial isostatic adjustments (*see* Chapter 2) resulted in increasing sea levels that reworked these sediments to form many of the beaches, spits and barrier islands seen today along the shorelines of the East Coast region (Davidson-Arnott and Ollerhead, 2011). However, apart from most of Newfoundland and Labrador, the abundant sediment resources contained on the continental shelf have largely been exhausted throughout the region, so most of the sediment presently supplied to the coastal beaches is sourced from shoreline erosion, the reworking of coastal sediments by littoral currents, and materials transported to the coast by rivers and streams. This leads to a chronic sediment deficit, which can be further exacerbated by the armouring of coastlines that is frequently associated with coastal urbanization (O'Carroll et al., 2006; Bernatchez et al., 2008b; Bernatchez and Fraser, 2012).

There is presently a generalized landward retreat of the coasts (Table 2) that will continue in the future. It is important to note that, apart from Prince Edward Island and sections of the New Brunswick coast, erosion rates have not been calculated in a consistent manner or with the same standards of measurement for comparison. Progradation (seaward advance of the coast) is occurring in some localized areas, often as a result of erosion along other shoreline areas (Forbes et al., 2004; O'Carroll et al., 2006; Jolicoeur et al., 2010; Davidson-Arnott and Ollerhead, 2011). The rate of shoreline erosion is associated with the lithology of the underlying bedrock (Davidson-Arnott and Ollerhead, 2011), coastal landforms or ocean-climate factors (e.g., storm surge, tidal stage and sea-level rise).

Rates of coastal erosion will also vary depending on the type of coastal landform. For example, rates of erosion in New Brunswick are highest in beach-dune systems (averaging 0.78 m/year) and lowest for cliffs (0.26 m/year; Table 3). Coastal landforms, such as beaches, dunes or marshes, have the capacity to re-establish following major erosion events (O'Carroll et al., 2006; Ollerhead et al., 2006), whereas a cliff or bluff will only recede. Eroded material plays an important role in supplying sediment to the rest of the coastal system within a littoral cell (*see* Chapter 2).

Human actions, such as coastal armouring (e.g., Finck, 2012), sediment extraction (e.g., Hunter, 1975; Taylor and Frobel, 2009) and building of dams (e.g., van Proosdij et al., 2009), interact with natural factors to influence sediment supply and coastal dynamics. For example, a study of barrier and non-barrier beaches along the head of South Bay Ingonish and Black Brook Cove, NS showed that seasonal sand accumulation resulted in fluctuations in beach width of 10–20 m at both sites. However, backshore areas varied significantly in their ability to repair themselves (Tibbetts and van Proosdij, 2013). At Ingonish beach, it took roughly 6–10 years to rebuild the crest elevation, whereas sites where the backshore areas were excavated and lowered by human activity still had not recovered 26 years later (Taylor and Frobel, 2009). A major challenge in projecting future changes in coastal geomorphology is the complex relationship between climate, coastal dynamics and human activity (Case Study 2 and *see* Chapter 2).

TABLE 2: Examples of historical bluff or cliff rates of retreat throughout the East Coast region. These rates may not be directly comparable due to differences in methodologies and types of measurements.

Location	Retreat rate	Time period	Reference
Quebec — Unconsolidated bluffs, Gulf of St. Lawrence coast	Up to 3.45 m/year	Various	(Bernatchez and Dubois, 2004)
New Brunswick — Till bluffs, Northumberland Strait	0.26 m/year (average)	1944–2001	(O'Carroll et al., 2006)
Prince Edward Island — Sandstone and till, entire island	0.28 m/year (average)	1968–2010	(Webster, 2012)
Prince Edward Island — Till bluffs, Gulf of St. Lawrence coast	Up to 2.24 m/year	1935–1990	(Forbes and Manson, 2002)
Prince Edward Island — Till bluffs, Northumberland Strait coast	0.74 m/year (average)	1935–2000	(O'Carroll, 2010a)
Newfoundland and Labrador — Unconsolidated bluffs, northeastern Avalon Peninsula	0.1 to 0.3 m/year	Undetermined	(Catto, 2011)
Nova Scotia — Till drumlin, Cape Breton	1.38 m/year (average)	2000–2007	(Force, 2012)
Nova Scotia — Till bluff, Bras d'Or Lakes	0.33 m/year (average)	1939–2014	(O'Carroll, 2015)
Nova Scotia — Basalt-sandstone bedrock, Bay of Fundy	0.06 to 0.8 m/year	Undetermined	(Desplanque and Mossman, 2004)
Nova Scotia — Till drumlin, Gulf of St. Lawrence coast	0.27 to 0.85 m/year	1939–2007	(Utting and Gallacher, 2009)
Nova Scotia — Till bluff, Northumberland Strait coast	0.4 m/year (average)	1964–2005	(Finck, 2007)

TABLE 3: Varying rates of erosion depend on coastal landform and geography in New Brunswick. Coastal erosion has been systematically monitored in the province for 45 years (New Brunswick Department of Energy and Mines, 2015). Abbreviation: N/A, not available.

Landform	Chaleur (m/year)	Northeast (m/year)	Northumberland (m/year)	All New Brunswick (m/year)
Cliff	0.18	1.17	0.26	0.26
Dune	0.35	1.20	0.85	0.80
Beach	0.32	1.01	1.00	0.76
Salt marsh	0.17	N/A	0.30	0.28

CASE STUDY 2

INTERACTIONS BETWEEN PHYSICAL, BIOLOGICAL AND HUMAN ASPECTS OF COASTAL DYNAMICS, MIDDLE COVE, NL

To better assess the vulnerability of a coastal site, location or community, a baseline study describing the links between the physical, biological and human aspects should be carried out. Middle Cove beach, located approximately 15 km north of St. John's, NL, is a prime spawning ground for capelin (capelin rolls) and is also a sought-after tourist site during the summer. The head of the cove and the beach were characterized as extremely sensitive to erosion by Catto and Catto (2014) due to the physiography of the coast; the fact that the cove faces the north to northeast storm-wave direction; the frequency of storm events (especially since 2001); the documented effects of storm activity since 1989; and the general absence of sea ice and limited snow cover.

The physical characteristics of Middle Cove beach (a moderate-wave-energy beach composed of relatively well-rounded, medium to coarse pebbles) make it an ideal spawning site for capelin (*Mallotus villosus*; Catto and Catto, 2014). Middle Cove is also one of the most heavily used beaches on the Avalon Peninsula. On warm summer days and evenings, and during capelin rolls season, more than 150 people can be found at Middle Cove beach. This visitor pressure results in gradual flattening of the upper parts of the beach, which alters the profile, destroys or restricts cusp development and results in compaction of the sediment.

The profile of Middle Cove beach, as is the case for most beaches, evolves on a seasonal basis, adjusting to coastal conditions. Of particular importance are the winter months, at which time a convex beach profile develops when waves are unable to reach the upper beach because of snow or an ice-foot cover. During winters where an ice foot is absent, the profile becomes concave (Catto and Catto, 2014). A steeper beach profile, caused by successive storm events or the absence of winter ice-foot protection, results in coarser beach material that is less favourable for capelin spawning. Warmer air and water temperatures in future will further impede winter ice-foot development (which has not been significant since the early 2000s), while relative sea-level rise could render the upper part of the beach more susceptible to scour and thinning. This will result in a beach even less favourable to capelin spawning during the roll season, and could also have economic and cultural effects.

4 CHANGES IN BIOLOGICAL PROCESSES AND COASTAL ECOSYSTEMS

Healthy coastal ecosystems provide a range of ecological services that are essential to the well-being of coastal communities. Enhancing and sustaining ecosystem resilience is of both ecological and socio-economic importance. Coastal ecosystems are integrated across terrestrial and marine environments, exchanging nutrients valuable for overall ecosystem function and providing habitats for species across a range of life-cycle stages. Direct economic benefits arise from a range of traditional and commercial activities, including fishing, shellfish harvesting and tourism. In addition, ecosystems such as wetlands, coastal dunes, spits and barrier islands enhance the sustainability of the built environment by acting as buffer zones that protect against severe wave and storm activity (e.g., Duarte et al., 2013).

Together, changing climate and increased anthropogenic pressures have led, and will continue to lead, to modifications to coastal habitats, affecting species distribution and dynamics, as well as altering and/or impairing ecosystem structure and function (Day et al., 2008; Rabalais et al., 2009; Michel and Pandya, 2010; Rabalais et al., 2010).

The following sections examine the ecological implications of changes in ocean climate (sea temperature, hypoxia, acidification and salinity), and the interaction of climate and human activities affecting water resources and ecosystem dynamics.

4.1 IMPLICATIONS OF CHANGES IN SEA TEMPERATURE

Sea temperature affects a range of biological processes (e.g., metabolic processes and growth rates) as well as species distribution and abundance (e.g., Hoegh-Guldberg and Bruno, 2010; Pankhurst and Munday, 2011). Global ocean primary productivity has declined since the early 1980s, with most of this decline linked to increased sea-surface temperatures in high and northern latitudes (Gregg et al., 2003; Hoegh-Guldberg and Bruno, 2010; Nye, 2010).

Primary productivity in the East Coast region is also affected by the scope and duration of sea-ice cover. In the Gulf of St. Lawrence, winter sea-ice contributes to water-convection processes, an important driver of primary production by phytoplankton (Le Fouest et al., 2005; Dufour and Ouellet, 2007). As sea-ice forms, it releases the salt content of the water in the form of denser brine, which sinks. This displaces less dense, nutrient-rich deeper waters toward the surface, causing upwelling and feeding nutrients to primary producers. Sea-ice melt also plays a major role in triggering phytoplankton blooms (Hoegh-Guldberg and Bruno, 2010). The likely cessation of winter sea-ice formation in the Gulf of St. Lawrence this century will affect phytoplankton abundance, timing and distribution, and alter primary production functions in this semi-enclosed marine basin (Dufour and Ouellet, 2007).

Ice also plays an important role in the redistribution and colonization of salt-marsh cordgrass (*Spartina alterniflora*) seeds and rhizomes in the East Coast region (van Proosdij and Townsend, 2006), and is an important contributor to the sediment budget of the high marsh (Dionne, 1985, 1989; Troude and Sérodes, 1988; Drapeau, 1992; van Proosdij et al., 2006). Ice in tidal flats is also important in the dispersal of macro-invertebrates and in the dynamics of spatially separated populations of the same species (Drolet et al., 2012).

Small changes in average seawater temperature have been associated with changes in abundance and distribution of coastal vegetation, finfish and shellfish (Burkett and Davidson, 2012). For fish such as salmon and eels, which use coastal habitats (salt-marsh creeks, estuaries and rivers) during part of their life cycle, temperature-induced changes will have great effects on some of their life stages and growth (Todd et al., 2008). Spawning is of special concern, as small increases in water temperature can reduce survivorship by affecting egg mortality and hatching (Pankhurst and Munday, 2011). Increased maximum summer water temperature was an important factor in the disappearance of marine eelgrass (*Zostera*) along Chesapeake Bay (east coast of the United States), near the southern distribution limit of this species (Burkett and Davidson, 2012). The condition of eelgrass beds is also a concern for Canada's East Coast region, as it is considered a prime indicator of overall coastal-ecosystem health.

Invasive species are another risk to ecosystems associated with warming water temperatures, with potential impacts on individuals, species' genetics, population and community dynamics, and ecosystem processes (Rockwell et al., 2009). These impacts can be localized or felt more broadly across the region (DFO, 2012a). Invasive alien species can disrupt food webs, resulting in a decrease in productivity for species such as oysters and eelgrass that are important in maintaining the structure of coastal ecosystems and habitats (Rockwell et al., 2009). Some studies attribute a marked decline in eelgrass health in Nova Scotia to an increase in invasive species such as the European green crab (*Carcinus maenas*; Garbary et al., 2014.) However, direct evidence of the effects of climate change on both eelgrass and invasive species such as green crab are still limited. Many of the invasive alien species that have already entered marine waters of the East Coast region are tunicates (filter feeders) that attach themselves to rocks or other surfaces of the sea floor. The shellfish aquaculture industry (e.g., mussel, oyster) is especially vulnerable to invasion by alien tunicate species, which can form significant colonies on the cultivated shells (Klassen, 2013). Examples include Club tunicate (*Styela clava*), observed in the Gulf of St. Lawrence and off Prince Edward Island; Diplosoma tunicate (*Diplosoma listerianum*), observed in eastern Canada; and European sea squirt (*Ascidiella aspersa*), observed off the coasts of Nova Scotia.

4.2 HYPOXIA

Hypoxia (also termed the 'dead zone') can result from eutrophication of coastal waters through overloading of nutrients (i.e., nitrogen, phosphorus, silicon and organic matter), leading to a depletion of the dissolved oxygen content of the water. Hypoxia can result in fish kills and mortality losses in other species, altered physiological development and growth (including reproductive abnormalities), altered migration patterns, loss of habitat for bottom-dwelling fishes and other benthic fauna, and habitat compression for pelagic fishes. These altered conditions result in reduced fish stocks, including those of valuable finfishes and crustaceans (Rabalais et al., 2010).

Hypoxia can also be related to large-scale ocean-water circulation. Historical data reveal that hypoxia is progressively worsening in the deep waters of the Gulf of St. Lawrence, especially at the heads of the Laurentian, Anticosti and Esquiman channels (Figure 8; DFO, 2010). Oxygen levels in these areas have declined since 1932 as a result of a higher influx of warm, oxygen-poor North Atlantic water and a reduced input of oxygen-rich cold water from the Labrador Current (DFO, 2012a). Hypoxic conditions drive away many fish, mollusc and crustacean species that cannot survive in oxygen-depleted conditions. In the St. Lawrence estuary, 5% of the Atlantic cod (*Gadus morhua*) tested died within 96 hours of exposure to 28% saturation, whereas half of the fish died within 96 hours when exposed to 21% saturation (DFO, 2012a). Cod almost completely avoid those areas of the estuary and Gulf of St. Lawrence where near-bottom levels of dissolved oxygen are less than 30% saturation (DFO, 2012a).

As surface-water temperatures increase due to climate change, it is likely that water stratification will strengthen, worsening hypoxia where it currently exists and facilitating its formation elsewhere. In areas of increased precipitation, increases in fresh-water discharge may result in increased

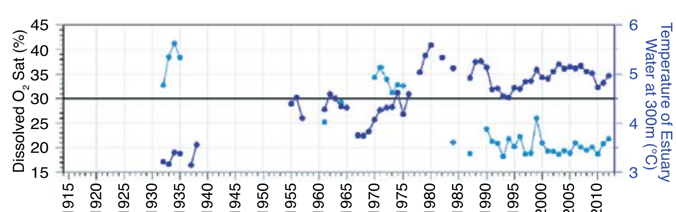

FIGURE 8: Dissolved oxygen saturation (O_2 Sat; light blue dots) and temperature (T; dark blue dots) between 295 m and the bottom in the deep central basin of the St. Lawrence estuary; 30% saturation marks the threshold of hypoxic conditions (DFO, 2010).

runoff of nutrients to coastal waters. The cumulative effect of increasing nutrient concentrations and enhanced water-column stratification will aggravate and accelerate hypoxia (Global Environment Facility Scientific and Technical Advisory Panel, 2011).

4.3 ACIDIFICATION

Increasing ocean acidification on a global scale is a major finding of the IPCC Fifth Assessment Report (IPCC, 2013). Effects of acidification include (Pörtner et al., 2014):

- dissolution of corals and carbonate exoskeletons;
- changes in benthic-invertebrate and fish productivity;
- increased growth of certain seaweeds and sea grass;
- changes in species composition and dominance;
- societal and economic impacts; and
- other potential impacts that presently remain unknown.

In the East Coast region, monitoring in the Gulf of St. Lawrence indicates that there has been no significant change in the pH of surface waters since 1934 (DFO, 2012a). In the St. Lawrence estuary, waters at greater than 100 m depth are acidifying faster than the surface waters because of *in situ* processes; this trend is not directly related to increased greenhouse gas emissions (Scarratt and Starr, 2012). In the Scotian Shelf area, pH has declined by about 0.1–0.2 units since the early 1930s (Stewart and White, 2001).

Many commercially important shellfish species harvested in Nova Scotia, such as the American lobster (*Homarus americanus*) and Atlantic deep-sea scallop (*Placopecten magellanicus*), and many aquaculture species, such as the blue mussel (*Mytilus edulis*), American oyster (*Crassostrea virginica*) and quahog clam (*Mercenaria mercenaria*), are vulnerable to acidification during the fertilization, cleavage, larval settlement and reproduction stages (Curren and Azetsu-Scott, 2013).

4.4 SALINITY

Records of ocean salinity for some areas of the East Coast region are available from the late 1940s, enabling calculation of decadal variability. Since the 1960s, for example, the Scotian Shelf area has seen oscillating periods of cold, fresh water (1960s, 1980s, 1990s) and warm, more saline water (1970s and 2000s; Breeze et al., 2002). The 1990 decadal mean surface salinities for the Gulf of St. Lawrence, the Scotian Shelf and the Bay of Fundy were the lowest ever recorded (Drinkwater and Gilbert, 2004).

Recent studies have reported a further decrease in salinity (freshening of water) off the coast of Nova Scotia (Scotian Shelf and Gulf of Maine; Drinkwater and Gilbert, 2004; Greene et al., 2008), potentially resulting from the melting of Arctic sea ice. As Arctic sea ice continues to melt in the future, the resulting pulses of fresh water will increase the strength of the southward-flowing Labrador Current and reduce sea-surface salinity. This could result in biogeographic changes of some species, such as was documented for the boreal plankton *Neodenticula seminae*, which is now common in the North Atlantic flora (Greene et al., 2008). Based on sedimentary records, this Pacific Ocean plankton species had not been present in the East Coast region for 800 000 years (Nye, 2010).

Under climate change, it is projected that the North Atlantic Oscillation (NAO; *see* Chapter 2) will be dominantly in a positive phase, shifting the warmer water of the Gulf Stream northward and increasing the volume of cold water transported by the Labrador Current (Frumhoff et al., 2007). A projected decrease in annual outflow from the Great Lakes watershed will also impact the circulation and salinity of the Gulf of St. Lawrence (Dufour and Ouellet, 2007).

Organisms can respond in several ways to these changes in temperature and salinity, but a shift in spatial distribution is the hypothesized first response (Nye, 2010). The responses of natural ecosystems are likely to be nonlinear, such that change may not occur until a threshold has been reached, at which time rapid, dramatic transitions may be expected (Dufour and Ouellet, 2007).

4.5 WATER QUALITY

Coastal water quality affects many parameters that govern the overall health and functioning of marine ecosystems (Burbridge, 2012). Water quality could suffer in areas experiencing increases in rainfall. For example, heavy precipitation events can cause problems for water infrastructure, as sewer systems and water-treatment plants can be overwhelmed by the increased volume of water. Heavy downpours can also increase the amount of runoff into rivers and lakes, washing sediment, nutrients, pollutants, trash, animal waste and other materials into water supplies, making them unusable, unsafe or in need of additional water treatment.

In the East Coast region, there has been no systematic monitoring of coastal-water quality that would enable a spatial or trend analysis of the quality of coastal marine waters (Burbridge, 2012) and possible linkages to climate change versus other human activities. Apart from data required to determine the safe levels of specified contaminants found in fish, shellfish and fish products (Stewart and White, 2001; Simms, 2002), water quality in nearshore coastal environments remains largely unknown (Mercer Clarke, 2010). Contaminant concentrations in water, sediments and/or biota have been measured in a number of provincial harbours and estuaries, as well as in the open waters of the Scotian Shelf, the Bay of Fundy and the Gulf of St. Lawrence. For most open-water sampling sites, contaminant concentrations are low (i.e., at or near background concentrations) and there is little or no indication that environmental harm can be attributed to the contaminants (CBCL Limited, 2009). Contamination has been documented at sites in proximity to urban and industrialized centres, such as Halifax Harbour, NS; Sydney Harbour, NS; Strait of Canso, NS; Clam Harbour, NS; and the area of Belledune, NB.

4.6 SALTWATER INTRUSION

Saltwater intrusion is the infiltration and mixing of seawater with fresh water stored in the pores and fractures of the underlying soil and bedrock of coastal lands. The seawater–fresh-water interface is naturally dynamic and fluctuates in response to changes in recharge, withdrawals and sea level. Displacement of fresh water by seawater occurs as seawater moves inland as a result of sea-level rise, storm surge, coastal erosion or prolonged dry periods (Phan, 2011; Loaiciga et al., 2012).

Saltwater intrusion is expected to become a more prominent issue as a result of climate change, although increasing demand for groundwater resources will be a more important driver than sea-level rise. Warmer summers are likely to lead to increased withdrawals of groundwater (Government of Prince Edward Island, 2011), particularly if this is associated with increased tourist demand. Although sea-level rise increases the risk of seawater intrusion and well contamination, the extent of this increase is not well understood (Chang et al., 2011). Increased coastal flooding associated with sea-level rise and storm surges could contaminate potable-water wells with saltwater.

A large proportion of the population of the East Coast region (nearly 100% in the case of Prince Edward Island and the Îles de la Madeleine) relies on groundwater for potable water (Rivard et al., 2008). Examples of groundwater impacts associated with natural and/or human factors are documented for every province in the East Coast region:

- **New Brunswick:** Shippagan and Richibucto (due to overpumping; MacQuarrie et al., 2012); many private wells are intermittently contaminated by seawater during storm surges in Le Goulet
- **Nova Scotia:** Upper Lawrencetown and Pictou (due to development and increased groundwater demand); Pugwash and Wolfville (Ferguson and Beebe, 2012)
- **Prince Edward Island:** Summerside (due to overpumping; Hansen, 2012); York Point and Souris West (caused by natural saltwater intrusion); Prince Edward Island is particularly vulnerable to saltwater intrusion because of its geography and dependence on groundwater for potable water (Barlow and Reichard, 2010)
- **Newfoundland and Labrador:** saltwater intrusion is well documented in L'Anse-aux-Meadows (N. Catto, personal communication, 2014); the extent of saltwater intrusion at a provincial level cannot be confirmed (Adams, 2011)
- **Quebec:** there is no documented saltwater intrusion, but drawdown saltwater cones exist beneath some wells on the Îles de la Madeleine and a migration of the saltwater interface has been reported for the Île du Cap aux Meules in the Îles de la Madeleine (Chaillou et al., 2012a, b); the Îles de la Madeleine archipelago is solely dependent on groundwater resources for its water consumption and is highly vulnerable to overpumping, particularly in summer when visitor traffic currently doubles the local population.

4.7 EFFECTS ON ECOSYSTEMS

Changes in environmental conditions often result in a shift in spatial distribution of species and ecosystems (Walther et al., 2002; Parmesan and Yohe, 2003). As waters warm, for example, populations of mobile marine organisms can change spatially as the area of favourable habitats changes (Section 4.1). This seems to have been the case for some fish species of the East Coast region during the late 1980s and early 1990s, when northern cod and capelin were detected in the northwest Atlantic (Rose et al., 2000). A study of fish stocks off the coasts of North America showed that 72% of fish species shifted their overall centre of biomass northward and increased their average depth of occurrence during the period 1968 to 2007 (Cheung et al., 2011). The temperature at which these species have been found over those same 40 years has not changed (Nye, 2010), suggesting that fish are maintaining their preferred ambient temperature range by moving to higher latitudes or to deeper waters. Distributions of some northeast Atlantic species are projected to shift northward at an average rate of around 40 km per decade (Cheung et al., 2009). Projections of changes in species distribution as a result of climate change for the Gulf of St. Lawrence and the Atlantic coasts suggest that there could be a high turnover in species (i.e., many losses and many gains; Cheung et al., 2011). Differential species responses to climate change are likely to lead to trophic mismatches and/or perturbed prey-predator relationships, breaking the ecological equilibrium and leading to community reassembly (Walther et al., 2002; Beaugrand et al., 2003; Edwards and Richardson, 2004; Collie et al., 2008).

Table 4 presents the major anticipated effects on habitats in the East Coast region arising from sea-level rise and changing storm patterns. Within intertidal areas, rising temperatures will affect different beach ecosystem components. For many beach species, range extension will be a limiting factor due to the lack of dispersal capabilities at the larval stage (peracarid crustaceans), while changes in plankton communities will also impact beach macrofauna (i.e., peracarids and insects; Defeo et al., 2009).

4.8 MIGRATION OF ECOSYSTEMS AND COASTAL SQUEEZE

Coastal ecosystems dynamically adjust to changes in sea level. Field observations, including *in situ* tree stumps and roots, and fresh-water peat layers exposed at low tide or after storm events at numerous locations (Figure 9), provide evidence of the migration of coastal ecosystems due to relative sea-level rise in the past 6000 years (e.g., Garneau, 1998; Quintin, 2010).

Beaches, dunes, sand spits, barrier islands and their associated coastal marshes can adjust to increasing sea levels by continuous landward migration (Davidson-Arnott, 2005). In sandy environments, landward migration is achieved through overtopping (where waves surmount a beach crest but do not erode it, gradually adding sediments to the crest), breaching and overwash (waves surmount and erode the beach crest, depositing sediments farther landward), tidal-inlet development (leading to the formation of tidal deltas) and wind action (strong offshore winds transporting sand in the backdune and in the marsh or lagoon; Taylor et al., 2008; Jolicoeur et al., 2010; Mathew et al., 2010; Stéphan et al., 2010; Ollerhead et al., 2013). This process, which is strongly related to storms, allows sandy features to move landward and adjust vertically as sea level rises. However, high rates of relative sea-level rise can result in drowning of coastal landforms (O'Carroll et al., 2006; Kelley et al., 2013).

FIGURE 9: Photos of *in situ* tree stumps exposed at low tide or after storm events. Photos **a)** and **b)** shows tree stumps and roots that have been uncovered by erosion and **c)** shows tree stumps that been submerged by rising water levels. Locations of photos: **a)** Le Goulet, NB; **b)** Barachois, NB; and **c)** Bras d'Or Lakes, NS. *Photos a) and b) courtesy of D. Bérubé, Department of Energy and Mines New Brunswick, and photo c) courtesy of S. O'Carroll, Geo Littoral Consultants.*

TABLE 4: Projected impacts of climate change related to sea-level rise and changes in storm patterns on the coastal habitats of the East Coast region (*adapted from* Nye, 2010).

Coastal feature	Impacts
Beaches	Large-scale morphological adjustments to absorb the wave energy, including: ▪ overwash and erosion ▪ potential formation of new beaches down-drift of erosion areas ▪ landward migration of barrier beaches
Salt marshes	More frequent tidal flooding Sedimentation and possible landward migration at a rate equal to sea-level rise, depending on sediment and organic matter supply Increased margin-edge erosion (van Proosdij et al., 2006) Changes in carbon storage (Chmura, 2011)
Fresh-water marshes	Gradually become salt marshes or migrate inland
Estuaries and tidal rivers	Increased tidal volume and exchange Further penetration of saltwater
Unconsolidated cliffs	Accelerated erosion
Species and ecosystems	Modification of coastal habitats Threatened viability from changes in numerous factors, including water temperature, salinity, sea-ice patterns, runoff and water quality

In coastal marshes, fine-grained material deposited on, and/or organic matter produced in, the marsh raises the surface, keeping it in the same position relative to sea level (Allen, 2000). Gradually, a transition from low-marsh to high-marsh vegetative communities evolves and, in ideal settings, the marsh migrates landward. Again, if sea level rises faster than the sediments can be supplied, marshes can be flooded and replaced by open water, as was observed in southeastern New Brunswick between 1944 and 2001 (Hanson et al., 2006). Changes in sediment supply will also affect marsh survival. Kirwan and Megonigal (2013) demonstrated that, under moderately rapid sea-level rise, a marsh that is stable under historical sediment loads would submerge if the sediment load is reduced. This suggests that dam construction and land construction that result in the reduction of sediment load could cause marshes to become less stable in the future, even if the rate of sea-level rise were to remain constant.

Marshes developed in areas of high tidal range and high sediment availability are generally considered more resilient to sea-level rise than those developed in areas of low tidal range and low sediment availability (Chmura et al., 2001; Paskoff et al., 2011; Bowron et al., 2012). In the East Coast region, historical rates of salt-marsh aggradation range from 1.3 mm/year along the Northumberland Strait coast of New Brunswick to 4.4 mm/year in the upper reaches of the Bay of Fundy (Chmura et al., 2001; Davidson-Arnott et al., 2002; van Proosdij et al., 2006; Bowron et al., 2012). Along the St. Lawrence estuary, average vertical accretion rates range from 1 to 2 mm/year, and as high as 3 mm/year in about 10% of cases (Dionne, 2004).

Vertical accretion rates can adjust to changes in the rate of relative sea-level rise (Kirwan et al., 2010). While cyclicity in edge erosion and progradation is part of natural marsh evolution at the decadal scale (Allen, 2000; Ollerhead et al., 2006; van Proosdij et al., 2006; van Proosdij and Baker, 2007; Allen and Haslett 2014), marshes will migrate landward if there is space for them. However, retreat cannot occur where natural slopes behind the marsh are too steep, or where the path is blocked by structures such as roads, seawalls, dikes or buildings, creating a situation known as 'coastal squeeze' (Figure 10; Doody, 2013; Pontee, 2013; Torio and Chmura, 2013).

Coastal squeeze is not exclusive to coastal marshes but can also apply to other types of coastal ecosystems (e.g., beaches, dunes) and includes natural constraints, such as cliffs, that may limit landward migration (Figure 10c; Sterr, 2008; Jackson and McIlvenny, 2011; Doody, 2013; Hapke et al., 2013). In the East Coast region, studies in the Baie des Chaleurs, NB (Bernatchez and Fraser, 2012) and in the Îles de la Madeleine, QC (Jolicoeur and O'Carroll, 2007) have shown that the presence of human infrastructure is causing the loss of coastal habitats. In the Baie de Kamouraska, QC,

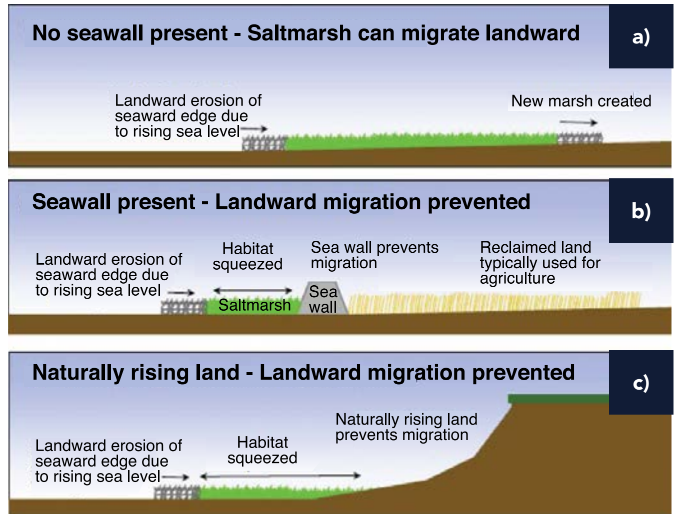

FIGURE 10: Illustration of the landward migration and prevented landward migration of coastal habitat that has been eroded by rising sea level: **a)** landward migration occurs naturally, **b)** migration has been prevented by a sea wall resulting in the 'squeeze' of habitat, and **c)** migration has been prevented by naturally rising land resulting in the 'squeeze' of habitat (Pontee, 2013 *adapted from* Doody, 2013).

dikes constructed to convert marsh into farmland are squeezing the intertidal zone as sea level rises. Increasing development of the coastal zone across the region increases coastal squeeze and could lead to loss of valuable marshes, dunes and beaches in coming decades (Jolicoeur and O'Carroll, 2007; Craft et al., 2009; Bernatchez et al., 2010; Feagin et al., 2010; Doody, 2013; Torio and Chmura, 2013; Cooper and Pile, 2014).

4.9 IMPACTS OF HUMAN ALTERATIONS ON THE COAST

Human activities leading to changes in land use, water-courses and shorelines have already impacted nutrient and contaminant runoff, storm-water management and water quality in areas of the East Coast region. Shoreline hardening with various protection methods (walls, rip-rap, dikes, groins, pavements and landfill) and dredging have altered coastal circulation patterns and sediment transport, potentially exacerbating shoreline erosion and reducing the ability to attenuate flooding (Section 6.3.4; e.g., Hapke et al., 2013; Pontee, 2013). Changes to land cover can destroy or impair native-species habitats (Ban and Alder, 2008; Halpern et al., 2008; Burkett and Davidson, 2012). The use of hard engineer-ing measures to protect societal assets can lead to the loss of intertidal sand habitat (Defeo et al., 2009; Leclerc, 2010; Bernatchez and Frazer, 2012; Spalding et al., 2014). Measures that promote the resilience of coastal areas include protec-tion, revegetation and stabilization of dunes; maintenance of sediment supply; and provision of buffer zones, rolling easements or setbacks that allow landward migration of the coastline (*see* Chapter 3; Defeo et al., 2009).

Understanding how, and to what degree, a coastal system will be modified by climate change remains a challenge, given the complex interrelationship between natural and human systems. This is highly evident within the extensively diked estuaries of the Bay of Fundy, where many of the main rivers draining into the bay have been fully or partially obstructed (van Proosdij and Page, 2012). An engineering structure, such as a dike, that reduces the extent of tidal flooding, a structure that decreases the cross-sectional area of a channel or the closure of a section of an estuary will, as a consequence, change the magnitude of the characteristic tidal discharge (van Proosdij and Baker, 2007; van Proosdij et al., 2009). This can lead, in turn, to rapid sedimentation and/or alteration of the intertidal morphology of the estuary and position of intertidal habitat. The response of the system, however, depends on a large number of factors, including sediment properties, estuary morphology and the timing and sequence of engineering alterations (*see* van Proosdij et al., 2009 for comparison of Petitcodiac River, NB to Avon River, NS).

5 COMMUNITIES AND ECONOMIC SECTORS

Coastal communities and economic activity in the East Coast region will be affected by the climate-related changes described in Sections 3 and 4, especially those associated with coastal hazards, including erosion and storm-surge flooding (Hughes and Brundit, 1992; Arkema et al., 2013). The impacts associated with climate change reflect both the degree of exposure to natural hazards and the vulnerability of the system exposed (Figures 11, 12). Vulnerability, or the predisposition to be adversely affected, encompasses a variety of elements, including sensitivity to harm and the capacity to cope with changes or to adapt to them (*see* Chapter 1, Box 4 for definitions of key terms). Adaptive capacity is influenced by access to resources, as well as important social factors. Adaptation actions are undertaken with the goal of reducing risks or taking advantage of opportunities. However, many human alterations to the coast have proven to be maladaptive in that they affect coastal processes in ways that increase the vulnerability of coastal ecosystems, communities and infrastructure.

This section examines the concepts of exposure, sensitivity and capacity to adapt, using examples from the East Coast region. It then provides an overview of recent initiatives to document vulnerabilities, and highlights climate change impacts as they relate to key economic activities (e.g., fisheries, transportation and tourism) and community health, well-being, culture and heritage.

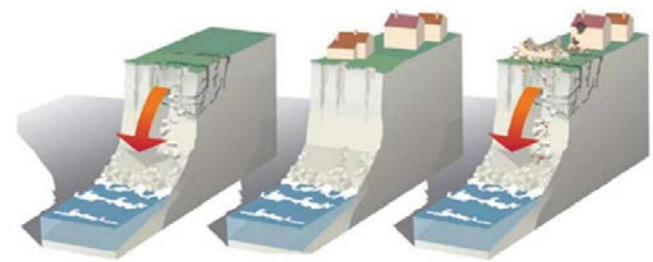

FIGURE 11: Coastal hazards, risks associated with exposure of valued assets (including ecosystem services) and impacts (*adapted from* Ministère de l'Écologie et du Développement durable de France, 2004).

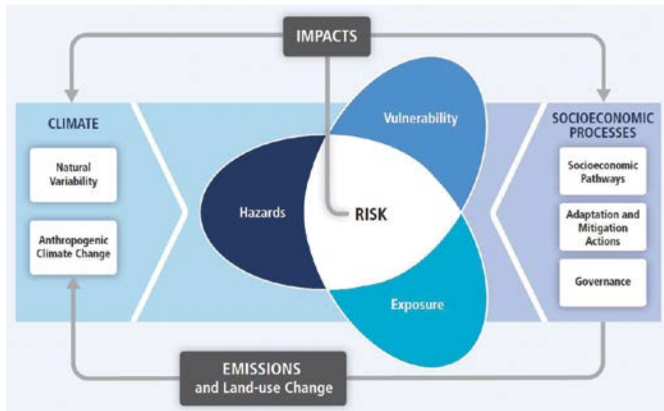

FIGURE 12: Climate impacts associated with coastal risks result from the interaction of coastal hazards and the vulnerability of exposed systems (*from* IPCC, 2014).

5.1 EXPOSURE

Exposure refers to the presence, in places and settings that could be adversely affected, of people; livelihoods; species or ecosystems; environmental functions; resources; infrastructure; or economic, social or cultural assets (IPCC, 2014). In coastal areas, exposure is influenced by physical attributes or characteristics of the coastal zone and is directly related to the likelihood that hazardous conditions will occur (Dolan and Walker, 2006; Tibbetts and van Proosdij, 2013). Settlements on a former low-lying marshland or eroding coastal bluff are more exposed to risks related to the impacts of sea-level rise, storm surge and accelerated erosion than are settlements located above the higher high tide water level or on resistant bedrock.

Exposure is often associated with the amount of wave energy reaching the coast. It is influenced by the orientation of the shoreline relative to wind and wave action, as well as features that decrease the amount of energy reaching the shoreline, such as shorefast ice, offshore sea ice, intertidal vegetation and nearshore bars. The direction of the most damaging waves varies throughout the East Coast region.

For example, winds in Prince Edward Island are mainly from the west, but the largest waves are generally from a north-northwesterly direction (Davies, 2011). In northern New Brunswick, local residents say that the most damaging wind and waves come from the northeast and refer to these winds and associated violent storms as 'les nordets' (O'Carroll, 2008). In western parts of Cape Breton, NS, damaging local winds are known as 'les suètes' and are created when a frontal inversion causes a funnelling effect over the Cape Breton Highlands. As the winds rush down the side of the highlands, strong gusts develop; these have been recorded to exceed 150 km/h.

With some exceptions, communities lying on coastlines exposed to the full swell and storm waves from the Atlantic Ocean receive the most wave energy. Wave climate and associated exposure varies throughout the year (Dufour and Ouellet, 2007) and between years (Davies, 2011). For example, the north shore of Prince Edward Island shows strong interdecadal variability, with the period 2000–2009 having more wave energy than any other decade since the 1960s (Davies, 2011). This relates, in part, to ice cover, which decreased from a mean of 103 days in the 1970s to a mean of 80 days in the 2000s (Davies, 2011) along the same shoreline.

Another factor influencing exposure is tidal range, which varies significantly across the East Coast region, from less than a metre near the Îles de la Madeleine to more than 16m in Cobequid Bay on the Bay of Fundy (e.g., Cooper and McLaughlin, 1998; Boruff et al., 2005; Rao Nageswara et al., 2008; Kumar et al., 2010; Pendleton et al., 2010; Tibbetts and van Proosdij, 2013). Coastal systems in areas with a small tidal range (microtidal) are generally less able to accommodate extreme water levels associated with storm surge, as there is a smaller area available to absorb the surge. In addition, since a storm surge would have greatest impact when it occurs at or near the high-tide level, the likelihood of damaging surge events is lower for areas with a large tidal range (macrotidal; Desplanque and Mossman, 2004).

The most common factors that reduce the flow of wave energy to coasts in the East Coast region are offshore sea ice (Section 3.3), shorefast ice (e.g., Northumberland Strait coast, Gulf of St. Lawrence, Newfoundland), sea-grass beds (e.g., Port Joli harbour, NS), foreshore marsh (salt marshes developed seaward of a dike structure; e.g., Minas Basin, NS) or dunes (e.g., north shore of Prince Edward Island), and beach barriers (e.g., spit in Bouctouche, NB or gravel barachois [coastal lagoon separated from the ocean by a sand or shingle bar] in Newfoundland). For example, coastal wave energy on the northeast coast of the island of Newfoundland can be largely muted once offshore ice cover develops, but coastlines along the southern side of the island remain vulnerable to erosion by winter storms (Taylor et al., 1997; Forbes et al., 2000; Ingram, 2004; Catto, 2011). Foreshore marshes are capable of attenuating up to 97% of incoming wave energy, depending on the size of the marsh (Möller and Spencer, 2002; Doody, 2008; van Proosdij and Page, 2012; Möller et al., 2014). Preservation and/or encouragement of foreshore-marsh habitat are examples of adaptation measures that aim to enhance and/or restore ecological processes to help decrease environmental impacts from built infrastructure (Chapman and Underwood, 2011; van Proosdij and Page, 2012).

5.2 SENSITIVITY

Sensitivity is the degree to which a system (e.g., ecosystem, community, infrastructure) is affected, either adversely or beneficially, by climate-related changes (IPCC, 2014) and is related to both the severity of the exposure and the potential consequences. Coastal settlements can be differentially sensitive to climatic risks, depending on their socio-economic and cultural characteristics, and their planning and operational structures.

Historical European settlement patterns in the East Coast region were driven largely by the need to access or transport resources such as fish, ore and wood, so infrastructure like warehouses and roads were built along or close to the shore. Throughout much of the region, communities had their beginnings providing homeports and infrastructure in support of inshore and offshore fisheries. Coastal villages were initially linked by boat transport and, when roads were built, they followed the historical pattern. Throughout French-Acadian Nova Scotia, extensive dike systems were constructed by early settlers to drain fertile salt marshes for agriculture purposes. Major ports constructed in Saint John, NB, Halifax, NS, St. Johns, NL and Québec, QC evolved to continue trade links with eastern North America and Europe.

Sensitivity to climate impacts is influenced, in part, by the persistence of these early settlement patterns despite the fact that, in some cases, contemporary industries bear little resemblance to activities of the past. This is particularly notable in diked marshlands, which were formerly harvested for highly valued salt-marsh hay (Lieske, 2012). For example, the Chignecto Isthmus region (which joins the provinces of Nova Scotia and New Brunswick) underwent a shift from a major hay-production centre to a critical transportation and communications corridor that annually moves $43 billion worth of international trade goods. Yet infrastructure throughout many of the towns and villages in the region continues to rely on approximately 33 km of the early agricultural dikes for protection against the rising tides

(Webster et al., 2012b; Wilson et al., 2012). A once-in-10-years storm surge could overtop approximately 90% of the existing dike system and temporarily inundate 20% of the Town of Sackville, NB (Lieske and Bornemann, 2012).

Contemporary development patterns are also influenced by tourism and recreation opportunities, such as cottages and seasonal rentals close to the coast. The small chalets and cabins that were once people's secondary residence are now often modified to become principal homes. This is evident along most shores of the East Coast region, particularly along the shores of Northumberland Strait, the north shore of Prince Edward Island and the southern shores of Nova Scotia. These changes significantly increase the asset value at risk from coastal hazards (Delusca et al., 2008), not only in terms of absolute dollars but also because different levels of risk are tolerated for secondary and principal residences.

Sensitivity is also related to the degree to which the hazard impacts areas of environmental, social, economic and cultural significance. For example, a community that becomes isolated from emergency services when its only transportation link has been flooded or destroyed is more sensitive than one that has more options for access to services and/or evacuation. This was illustrated in 2010, when rainfall associated with Hurricane Igor washed out roads and bridges across the Burin and Bonavista peninsulas of Newfoundland. Sensitivity is also influenced by social conditions (i.e., income, age and education), community resources and social structures (Dolan and Walker, 2006; Garmendia et al., 2010; Rapaport et al., 2013). In some areas of the East Coast region, the aging rural population and their greater sensitivity to direct (e.g., flooding and excessive heat) and indirect (e.g., inability to access social support, food and medical care) climate stressors is a particular concern (Rapaport et al., 2013). Other considerations with respect to economic sensitivity include possible impacts of extreme weather events on employment and industrial infrastructure.

5.3 CAPACITY TO ADAPT

Adaptive capacity refers to the ability of a country, region, community or group to implement effective adaptation measures (e.g., IPCC, 2007; Lemmen et al., 2008). It is influenced by a large number of social, economic, regulatory and political factors (e.g., Smithers and Smit, 1997). As change becomes more rapid, the adaptive capacity of many communities may be challenged. Extreme impacts can exceed human and financial resources to address them, and can cause physical, financial and psychological stress. Stress on local governments and service providers, and other responders to disasters, can reduce adaptive capacity to address climate change impacts in both the short and long terms (Manuel et al., 2012).

Within the East Coast region, there has been a surge in provincial and local government initiatives and community-university research partnerships during the past decade, all focused on improving adaptive capacity and moving forward on adaptation planning for climate change. For example, the Atlantic Climate Adaptation Solutions Association is a partnership among the governments of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador that is working with the Government of Canada to assist Atlantic Canadians to better prepare for, and adapt to, climate change (Atlantic Climate Adaptation Solutions Association, 2012). In Quebec, Ouranos, a joint initiative of the Government of Québec, Hydro-Québec and Environment Canada, with the financial support of Valorisation-Recherche Québec, was created as a consortium on regional climatology and adaptation to climate change and has brought together more than 400 scientists and professionals from across relevant disciplines.

Numerous initiatives have been undertaken in recent years throughout the East Coast region to develop practical tools for adaptation planning (*see* Chapter 3) and to incentivize adaptation action (Case Study 3). Many smaller communities with limited resources have benefited by collaborating with universities and colleges across the region that can provide expertise and technological innovations (e.g., Bernatchez et al., 2008a; Fedak, 2012; Lieske, 2012; Manuel et al., 2012).

CASE STUDY 3

FINANCIAL INCENTIVE FOR ADAPTATION PLANNING: THE MUNICIPAL CLIMATE CHANGE ACTION PLAN OF NOVA SCOTIA

The federal government transfers funds equivalent to a portion of the federal excise tax on gasoline to municipalities for infrastructure projects that contribute to cleaner water, cleaner air and/or reduced greenhouse-gas emissions. In Nova Scotia, terms and conditions for 'gas tax' eligibility are defined in the Canada–Nova Scotia Agreement on the Transfer of Federal Gas Tax Funds. As a requirement for funding, Nova Scotia municipalities had to submit a Municipal Climate Change Action Plan (MCCAP) by the end of 2013. The MCCAP has served as a means of identifying priority areas for adaptive action.

Service Nova Scotia and Municipal Relations, and the Canada–Nova Scotia Infrastructure Secretariat provided a guidebook (Fisher, 2011) that outlines a six-step framework to assist municipalities with the adaptation portion of MCCAP development. Each step consists of a series of questions that, cumulatively, assess if and how local climate trends and projections would introduce or exacerbate hazards, and in what ways these changing conditions may affect people's safety, municipal services and assets, and other community characteristics (e.g., local economic functions, sense of place and community well-being, emergency preparedness planning and capacity for response).

A key to successful MCCAP development for all municipalities in Nova Scotia was the document *Scenarios and Guidance for Adaptation to Climate Change and Sea Level Rise – NS and PEI Municipalities* (Richards and Daigle, 2011), which provided a common starting point with respect to climate trends and projections. Beyond this foundation document, the quality of an MCCAP was defined largely by a municipality's internal capability to interpret climate trends and projections in a local context, in order to understand what impacts are likely and the potential severity of their consequences.

A recent survey of municipal climate change adaptation around the Bay of Fundy indicated that a combination of factors, including limited staff time and expertise, stretched budgets and lack of jurisdictional authority, make it difficult for municipalities to address even well-documented vulnerabilities to climate change (Schauffler, 2014). The MCCAP process highlighted several findings, including that key factors such as geology are often excluded in land-use planning decisions. In large part, this is a reflection of the high daily demands placed on the land-use– and community-planning sector, and the lack of support to seek out and include additional information when developing long-term land-use strategies. Other challenges highlighted by the MCCAP process include the following:

- The limited jurisdiction of municipalities makes it difficult to address some key climate risks. For example, private wells are controlled provincially. Therefore, although a community may experience significant social and economic impacts from wells going dry, it is not involved in groundwater monitoring, management or well permitting. In addition, there are a number of issues (e.g., extension of water services) that fall under provincial jurisdiction where municipal units could play a greater role in shaping regional responses to climate change adaptation.
- Some of the scientific and technical information that municipalities sought was unavailable or not easily accessible. The MCCAP process highlighted what information or tools are helpful for municipalities to enhance climate resilience, and raised the question of who should be responsible for the collection and dissemination of that information. As municipalities do not have experts in coastal processes on staff, they must seek external expertise if, for example, erosion is an issue worthy of investigation.

Despite these challenges, the Nova Scotia MCCAP process can be considered a success in many ways. For example, the inclusion of emergency-management personnel on municipal climate change committees and the collaborative assessment processes renewed recognition of the relationship between land use and disaster-risk reduction and response. This prompted improvements in information exchange (i.e., mapping) and collaboration between these two facets of municipal management.

Municipalities generally came to a shared conclusion that they had an important role to play in helping residents manage their own risk by sharing what was learned about climate risks during the MCCAP process. Simultaneously, judgments were made as to when providing information may prove insufficient, and when policy is needed to control development with the aim of reducing risks. It was also recognized that seldom will 'one-size-fits-all' policies work when addressing coastal hazards, so site-specific work is needed to balance a municipal responsibility to respond to known (or suspected) risk and the desire to allow appropriate use of a property. The MCCAP process has led to notable progress at the provincial level to organize, improve upon and disseminate relevant data to municipalities.

By requiring that MCCAPs consider social and economic climate impacts, there has been a subtle yet profound shift from climate-adaptation planning being considered a one-off research topic to it becoming a process through which a municipal corporation actively gauges trends in external forces (i.e., macroeconomics, demographics, health and governance) in combination with honest self-evaluation. This is an approach that provides benefits no matter how the climate unfolds.

Advances in technology and an increased ability to translate data into knowledge have increased adaptive capacity across the East Coast region. High-resolution LIDAR (Light Detection and Ranging) topographic surveys and advanced geographic information systems have enabled inundation studies at many sites in the East Coast region (e.g., Daigle, 2006; Robichaud et al., 2011; Fedak and van Proosdij, 2012; Webster et al., 2012a; Lieske et al., 2014; Daigle et al., 2015). Effective identification of hazard areas for planning purposes has also been conducted with coarser, digital elevation models (e.g., Isle Madame, St. Margarets Bay, Cape Breton and parts of the south coast of Nova Scotia; Lane et al., 2013; Rapaport et al., 2013).

5.4 VULNERABILITY ASSESSMENTS

During the past decade, there has been a significant increase in the number of vulnerability assessments performed in the East Coast region, most in the form of technical reports. In developing this chapter, 226 individual studies conducted since the late 1990s were inventoried for the East Coast region. Many of these studies covered more than one community. The studies were grouped in broad categories in order to paint a picture of the work carried out and the focus of research so far (Figure 13). Note that the inventory is limited to publicly and readily accessible documents, and is therefore not exhaustive.

Of the studies compiled, more than 40% of those conducted in Prince Edward Island, Quebec and New Brunswick focused on coastal erosion. Vulnerability and ecosystem restoration studies are prominent in Nova Scotia, with special reference to the MCCAPs and the extensive diked areas of the province. In Newfoundland and Labrador, flooding dominated the literature examined (60%). It should be noted that the extensive province-wide assessments of erosion by Catto (2011) and Webster (2012) in Newfoundland and Prince Edward Island, respectively, are likely not adequately represented in this analysis.

Areas where communities currently lack significant assessment, such as the eastern shore of Nova Scotia, the mid-Fundy shore of New Brunswick, much of Newfoundland and Labrador, and the Quebec North Shore, are evident in Figure 13. Addressing some of these gaps may be assisted by increased accessibility of public data. For example, the New Brunswick Government is in the process of making its Coastal Erosion Databank public, so that more than 14 500 erosion rates will be accessible online via an interactive map (D. Bérubé, personal communication, 2015). Erosion data for Newfoundland and Labrador will also soon be available online as an interactive map (N. Catto, personal communication, 2015).

Although there are multiple methods for assessing coastal vulnerability, the most common methods utilize indices that simplify a number of key parameters to create a single indicator (Carrasco et al., 2012). The earliest studies of coastal vulnerability were based largely on biophysical characteristics, defining vulnerability in terms of exposure to a hazardous event regardless of impacts on social conditions (Abraham et al., 1997; Dolan and Walker, 2006). This approach has been commonly used in the East Coast region with a primary focus on coastal erosion and flooding due to sea-level rise and/or storm surge. In limited areas, two- and three-dimensional hydrodynamic modelling studies have been performed to assess the velocity of flood water versus depth (e.g., Wolfville, NS; Fedak, 2012; van Proosdij, 2013), the coupled effect of fresh-water drainage and tidal surge in an estuarine area (e.g., Oxford and River

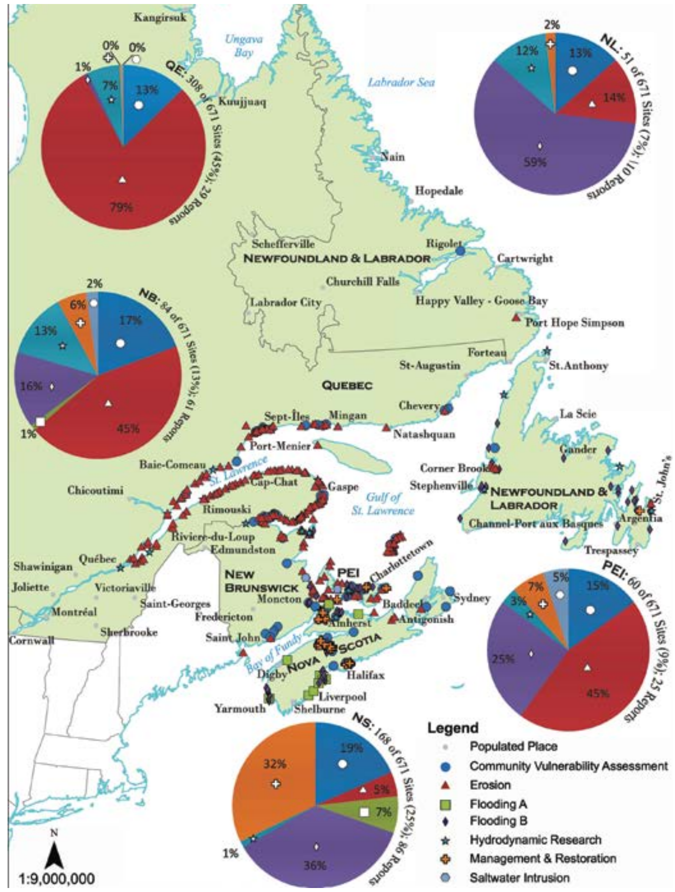

FIGURE 13: Spatial compendium of sites examined through vulnerability studies in the East Coast region. Legend categories include community vulnerability assessments, erosion (rate, shoreline adjustment, geological studies), flooding A (general extent with SLR), flooding B (SLR and/or storm surge with infrastructure and/or social variables), hydrodynamic (1-D and 2-D models and scenarios), management and restoration (shoreline restoration and management/policy assessments), and saltwater intrusion (intrusion or transition studies). The inventory was limited to publicly and readily accessible documents, and is therefore not exhaustive. Compendium compiled by B. MacIsaac and cartography by B. Perrott (Maritime Provinces Spatial Analysis Research Centre, Saint Mary's University).

Philip, NS; Webster et al., 2012b) and the effect of wave run-up (e.g., Halifax Harbour, NS; Xu and Perrie, 2012).

Coastal erosion indices have been produced for the entire coasts of the island of Newfoundland (Catto, 2011), the North Shore of the Gulf of St. Lawrence (Dubois et al., 2005), the Îles de la Madeleine (Bernatchez et al., 2012b), New Brunswick (O'Carroll et al., 2006; O'Carroll, 2008) and Prince Edward Island (O'Carroll, 2010b; Webster, 2012). Smaller, geographically focused studies of rates of coastal erosion have been conducted in Nova Scotia (Fink, 2007; Utting and Gallacher, 2009; Force, 2012), Quebec and New Brunswick (Section 3.4). Catto (2012) has advocated the differentiation of long-term (e.g., sea-level rise) versus short-term (e.g., episodic storms) drivers of coastal erosion.

Individual events, such as the January 2000 storm that impacted southwestern and southern Newfoundland (Forbes et al., 2000; Catto et al., 2006) and Hurricane Igor in 2010 (Catto, 2011), can result in extensive coastal erosion unrelated to sea-level rise or other long-term changes. Other studies that have documented significant morphological changes in response to storm conditions include those of post-tropical storm Noel (Taylor et al., 2008) and the surge associated with a February 2013 blizzard in Nova Scotia (Taylor, 2014).

With respect to future rates of change in shoreline position, most studies make inferences based on historical analyses and assume a linear relationship. Alternative approaches include those applied to Prince Edward Island, in which erosion rates and shoreline position were based on computer analyses of longshore transport within littoral cells and the derivation of a coastal-sediment budget per cell (*see* Chapter 2; Davies, 2011). This approach permits consideration of seasonal cyclicity and movement of sediment within each cell. MacDonald (2014) incorporated these processes to document changes in physical coastal vulnerability over time as the position of the coastline changes. An economic assessment of the impacts of erosion on the coastal infrastructure in Quebec revealed that, by the year 2065, 5426 buildings will be exposed to erosion if no adaptation measures are undertaken (83% of these buildings being dwellings), and 294 km of roads and 26 km of railroads will likewise be exposed. The combined value of this infrastructure is 1.5 billion dollars (Bernatchez et al., 2015).

Studies focused on the physical effects of erosion and/or inundation on residential, commercial and institutional infrastructure include those initiated in response to concerns in the communities of Le Goulet, Shippagan and Bas-Caraquet in northeastern New Brunswick, that were seeking detailed information on storm-surge levels and coastal-erosion maps to aid in the development of municipal plans (Robichaud et al., 2011; Aubé and Kocyla, 2012; Jolicoeur and O'Carroll, 2012). The studies assigned levels of risk to infrastructure based on a ratio of building height to flooding depth (Robichaud et al., 2011; Aubé and Kocyla, 2012). Maps were produced showing the intersection of flood extent and erosion zones with known infrastructure using aerial images, LiDAR surveys and available tidal and/or storm-surge data. The maps facilitated the participation of community members in identifying and agreeing to zoning-plan proposals with specific future time references (Robichaud et al., 2011; Aubé and Kocyla, 2012; Jolicoeur and O'Carroll, 2012). The five Mi'kmaq communities of the Bras d'Or Lakes recently completed a similar assessment of their coastal reservations as part of a first phase of assessing their vulnerability to climate change and identifying adaptation options (Daigle et al., 2015).

Another method for determining vulnerability involves integrated assessment of physical and social vulnerabilities. For example, an integrated team approach that combined physical-risk assessment (i.e., effects of sea-level–rise scenarios and/or storm surges on infrastructure) with social assets (i.e., beaches, parks and walking trails) and social values was used to examine avoidance, protection, accommodation and retreat options for specific locations in Yarmouth and Lunenburg, NS, and uses of community structures and spaces (Cochran et al., 2012; Johnston et al., 2012; Muise et al., 2012; Wollenburg et al., 2012). The work also tested different visualization techniques, ranging from static to interactive computer displays and a three-dimensional (3-D) physical model to depict flooding levels, in terms of their effectiveness in communicating risks. Although photo simulations were found to be the most engaging, a range of tools was considered to be beneficial (Maher et al., 2012). Coastal Impact Visualization Environment (CLIVE) is a geovisualization tool that allows users to combine data from numerous sources, including an extensive province-wide archive of aerial photographs, and the latest high-resolution digital elevation data (LIDAR) to develop analytical visualizations of coastal erosion regimes and scenarios of potential future sea-level rise (Hedley et al., submitted). The tool has been used to assess the vulnerability of coastal infrastructure on Prince Edward Island (Fenech et al., submitted).

Vulnerability assessments often emphasize the importance of incorporating the views of local residents, their experiences in dealing with past climate impacts and traditional knowledge. Community-level assessments can stimulate change, enhance community buy-in for solutions and provide a voice for those being affected, as well as record experiences of elders in the communities. Reports on the Prince Edward Island communities of Victoria, North Rustico, Mount Stewart and Souris incorporated key informant interviews with community members that included their personal historical photos and memories (Government of Prince Edward Island, 2011). In other areas, such as Sackville, NB, simple climate change adaptation tool kits have been developed for use by the local community (e.g., Marlin, 2013). The community of Cheticamp in Cape Breton, NS experienced a range of engagement activities from coastal monitoring to social media and the arts led by the Ecology Action Centre and academic and public partners (Brzeski, 2013).

5.5 IMPACTS

The effects of climate change are already being felt in the East Coast region and will continue to affect many aspects of life, ranging from health and well-being of human populations to the economy. A large number of the broad policy areas related to coastal planning and management, including economic development and public safety, will be impacted to greater or lesser degrees by climate change

(CBCL Limited, 2009). Although quantitative analysis of economic impacts is lacking for almost all sectors, ongoing research is beginning to address this gap (*see* Chapter 7, FAQ 11). This section briefly addresses three areas of impacts and associated vulnerabilities in the East Coast region: economy, public safety, and culture and heritage.

5.5.1 ECONOMY

The East Coast region's economy will experience both negative (e.g., infrastructure damage) and positive (e.g., longer tourism season) impacts as a result of climate change. Available research identifies agriculture, fisheries and tourism as being particularly sensitive to climate change, along with development and transportation of offshore oil and gas (Vasseur and Catto, 2008). A cross-sectoral concern is the potential impacts on infrastructure, including residential, commercial and institutional buildings.

While available literature focuses primarily on risks to economic sectors, one example of a potential opportunity arising from climate change is increased crop production and diversification of the agriculture industry as a result of longer growing seasons (Vassseur and Catto, 2008). This positive impact for agriculture could be partially or completely offset by negative impacts associated with insect outbreaks and other disturbances (Vasseur and Catto, 2008).

FISHERIES

The 598 small-craft harbours in the East Coast region reflect the importance of fisheries to this part of the country (Table 5). In 2010, East Coast fisheries accounted for 80% of the total volume of landings by weight and 86% of registered salt- and fresh-water fishing vessels in Canada (DFO, 2013a). In 2011, the commercial sea fishery in the East Coast region accounted for $1.82 billion in landed value and 710 530 metric tonnes (live weight) in commercial landings. The bulk of these landings were located in Nova Scotia, and Newfoundland and Labrador (Table 5).

The economic value of fisheries extends well beyond the landed value. In Nova Scotia, for example, commercial fisheries, post-catch processing and aquaculture cumulatively contributed more than $1.1 billion to the province's gross domestic product in 2006, with the majority of this being attributed to shellfish (Gardiner Pinfold Consulting Economists Ltd., 2009). The lobster fishery alone in the four Atlantic Provinces is valued at $550 million/year (Seiden et al., 2012).

Changing climate affects many aspects of fisheries ecology, including migration patterns and the timing of spawning and life-stage development, with significant economic implications. Wahle et al. (2013, p. 1571) termed 2012 "the year that drove climate change home" to the American lobster fishery. An ocean heat wave resulted in a glut of lobsters from the New England states before the close of the Canadian fishery, causing a dramatic drop in prices (Wahle et al., 2013). Changing migration patterns are resulting in mackerel (*Scomber scombrus*) arriving in the East Coast region later in the summer, such that their appearance no longer overlaps with the spring lobster and snow crab (*Chionoecetes opilio*) seasons. As mackerel is a staple bait species, the lack of bait is another stress for the local lobster-fishing industry. Bait purchased elsewhere is not cost effective for fishers, as bait prices increase with transportation and refrigeration costs (Brzeski, 2013).

In situations where capture-species populations become so depleted, whether as a result of changing climate, overfishing or other stressors, there are historical examples of fishers changing to focus on other species (Brzeski, 2013). However, regulatory regimes tend to limit this adaptation response (Charles, 2009; Miller et al., 2010), and Vasseur and Catto (2008) noted the need to make changes to licensing regulations to take into account the potential for species to migrate to new areas or disappear due to climate change.

Changing climate places additional stress on the fisheries sector as a whole. Fishers in the East Coast region already face maintenance and repair costs associated with aging infrastructure (e.g., wharves and processing plants), as well as conflicts over access, harbour management and competing land use. Existing infrastructure may become less usable with higher tides and storm surges, and/or accelerated erosion through increased wave action.

TABLE 5: Commercial fishery in the East Coast region, 2011 (DFO, 2013b, c).

Province	Small-craft harbours (fishing)	Live weight (metric tonnes)	Landed value ($)	Landed value ($/tonne)
Nova Scotia	163	258 677	731 992 000	2 829
New Brunswick	68	81 760	175 196 000	2 143
Prince Edward Island	46	30 789	111 106 000	3 609
Newfoundland and Labrador	264	283 923	641 978 000	2 261
Quebec	57	55 381	154 898 000	2 797

Breakwaters may be ineffective at certain points during the tide cycle or more susceptible to frequent surges. Fish plants located close to shore may be undermined or destabilized by erosion, or inefficient if wharves can no longer receive fish landings due to sea-level rise. A risk assessment by DFO (2012b) for the Atlantic basin identified damage to infrastructure (including harbours, breakwaters, wharves and navigation aids) as the greatest risk exposure to the department (Figure 14). The estimated impact of climate-related damages is very high and the likelihood of such damages is moderate to almost certain at the 10- to 50-year time scale (DFO, 2012b).

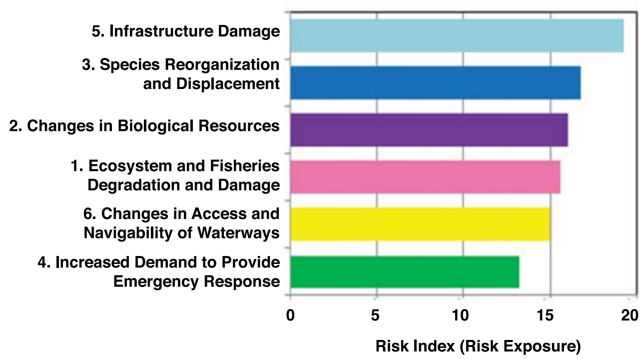

FIGURE 14: Index of climate change adaptation risks on the 50-year time scale for each of six risks identified by the Fisheries and Oceans Canada (DFO) with respect to their department operations. Risk evaluation was based on expert opinion of magnitude of impact (ranked from 0 to 5, where 5 is very high) and probability (also ranked from 0 to 5, where 5 is very high). The risk index is the product of the risk's impact and probability rankings. See DFO (2012b) for additional details on methodology.

AQUACULTURE

Climate change presents risks, and potentially some opportunities, to aquaculture, which is a rapidly growing part of the regional economy. In 2013, the East Coast region produced 49% of Canada's aquaculture by weight and 45.4% by total value ($427 million; Statistics Canada, 2014b). Newfoundland and Labrador, and Prince Edward Island are the top producers by weight, whereas Newfoundland and Labrador, and New Brunswick are the top producers by value (Table 6). Atlantic salmon (*Salmo salar*) is the most valuable species. Shellfish, particularly the blue mussel (*Mytilus edulis*), are the core of the aquaculture industry in Prince Edward Island, where the larvae are recruited from the wild and then cultured (Feindel et al., 2013).

Climate change will affect aquaculture via acidification, changes in seawater temperatures and circulation patterns, the frequency and severity of extreme events, and sea-level rise and associated ecological changes (Feindel et al., 2013; Shelton, 2014; Gurney-Smith, 2015; Reid et al., 2015). Possible operational impacts on aquaculture include infrastructure damage, loss of stock, positive and negative changes in production levels, and changing insurance costs (Table 7; Feindel et al., 2013).

Unlike wild species, cultured species cannot migrate to areas that are optimal for growth and survival. Although some environmental conditions can be moderated artificially for some species (e.g., land-based pens for Arctic char), others require *in situ* pens exposed to local oceanographic conditions of temperature, salinity, oxygen and acidity. Tolerance ranges differ greatly between species and for different conditions, and tolerance will also vary by life-cycle stage. Larvae are most sensitive to changes in optimal conditions. Some cultured species require the larvae to be harvested from the wild before being grown in compounds.

Impacts of ocean acidification are already a major issue globally for both wild and cultured populations of marine shellfish (Gurney-Smith, 2015). Negative responses have been reported in a large majority of North American studies on commercial species to date (Gazeau et al., 2013). These responses include shell deformation, low growth rates and high mortality of commercially important bivalves, such as the blue mussel (*Mytilus edulis*; Gazeau et al., 2010; Gazeau et al., 2013).

Research on Atlantic salmon has shown that an average increase in water temperature of 1°C over the production cycle will decrease time to market by approximately two months, thereby decreasing overall production costs (Reid et al., 2015). Although this suggests that small increases in average temperature could benefit aquaculture production, there are other stresses that must also be considered. For example, increased water temperatures may increase infection potential by reducing the time required for sea lice to complete their life cycle (Stien et al., 2005; Reid et al., 2015). Higher water temperatures may also lead to the introduction of pathogens to which the current genetic stocks in the East Coast region are unaccustomed (Reid and Jackson, 2014).

Selective breeding programs may be an adaptive solution (Waldbusser et al., 2010; Quinn et al., 2011), as could genomic research to select for genetic improvements within a species (Zhang et al., 2012; Millar, 2013). Otherwise, the geographic range of a species may be extended or narrowed depending on the individual species (Shackell et al., 2013). An obvious but operationally challenging option is to relocate the industry to cooler waters.

Both land-based and open-water aquaculture sites can be impacted by severe weather events, potentially rendering them inaccessible or facilitating escape of penned stock. For example, land-based pens within the Oak Bay Hatchery in New Brunswick, critical sites for egg production and brood-stock development and protection of Atlantic salmon, were flooded, and access restricted, in December 2010 (Reid and Jackson, 2014).

TABLE 6: Aquaculture production and value in 2013 in the East Coast region (Statistics Canada, 2014b). Source notes that the production and value of aquaculture include the amount and value produced on sites and exclude hatcheries or processing. Shellfish also includes some wild production. Detailed species-level data for finfish were not available for Newfoundland and Labrador or for Prince Edward Island. Abbreviation: N/A, not available for a specific reference period.

a) Production (tonnes)

Aquaculture Type	NL	PE	NS	NB	QC	All Canada
Finfish — Salmon	N/A	N/A	6 517	18 837	0	100 027
Finfish — Trout	N/A	N/A	203	0	1262	6 736
Finfish — Steelhead	N/A	N/A	0	0	0	682
Other finfish	N/A	N/A	60	0	1	696
Total finfish	22 196	N/A	6 780	18 837	1 263	130 337
Shellfish — Clams	0	0	358	0	0	2 834
Shellfish — Oysters	0	2 812	356	739	10	9 509
Shellfish — Mussels	4 354	22 894	1 051	41	448	29 080
Shellfish — Scallops	0	0	0	5	11	107
Other shellfish	0	0	203	5	22	230
Total shellfish	4 354	0	1 968	790	491	41 760
Total aquaculture	26 550	25 706	8 748	19 627	1 754	172 097

b) Value (thousands of dollars)

Aquaculture Type	NL	PE	NS	NB	QC	All Canada
Total finfish	181 833	3 229	43 386	117 334	10 854	870 346
Total shellfish	15 139	37 970	10 871	5 724	925	92 549
Total aquaculture	196 972	41 198	54 257	123 058	11 779	962 895

TABLE 7: Potential impacts of climate change on cultured species in the Atlantic Basin (*from* Feindel et al., 2013 [*as modified from* Handisyde et al., 2006] and Cochrane et al., 2009).

Drivers of change	Impacts on culture systems	Operational impacts
Changes in sea-surface temperature	▪ longer growing seasons ▪ changes in locations and ranges of suitable species ▪ reduced winter natural mortality ▪ enhanced growth and food-conversion rates ▪ decreased dissolved oxygen ▪ increased disease and parasites ▪ increased harmful algal blooms ▪ competition, parasitism and predation from altered local ecosystems, competitors and exotic species	▪ changes in infrastructure and operation costs ▪ increased fouling, pests, nuisance species and predators ▪ expanded geographic ranges for species ▪ changes in production levels
Changes in other oceanographic variables (wind velocity, currents and wave action)	▪ decreased flushing rates and food availability to shellfish ▪ changes in abundance of species used for food and fishmeal	▪ accumulation of wastes under nets ▪ increased operating costs
Sea-level rise	▪ loss of areas for aquaculture ▪ loss of areas providing physical protection	▪ infrastructure damage ▪ change in aquaculture zoning ▪ increased insurance costs
Increased storm activity	▪ larger waves ▪ higher storm surges ▪ salinity changes ▪ structural damage	▪ loss of stock ▪ facility and net-pen damage ▪ higher costs of designing new facilities and net pens ▪ increased insurance costs

TRANSPORTATION

Transportation by road, rail and ship, and the associated infrastructure, are critical elements of local and regional economies and social connectivity within and between communities. Most existing transportation infrastructure and operations were designed and constructed based on historical climate records and therefore might not be adequate to withstand future weather patterns and climate extremes (Auld and MacIver, 2007). Roads were commonly built to minimize the number of bridges required or limit the number of curves, with little consideration of coastal-erosion hazards (e.g., Drejza, 2010).

Climate change has the potential to substantially affect the effectiveness and lifespan of infrastructure in all of Canada, particularly infrastructure related to transportation and to marine and water management (Boyle et al., 2013). The exposure and vulnerability of these different types of infrastructure varies greatly. Adaptive measures can enhance climate resilience and lead to reduced costs over time. Local impacts associated with severe weather can be costly. For example, the New Brunswick Department of Transportation and Infrastructure reported repair estimates of approximately $750 000 throughout Charlotte County due to flooding on July 26, 2013 (Signer et al., 2014).

Road and rail freight in the East Coast region includes a wide range of imports and exports (Yevdokimov, 2008), with much of this traffic travelling between New Brunswick and Nova Scotia through the Chignecto Isthmus (Webster et al., 2012b). Disruption of this low-lying route stalls $50 million of trade per day (Webster et al., 2012b). Areas such as Prince Edward Island, Quebec's North Shore, Anticosti Island and the Îles de la Madeleine, and Newfoundland and Labrador are reliant on ferry or bridge connections that are very exposed to meteorological hazards. In Quebec, 60% of provincial roads in the estuary and Gulf of St. Lawrence areas are located less than 500 m from the coastline (Friesinger et al., 2013). Quebec's Department of Transportation is concerned about maintaining this essential service in light of changing coastal hazards, and has conducted several studies (Bernatchez et al., 2010). The road network is particularly important in the Îles de la Madeleine archipelago because it provides the only link between the islands and is vulnerable to being severed by major coastal erosion events (Section 6, Case Study 5).

Ports are another important element of the East Coast region's transportation network. There are 25 industrial sea ports that handle much of the import and export of bulk products and resources. Eight of those ports are managed by port authorities (Table 8). Changes in sea level, sea-ice conditions and the frequency of severe storms are likely to affect port operations in the region. Potential positive effects of climate change on commercial shipping include improved access by deeper draft vessels as water depths in harbours increase, and the reduction of sea ice in the Gulf of St. Lawrence that will increase the potential for more shipping to the Port of Montréal and the St Lawrence Seaway. Potential negative effects on shipping tend to be associated with damage to port infrastructure due to extreme weather events (Dillon Consulting and de Romilly & de Romilly Ltd., 2007).

TABLE 8: Tonnage handled by port authorities in the East Coast region (Association of Canadian Port Authorities, 2013). Port authorities account for 60% of cargo handled by Canadian ports (Statistics Canada, 2012).

Port Location	Tonnage handled (million tonnes)
Québec (QC)	29 (2011)
Sept-Îles (QC)	28 (2012)
Saint John (NB)	28 (2012)
Halifax (NS)	9.5 (2012)
Belledune (NB)	1.9 (2012)
St John's (NL)	1.4 (2012)
Saguenay (QC)	0.35 (2011)

Planning and co-ordination to address climate risks to transportation can be challenging due to the diversity of agencies involved. In Halifax, the second largest natural, deepwater, ice-free harbour in the world, for example, the federal government operates the home port and associated facilities of the Canadian Navy's Atlantic fleet and Air Command's Canadian Forces Base Shearwater, as well as bases for the Canadian Coast Guard and offices for a range of federal departments and agencies. The Halifax Port Authority, an agency of the Crown under Transport Canada, oversees operations of the Port of Halifax. Major industrial facilities, such as the Irving Shipbuilding Inc. shipyard, infrastructure of Canadian National Railway Company, the Imperial Oil Limited oil-storage facility and the Tuft's Cove Generating Station, occupy a significant proportion of the nearshore lands (Dillon Consulting and de Romilly & de Romilly Ltd., 2007).

TOURISM

International research indicates that climate change will affect a range of coastal recreational activities (e.g., beach visits, fishing and boating) both positively and negatively (e.g., Coombes and Jones, 2010). Direct and indirect tourism revenues are a significant component of the economy for many communities in the East Coast region. In New Brunswick, for example, visits to and within the province contributed almost $1 billion in tourism-related expenditures in 2008 (New Brunswick Department of Tourism and Parks, 2010), the vast majority of which were linked to the coast. In

Prince Edward Island, tourism is a critical driver of economic activity, employment and tax revenue, accounting for 6.9% of the island's GDP and $373 million in revenue in 2009 (Tourism Industry Association of Prince Edward Island, 2014). The economic contribution of the 500 000 tourists to Newfoundland and Labrador is estimated at approximately $450–470 million annually and also contributes to employment and small-business establishment (N. Catto, personal communication, 2015). In 2014, the Quebec Government unveiled an action plan (Stratégie de mise en valeur du Saint-Laurent touristique 2014-2020) to promote tourism within the St. Lawrence river, estuary and gulf regions, where tourism is already a key component of local economies (Tourisme Québec, 2014). For example, visitor traffic in the Îles de la Madeleine in the summer currently doubles the local population.

In examining approaches to adaptation, researchers have assessed the potential for collaboration between fishing and tourism industries, to improve overall economic stability within local areas. In Bonne Bay (NL), for example, the fishing and tourism sector are economically important to six small local communities. By enhancing the local experience for tourists through boat tours of the bay, improving local culinary services and offering historical interpretation of area, the economic future for both fishing and tourism sectors has improved (Lowitt, 2012). In Chéticamp, NS, a multidisciplinary research team developed a toolkit to help fisheries and tourism sectors adapt and remain competitive. The Chéticamp and Grand Étang harbour authorities are working to diversify harbour uses to enhance resilience, and the tourism association is promoting cultural tourism that provides indoor activities as an alternative to weather-dependent activities (Brzeski et al., 2013).

5.5.2 PUBLIC SAFETY

Changes to water quality, flooding and temperature extremes could impact the health and well-being of local residents. Flooding may adversely affect the ability of a geographically isolated group of residents to access emergency services, such as fire, medical and police (Muise et al., 2012; van Proosdij, 2013; Masson, 2014). In Windsor (NS), for example, a 1.2 m storm surge during an average high tide would flood road access to the hospital, including the access ramps to the major highway linking communities, whereas a 1.8 m surge would prevent emergency-response vehicles from leaving their station (van Proosdij, 2013). Even where hospitals and nursing homes may not be directly at risk from flooding, infrastructure and assets in support of daily living, such as grocery stores and pharmacies, as well as infrastructure that supports recreational, social and spiritual needs, can be directly or indirectly affected (Rapaport et al., 2013).

Costs associated with climate hazards can directly impact individual well-being. Homeowners in Canada generally cannot purchase insurance coverage for damages caused by overland flooding, including flooding from rivers, storm surges, tides and sea-level rise. In addition, erosion associated with overland flooding, including coastal erosion, is not covered under typical homeowner policies (Sandink, 2011). Behavioural changes, such as avoiding building or living in areas at high risk from such hazards, and heeding evacuation notices, would reduce the direct impact on individuals.

Major financial costs tend to be associated with extreme weather events. Flooding has been the most common type of disaster in the East Coast region, followed by hurricanes and winter storms (Public Safety Canada, 2014). Between 2003 and 2011, damage caused by three hurricanes and one major winter storm in the region resulted in insured losses ranging from $51 million to $132 million (Kovacs and Thistlethwaite, 2014). Catastrophic losses due to rising water and weather events, including more frequent rain-on-snow flooding and more frequent winter thaws that are anticipated to affect ice-jam flooding and river/estuarine drainage, will continue to increase with projected changes to climate in the East Coast region. Combined with current development pressures and practices, this may set the course for higher damages to built infrastructure and services (e.g., PIEVC, 2008).

5.5.3 CULTURE AND HERITAGE

At a global scale, the vulnerability of coastal archeological resources is well acknowledged (e.g., English Heritage, 2008; Blankholm, 2009; Marzeion and Levermann, 2014). Canada's East Coast region has a wealth of cultural and heritage resources, such as parks (national, provincial, municipal), UNESCO sites, museums, heritage architecture, undeveloped archeological sites, abandoned cemeteries, and sites of important aesthetic and spiritual value. Climate change can affect culture and heritage directly through physical damage to sites, structures and landscapes, or indirectly through impacts to economic resources that could undermine efforts to maintain and preserve cultural heritage. The prospect of loss or damage to historical and archeological resources in nearshore areas is often more significant to society than damage to contemporary structures that can be rebuilt.

Coastal erosion plays both destructive and discovery roles with respect to cultural heritage. Within the East Coast region, there are coastal and watercourse sites from all chronological periods of history (Paleo-Indian, Archaic, Woodland Ceramic, Proto-Historic/Contact and Historic). Examples include Tyron, PE; Meadford, NS; Sainte-Anne-des-Monts and Marsoui, QC; Port-au-Choix, NL; and Amherst Shore, NS (Chapdelaine, 1996; Bell and Renouf, 2003; Kirstmanson, 2011). For sites such as Pointe-aux-Vieux, PE, located on an actively eroding shoreline, the constant threat from climate impacts raises fundamental issues about the identification, protection and management of archeological sites. Although it would generally be preferable to leave portions of the archeological deposits intact for future generations to interpret, many sites, or a substantial portions of them, will eventually be lost to erosion by increments or by a catastrophic event (Case Study 4).

CASE STUDY 4

COASTAL ARCHEOLOGICAL RESOURCES AT RISK

Although coastal archeological sites have been inundated by rising water levels in many parts of Atlantic Canada for millennia (Lacroix et al., 2014), recent loss or damage by storm surges and erosion has raised the alarm for heritage managers to potential future threats (e.g., Duggan, 2011; Finck, 2011; McLean 2011). One study estimated that one-fifth of all coastal archeological sites in three regions of Newfoundland are highly vulnerable to sea-level rise during the next 15–20 years, including national historical and world heritage sites (Westley et al., 2011). A similar study is underway for Prince Edward Island (Kirstmanson, personal communication, 2014). At a more local scale, Parks Canada classified 16 of 18 areas of the Fortress of Louisbourg National Historic Site as vulnerable to impacts from sea-level rise within the next century (Duggan, 2011). The Coastal Archaeological Resources Risk Assessment (CARRA) project, based at Memorial University of Newfoundland, aims to refine and expand on the vulnerability-assessment approach for heritage managers so they can readily identify at-risk sites, prioritize those for immediate action and learn through a community of practice how best to respond (Pollard-Belsheim et al., 2014).

For the most part, the response of the heritage management community to the impacts of sea-level rise and coastal change has been reactive. Regular monitoring for erosion of coastal archeological sites is rare and typically limited to protected areas (e.g., national parks) or sites near communities. As a result, loss of or damage to many sites goes undetected. Response measures range from rescue excavation of rapidly eroding or submerging sites to protection of sites through armouring or hardening of eroding shorelines (Figure 15). Protective measures are mostly informal and have had mixed results. In Bonavista Bay, NL, for example, a gabion rock wall has effectively protected the Inspector Island site for almost 30 years, whereas wooden breakwaters at the Beaches site failed within five years of installation (Figure 16; Pollard-Belsheim et al., 2014). Proactive adaptation requires the prioritization of at-risk sites, a process that should integrate cultural values, socio-economic factors and public input (e.g., Duggan, 2011) with an assessment of physical threats and the adoption of site action plans that enable implementation of excavation, protection or abandonment.

FIGURE 15: Malagawatch Cemetery, NS, where buried human remains eroded into the sea following several storm events. Initial protection of the site involved the use of stone armouring (as seen below the cross). Subsequent storms and erosion led to temporary protection of burials using anchored hay bales and a permeable membrane (centre of photo). Planning for more permanent protection is ongoing. *Photo courtesy of Heather MacLeod-Leslie.*

FIGURE 16: Two different construction methods used to protect archeological sites in Bonavista Bay, NL: **a)** the stone gabion wall constructed at Inspector Island (Pastore, 1987) has successfully protected the site for three decades; **b)** wooden breakwaters have consistently failed at the Beaches site. *Photo b) courtesy of Anita Johnson-Henke.*

Coastal erosion can also expose previously unknown archeological and paleontological resources. For example, coastal erosion at the Joggins Fossil Cliffs, NS, a UNESCO World Heritage Site, has led to the recent discovery of fossilized footprints from the smallest known Tetrapod (*Batrachichnus salamandroides*) from the Carboniferous Period (approximately 360–299 million years ago; Stimson et al., 2012). New fossils are exposed with every storm and the challenge becomes accessing the new resources before they are washed away with the tide.

As the impacts of climate change accelerate, it will become increasingly important to determine which heritage sites are most at risk and which have the most value culturally and economically (Westley et al., 2011). For example, of the archeological sites at L'Anse-aux-Meadows, NL, 60% are considered to be of high vulnerability (mostly in Sacred Bay), 16% moderate and 24% low (Westley et al., 2011). This type of assessment can help concentrate preservation/recovery efforts or to understand the realities of abandonment.

Climate change will directly affect the assets of many parks in the East Coast region (e.g., Vasseur and Tremblay, 2014), and management plans are beginning to reflect these risks. Prince Edward Island National Park, for example, faced with a 1 m/year recession rate and with storms capable of eroding 10 m in a single event, has accepted planned retreat as an appropriate approach to adaptation, abandoning campgrounds and relocating the main coastal road landward in an effort to maintain and enhance natural coastal processes.

Most First Nations communities in the East Coast region have traditional ties to the coast. For example, Malpeque Bay (PE) has been crucial to the Mi'kmaq for food harvesting, transportation and recreation, among other uses, during a long history that spans thousands of years (Charles, 2012). Many First Nations continue to occupy areas vulnerable to climate change and to rely on coastal natural resources. The community centre of the Mi'kmaq Confederacy of Prince Edward Island on Lennox Island, for example, occupies a highly erodible island joined to the mainland by a short causeway and bridge. Concerns related to climate change include potential saltwater intrusion and threats to Mi'kmaq archeological sites in the area. These concerns are being addressed in an ongoing study led by the Confederacy: *Adapting the PEI First Nations' Coastal Residences, Infrastructure and Heritage to a Changing Climate on Prince Edward Island* (Mi'kmaq Confederacy of PEI, 2014).

6 ADAPTING TO CLIMATE CHANGE

Adapting to climate change in the East Coast region brings direct economic benefits (*see* Chapter 3) and is important for preserving vulnerable ecosystems and landscapes, and for securing sustainable regional development. In implementing adaptation, attention must be given to the multiple biophysical and socio-economic factors that together produce the complexity inherent to coasts and coastal communities, including climate, geomorphology, coastal dynamics, and environmental, legal and regulatory processes. Adaptation is a process that includes assessing risks and vulnerability at various time scales, identifying options to reduce or eliminate these risks, and assessing these options in terms of their impact on the neighborhood, on coastal ecosystems and on the economy. Often, adaptation is not an individual process but rather involves multiple levels of decision makers, including community members. Examples of maladaptation, actions that lead to increased risk of adverse climate impacts (IPCC, 2014), are also common in the region. Many factors have contributed to this maladaptation, including a frequently limited understanding of coastal dynamics, conflicts of interest and lack of knowledge about alternative options (Friesinger and Bernatchez, 2010; Novaczek et al., 2011; Graham et al., 2013; Niven and Bardsley, 2013; Cooper and Pile, 2014).

The following sections address many of the complexities of the natural and human (institutional) environment as they relate to the identification, assessment and implementation of adaptation measures in the East Coast region. Such analysis commonly forms the foundation for selecting specific adaptation options. An overview of the broad categories of adapting to coastal erosion, sea-level rise and coastal flooding, with examples from the East Coast region, precedes a summary that focuses on future directions.

6.1 THE CHALLENGE OF A CHANGING ENVIRONMENT

The preceding sections have highlighted many of the biophysical and socio-economic factors that influence changes in coastal environments (*see also* Chapters 2 and 3). Understanding the dynamics of such environments is fundamental to the development of adaptation measures (Spalding et al., 2014). With respect to changes in the coastline, the projected acceleration of sea-level rise, decreases in sea-ice and ice-foot cover, and the potential increase in effective storms suggest that historical erosion rates almost certainly underestimate future coastal retreat. In a study of three areas in the East Coast region (Îles de la Madeleine, Percé and Sept-Îles QC), Bernatchez et al. (2008a) developed three scenarios for future coastline position by the year 2050 (Case Study 5). Modelling of these scenarios contributed to the delineation of three setback zones of varying vulnerabilities to coastal erosion. A similar project undertaken along the north shore of Prince Edward Island incorporated changes in shoreline configuration due to exposure and wave stress at the coast (MacDonald, 2014).

CASE STUDY 5

PLANNING FOR COASTLINE MOBILITY IN THE ÎLES DE LA MADELEINE

Located in the centre of the Gulf of St. Lawrence, the Îles de la Madeleine is an archipelago of 10 islands (total area about 190 km^2) with a population of approximately 12 600. The living area of the archipelago is restricted, with the maximum width of rocky outcrops not exceeding 10 km and their central part often being high and steep (Figure 17). Tourism is a key component of the local economy (Section 5.5.1). The Îles de la Madeleine are vulnerable to coastal hazards, and the archipelago is particularly sensitive to erosion. Coastal infrastructure on the Îles de la Madeleine is threatened by shoreline retreat at several sites, including the main road network of the archipelago and the sewage purification ponds of the main community. In its master plan, the Municipality of Les Îles-de-la-Madeleine identified 23 areas where erosion is an issue and where action is deemed necessary (Municipality of Les Îles-de-la-Madeleine, 2010).

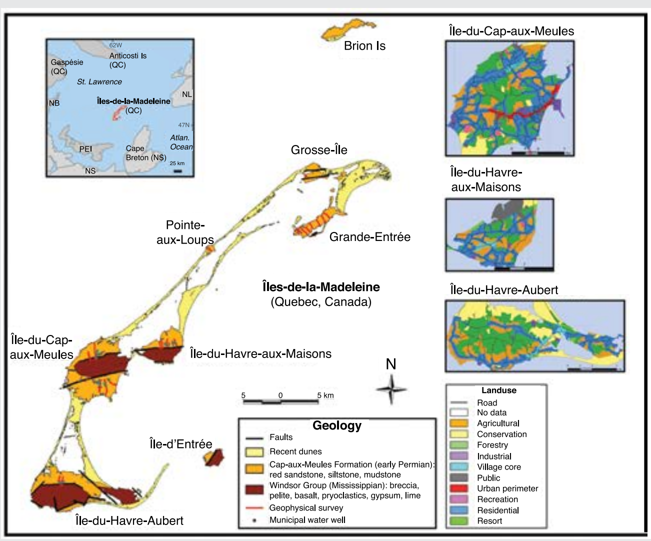

FIGURE 17: Location, geology and land use on the Îles de la Madeleine (Rémillard et al., 2012).

The archipelago is more vulnerable to relative sea-level rise than any other area in Quebec. This relates, in part, to the fact that it is a microtidal environment, with only about 1 m difference in height between low tide and high tide. With sea level around the Îles de la Madeleine in the year 2100 projected to be 50–83 cm higher than at present, and as much as 150 cm higher in the scenario involving partial collapse of the West Antarctic Ice Sheet (based on curves for Charlottetown presented in Figure 5 and Appendix A; James et al., 2014; *see also* Chapter 2), the current position of the high tide could roughly correspond to the position of the low tide in 2100. This shifting of the intertidal zone will change the position of the coastline and affect habitats, coastal ecosystems, coastal dynamics and erosion rates.

To assess the potential impacts of future changes in climate, Bernatchez et al. (2008a) proposed three possible positions of the coastline for the year 2050 (Table 9). The mapping of these scenarios along the coasts of the archipelago enabled stakeholders, scientists and members of working groups to identify adaptation options for targeted priority sites. Options considered included sand nourishment; a combination of sand nourishment, groynes and eolian sand traps where the main road is threatened; and rip-rap defence structure (armour stone) where erosion is threatening the community core (Figure 18; Savard et al., 2008).

TABLE 9: Erosion scenarios developed for communities in the Gulf of St. Lawrence and used to map the evolution of the coastline to the year 2050 (*translated from* Savard et al., 2008).

Scenarios for 2050	Description
S1: average coastline displacement rate between 1931 and 2006	Assumes that the effect of climate change will not modify the average rates of coastline retreat to 2050
S2: average erosion rates measured for a range of 10–15 years where erosion was most intense during the period 1931–2006	Considers probable accelerated coastal erosion due to climate change
S3: average values of higher-than-average rates of retreat for a range of 10–15 years where erosion was most intense during the period 1931–2006	Considers as likely a high acceleration of erosion due to climate change and aggravating anthropogenic factors

Their analysis concluded that, by 2050, the rocky cliffs of the Îles de la Madeleine could erode by about 38 m (–0.9 m/year) and sandy coasts could retreat by about 80 m (–1.9 m/year) (Bernatchez et al., 2008a; Savard et al., 2008). Under this scenario, many sites in the archipelago will be at high risk in the near future, including portions of the main road where only a single foredune ridge separates it from the westerly exposed beach and some community infrastructure and tourist sites. The overall picture demonstrates that coastal erosion exacerbated by climate change is a chronic and serious problem in the Îles de la Madeleine. Nevertheless, based on an understanding of coastal dynamics and acceptance of inevitable changes, the decision was made to leave 95% of the archipelago's territory unprotected from natural processes such as erosion and flooding. This approach preserves the natural beauty of the archipelago, which is a primary draw for tourists, and the islands are sufficiently high and large to endure shoreline retreat for many centuries. Only a few town centres with critical infrastructure are protected with a mix of hard and soft protection methods (Section 6.3.4).

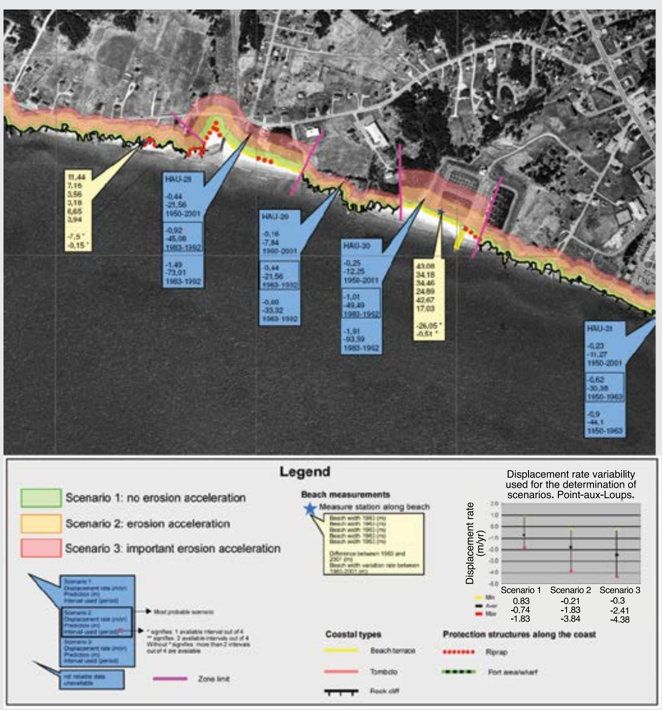

FIGURE 18: Example of digital-mapping scenarios and setbacks S1, S2 and S3 in Cap-aux-Meules, Îles de la Madeleine (*adapted from* Savard et al., 2008).

The study by Bernatchez et al. (2008a) was a first attempt to address how the local coast will evolve in the 21st century, knowing that the past does not represent an analogue for the future. Continued research and production of rigorous scientific documentation on the response of coastal systems to projected conditions will help better support decision making.

Risk management, analysis and the implementation of adaptation solutions to address changes in the coast often benefit from an approach based on uniform coastal units, usually littoral cells (*see* Chapter 2; Schéma Directeur d'Aménagement et de Gestion des Eaux du bassin Rhône-Méditerranée-Corse, 2005; de la Vega-Leinert and Nicholls, 2008; Dawson et al., 2009). Interventions made in one area of a littoral cell will impact the rest of the cell (MacDonald, 2014). Failure to take account of this important aspect of coastal dynamics can lead to maladaptation.

6.2 INSTITUTIONAL FACTORS AFFECTING ADAPTATION

The legal and institutional frameworks defining land policy in coastal regions can be key in facilitating adaptation or, in some situations, can serve as barriers to adaptation (e.g., Doiron, 2012). Policies may include defining areas with protection status for biodiversity, municipal zoning and development strategies and plans. The majority of laws, regulations and codes of practices in place today do not include consideration of changing climate and would benefit from review with a climate change lens. Indeed, much recent construction in the East Coast region has occurred in areas of high flooding risk yet is compliant with existing land-planning regulation and legislation. There are, however, important exceptions to this general characterization that reflect recent advances in adaptation planning (Case Study 6).

CASE STUDY 6

DEVELOPED WATERFRONT AND VERTICAL ELEVATION LIMITS IN HALIFAX REGIONAL MUNICIPALITY

Halifax Regional Municipality (HRM) is the capital of Nova Scotia and Atlantic Canada's largest city. The municipality covers more than 5500 km^2 and has a population of more than 414 000 (Statistics Canada, 2014a). Halifax Harbour, at the heart of HRM, is a major seaport with significant industrial, military and municipal infrastructure, including culturally important assets. In response to extreme weather events, such as Hurricane Juan, a Category 2 hurricane that caused an estimated $200 million in damage in Nova Scotia and Prince Edward Island in 2003, and a major winter storm in 2004, HRM began to actively implement climate change adaptation measures (Charles and Wells, 2010). In 2006, the HRM Council adopted the Regional Municipal Planning Strategy, which explicitly included policies to address climate change impacts. The strategy highlighted that scientific information is the foundation for adaptation-planning processes, particularly as it relates to sea-level change, storm surges and coastal vulnerability, to inform development of an area-specific land-use plan for Halifax Harbour (HRM Department of Energy and Environment, 2013).

In partnership with Natural Resources Canada, the HRM Department of Energy and Environment evaluated future sea-level rise and flooding risk around Halifax Harbour during the next 100 years for three scenarios that considered present and future sea-level rise, vertical land motion, statistics of extreme water levels (combined tide and surge), wave run-up and harbour seiche (Forbes et al., 2009). Mapping of future flood-hazard zones (Figure 19) utilized a high-resolution digital elevation model based on LiDAR data.

The scenarios of global sea-level rise used by Forbes et al. (2009) were based on projections of the IPCC Fourth Assessment Report (IPCC, 2007) and subsequent scientific literature. Although those scenarios are superseded by the projections presented in this report (Section 3.1 and *see* Chapter 2), both sets of scenarios cover a similar range. The 57 cm sea-level rise presented in Figure 19 compares with updated projections of relative sea-level rise for 2010–2100 at Halifax of 60.6 cm for RCP4.5 (median) and 84.7 cm for RCP8.5 (median; James et al., 2014, 2015). It is therefore quite a conservative scenario.

Based on available analysis, and following a precautionary approach, the Municipal Planning Strategy and Land Use By-Law for the downtown Halifax waterfront area prescribes any ground-floor elevation development to be a minimum

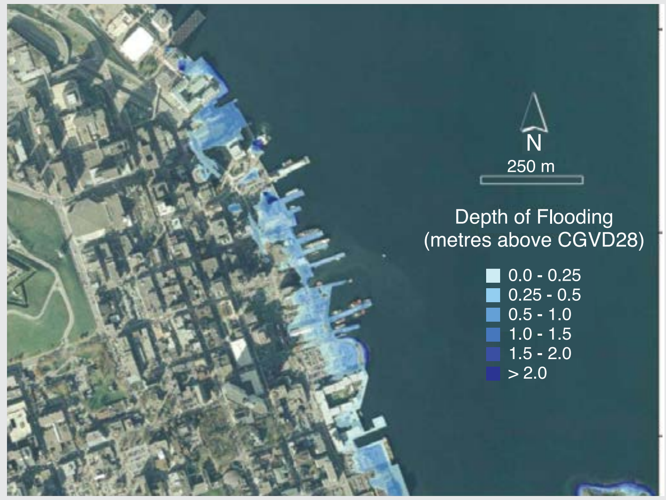

FIGURE 19: Flooding extent and depth (still-water) for a 57 cm sea-level rise with a once-in-50-years extreme-water-level event in downtown Halifax, derived using a light detection and ranging (LiDAR) digital elevation model displayed over a digital airphoto image (Forbes et al., 2009).

2.5 m above the ordinary high-water mark. Provisions were made for this figure to be adjusted based on ongoing monitoring and analysis of sea-level rise. This is an example of an adaptation measure being incrementally adjusted as new information becomes available. In the interim, HRM staff have used development agreements (i.e., bilateral contracts between the municipality and the landowner) for a number of waterfront parcels to encourage safe development while a formal adaptation plan is being completed (Charles and Wells, 2010).

Building upon the findings of Forbes et al. (2009), Xu and Perrie (2012) modelled extreme wave run-up within Halifax Harbour. Although development proponents are not presently required to demonstrate that extreme waves and wave run-up effects have been incorporated into their project design and engineering, information from this research study could be considered in amendments to land-use by-laws. For instance, development proponents could be required to conduct site-specific wave studies and demonstrate that appropriate adaptive responses have been incorporated into the overall design (HRM Department of Energy and Environment, 2013).

The availability of a high-resolution digital elevation model for a complex coastal urban landscape such as HRM has provided significant opportunities for community engagement and visualization of hazards. It assists in delineating zones of vulnerability and prioritization of sites for protection, relocation and enforcement of setbacks. Setbacks can be updated as new data and information become available.

Vertical and horizontal setbacks are useful mechanisms to promote adaptation, and their utility is not limited to large municipalities. For example, the Municipal Council of Beaubassin-Est, NB passed an updated zoning by-law in March 2011 to enhance protection of new construction in its coastal zone (Eyzaguirre and Warren, 2014). The by-law requires that the minimum ground-floor elevation of any new building be at least 1.43 m above the current once-in-100-years flood mark to account for anticipated sea-level rise (Doiron, 2012). All previous zoning conditions still apply. In Prince Edward Island, coastal setbacks are legislated based on measured erosion rates (1958, 2000 and 2010), supplemented with field observations. Wetlands and streams near cliffs must be protected by a buffer of 15 m or 60 times the erosion rate of that section, whatever is greatest (Arlington Group et al., 2013; Weissenberger and Chouinard, 2015). In Quebec, construction is prohibited below the high-tide line as part of a policy on the protection of shores, littoral zones and floodplains. Although construction in the flood plain is permitted, no living space, door or window may be located below the level of a once-in-100-years flood (Weissenberger and Chouinard, 2015).

Opportunities exist for the integration (mainstreaming) of coastal and/or climate-change adaptation elements into existing legislation, policies and practices, including building codes and codes of practice for engineers, planners and landscape architects. In most jurisdictions, municipalities and other land-management organizations identify areas at risk for erosion, landslide and flooding. Municipalities in Quebec, Nova Scotia, and Newfoundland and Labrador are required to prepare public-safety plans that are integrated in the municipality's land-policy and land-management plan. Such plans can be important in driving adaptation if they are developed with an understanding of how climate change is impacting coastal hazards.

Changing legal and regulatory frameworks tends to be a slow process. One of the earliest examples of planning for coastal change is the New Brunswick *Coastal Areas Protection Policy*, developed in 2002 in recognition of the stresses that threaten public safety, infrastructure, agricultural lands and the biodiversity of plant and wildlife within the region. This policy identifies sensitive coastal features, allowing these to continue to function naturally and maintain their buffering capacity, then identifies a 30 m limited-activity and -development buffer that begins at the farthest landward extent of the dynamic coastal zone (Figure 20; New Brunswick Department of Environment and Local Government, 2002). Although proactive and innovative at the time it was introduced, challenges in implementation have been ongoing and, as of 2013, it still did not have the force of law (Weissenberger and Chouinard, 2015). Interim measures are sometimes employed while broader regulatory changes are being considered. In Quebec, an interim regulation has been implemented to prohibit construction in areas of coastal risk on the North Shore from Québec to Blanc-Sablon (Case Study 7). The regulation is subject to review and adjustment as new scientific knowledge becomes available.

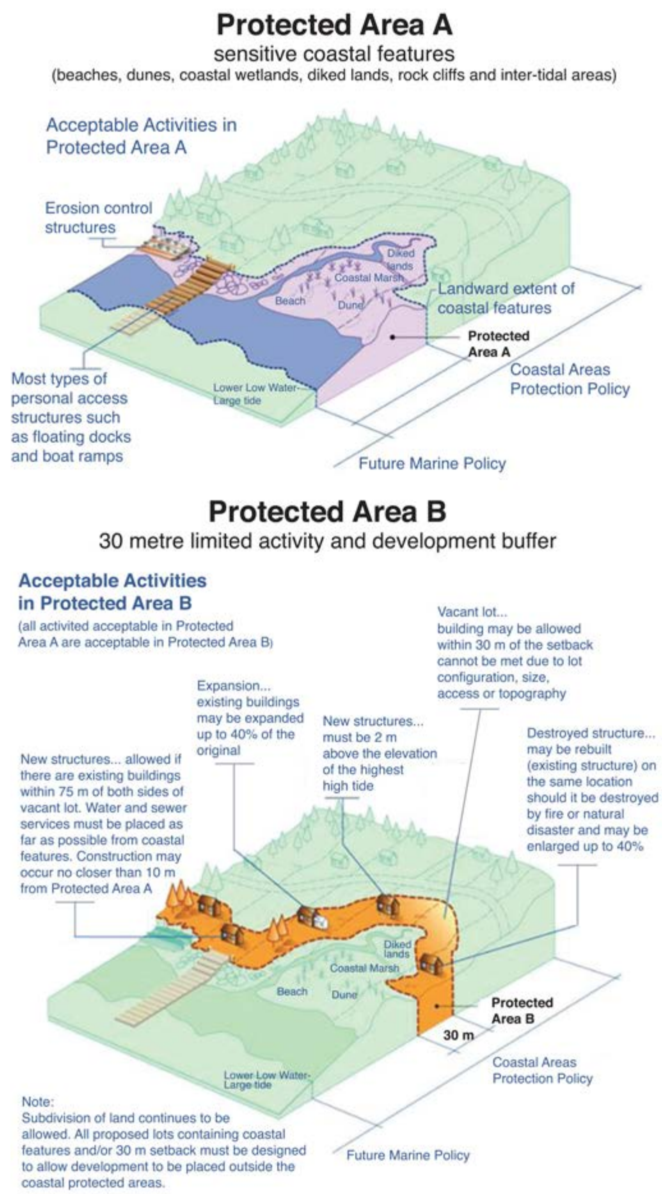

FIGURE 20: Zones A and B of the New Brunswick *Coastal Areas Protection Policy* (New Brunswick Department of Environment and Local Government, 2002).

CASE STUDY 7

ADDRESSING COASTAL EROSION IN SEPT-ÎLES, QC

The Municipality of Sept-Îles, QC has been dealing with erosion and coastal change, related to natural processes and human influences, for decades (Bernatchez and Dubois, 2004; Bernatchez and Fraser, 2012). In the late 1990s, the municipality requested a detailed study on the issue of erosion and a plan for coastal management based on integrated solutions (Dubois et al., 2005). The resulting four-year (2000–2004) scientific assessment concluded that coastal erosion had accelerated in recent decades, that human interventions at the coast were amplifying natural rates of erosion and that climate change could accelerate erosion in the future (Dubois et al., 2005). A follow-up study (2005–2008), led by the Ouranos consortium and the Quebec Department of Public Safety, assessed the vulnerability of coastal communities along the province's eastern shores, including the Municipality of Sept-Îles (Figure 21). The study used a participatory approach, taking into account the views of stakeholders and transferring climate science to decision makers to facilitate an integrated coastal-management approach and to identify adaptation options (Savard and Bourque, 2008, 2010; Savard et al., 2009). Local stakeholder representatives were invited to participate in a series of day-long workshops to identify adaptation solutions. The approach required that decision be achieved by consensus (Savard et al., 2008; Savard and Bourque, 2010).

The study highlighted that changes in storm frequency lead to significant retreat of sandy coasts; that increased winter thaws intensify freeze-thaw processes on clay cliffs; that decreases in seasonal sea-ice coverage in the Gulf of St. Lawrence increase the development of energetic winter waves that reach the coast; and that all of these climate-related factors are acting in the context of a rising sea level. The study was a catalyst for many events, meetings and consultations among community representatives, municipal and government policy makers, and members of the study's scientific committee.

The scientific documentation and the consultation with community stakeholders arising from the study were crucial in the adoption of control measures in the Sept-Rivières Regional County Municipality, measures with which the City of Sept-Îles must comply (Municipalité régionale de comté de Sept-Rivières, 2005; Natural Resources Canada, 2015). These include:

- adoption of a safety setback margin calculated over a period of 50 or 100 years, depending upon whether it is private or public land;
- development of future erosion scenarios (2050) to identify appropriate adaptation options;
- a ban on the installation of traditional protection structures (rip-rap, concrete walls, wooden walls, groynes and revetments); and
- a ban on any increase of habitable surface area for buildings in designated no-construction zones.

This regulation is now fully enacted across the Province of Quebec. Representatives of the provincial government, regional county municipality and the City of Sept-Îles are working to establish a master plan for coastal intervention, in order to deal with erosion and coastal management problems over the short, medium and long term (Natural Resources Canada, 2015). For example, the municipality decided to move part of the coastal population living on a sand cliff located along the gulf shores of the Sainte-Marguerite River estuary.

A final component of the study was a cost-benefit analysis over a 25-year period (2008–2032) of the adaptation options identified through the consultation process (Tecsult

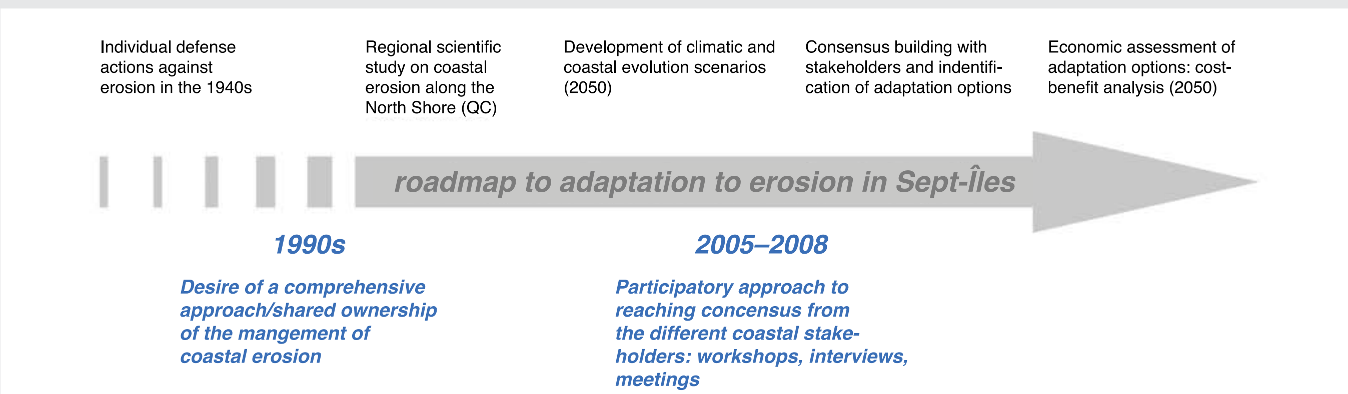

FIGURE 21: Main actions and interventions in the process leading to adaptation to erosion in Sept-Îles, QC.

Inc., 2008). The options studied, which varied from location to location, were sand nourishment, linear rock armourment, a combination of groynes and sand nourishment, revegetation, and planned relocation. The analysis showed that the optimal adaptation scenarios were those favouring sand nourishment or planned relocation. Under the Major Natural Hazards Prevention Guidelines (Cadre de prévention des principaux risques naturels), the Quebec Department of Public Safety had funds specifically earmarked for adaptation to coastal erosion. The Regional Municipality of Sept-Îles was approved for funding under this program for an $8 million sand-nourishment project, with the municipality required to provide 25% of the funding (approximately $2 million). A tax levy was proposed to raise the funds, but the local government had difficulty obtaining public support as the levy would have been applied to all residents, whereas only the ocean-front property owners were perceived to benefit from the project (Arlington Group et al., 2013).

Availability of financing is another example of an administrative control on adaptation. It is often easier to obtain financing for hard engineering projects, such as seawalls and rip-rap, than for more flexible options, such as beach nourishment and dune or marsh restorations that require ongoing financing over a long-term period (even though the cost-benefit ratio can be better than for hard protection methods; Spalding et al., 2014). Some financing may be available through avenues such as habitat compensation projects for loss of aquatic habitat due to infrastructure construction, with the primary goal of such coastal wetland restoration projects being habitat creation (Bowron et al., 2012). Lack of public support can also be a barrier to funding of implementation measures (Case Study 7).

6.3 COASTAL ADAPTATION OPTIONS

Although specific adaptation measures are diverse, adaptation options in coastal areas can be grouped into four broad categories: no active intervention, avoidance/retreat, accommodation, protection, or a combination of these approaches (*see* Chapter 3; Chouinard et al., 2008; Vasseur and Catto, 2008; Pilkey and Young, 2009; Linham and Nicholls, 2010; Nicholls, 2011; Burkett and Davidson, 2012; Arlington Group et al., 2013; Macintosh, 2013; Niven and Bardsley, 2013). Coastal settings located between urban areas and relatively natural areas can be particularly challenging with respect to determining appropriate adaptation measures. There is a large array of feasible adaptation options where the coast is occupied by low-density settlements, such as a line of cottages, houses or suburban commercial assets. Rapid linear urban expansion, often referred to as ribbon development, has occurred along many stretches of the coast in this region during the past few decades, resulting in significant economic assets being at risk from coastal hazards and exacerbating coastal squeeze (Section 4.8).

6.3.1 NO ACTIVE INTERVENTION

No active intervention can be a legitimate adaptation response when, based on a thorough understanding of the risks involved, decision makers choose to take no action at this time. No active intervention may be appropriate when there is no significant risk, when little can practically be done to avoid or reduce the impacts of coastal hazards, or when action taken now is an inappropriate allocation of resources against the potential of a future threat. As described in Case Study 5, a rigorous adaptation planning process for the Îles de la Madeleine led to the decision to make no active intervention with respect to 95% of the archipelago's territory.

6.3.2 AVOIDANCE AND RETREAT

The option of avoidance and retreat involves identifying risk areas and defining where development will be prohibited, while enabling existing housing and infrastructure at risk to be relocated to safer areas. These options are most commonly suggested for the preservation of natural landscapes and coastal ecosystems, and applied in areas with few coastal-infrastructure assets. For example, Prince Edward Island National Park acquired 12.5 km^2 of land in the mid-1970s along the landward portion of the park boundaries to compensate for the land losses along the shoreline. This land is now being managed as a buffer to gradually relocate coastal infrastructure as the shoreline moves landward (Parks Canada, 2007). In urban centres, where major assets are concentrated, retreat options are challenging because there is no room for accommodation and the cost of retreat, both economically and culturally, would be enormous.

Even outside urban centres, avoidance and retreat may not be generally preferred strategies on the basis of short-term economics. Coastal land is often a significant source of revenue for municipalities and leaving this land unoccupied by direct revenue-generating activity is often seen as a negative economic factor. Another drawback of avoidance is that facilities and people are commonly already present in the high-risk area (Lieske and Borneman, 2012; van Proosdij et al., 2014). Public consultation and information are particularly important in achieving successful adaptation through avoidance and retreat (Savard and Bourque, 2010; Drejza et al., 2011).

Avoidance and retreat in the East Coast region also includes managed realignment in diked areas, such as in the upper Bay of Fundy. There has been increasing interest in this concept during the last few years with the recognition that the cost of maintaining the existing system of dikes in Nova Scotia and New Brunswick is not sustainable (Lieske and Borneman, 2012; van Proosdij and Page, 2012; Wilson et al., 2012; van Proosdij, 2013). Although most salt-marsh restoration projects in the bay have been conducted as habitat compensation (van Proosdij et al., 2010; Bowron et al., 2012), there is growing interest in maximizing the adaptation potential of such projects while enhancing ecosystem services (van Proosdij et al., 2014). Close monitoring of selected salt-marsh restoration projects has shown rapid recolonization of vegetation, and therefore enhanced potential for wave-energy dissipation, after tidal flow is restored. The pace of this recovery, however, is not spatially uniform (Millard et al., 2013; van Proosdij et al., 2014).

6.3.3 ACCOMMODATION

Accommodation responses seek to lower the risks of climate hazards without fundamentally changing land usage by allowing for occasional short-term impacts (e.g., impacts from storm events or seasonal flooding). Accommodation is an appropriate response when the practicality of protecting coastal assets is outweighed by the economic, environmental or social costs, and/or when the effectiveness of protection measures would be limited to a relatively short period of time (*see* Chapter 3).

In the East Coast region, there are a few examples of structures planned to accommodate sea-level rise or storm surge, such as homes or other buildings constructed on stilts, or modular buildings designed to be easily moved (Vasseur and Catto, 2008; Doiron, 2012). Storm-water management that decreases runoff (e.g., vegetated swales and green space), increases conveyance (e.g., dredging channels and engineering drainage design with culverts that are appropriately sized for climate change) and increases storage (e.g., storm-water retention ponds and rain gardens) can be a very important accommodation option in addressing flooding. For example, evaluation of the 2003 storm-water management plan for Stratford, PE determined that numerous culverts within the town would not be able to accommodate projected changes in rainfall intensity associated with climate change, and that there was a need for increasing drainage capacity in order to accommodate larger runoff volumes. Increasing culvert size may not be beneficial, as larger and stronger drainage flows could lead to increased erosion. Instead, a combination of pipe upgrades, additional storage within tributary watersheds, abandonment and appropriate flood-proofing and hazard-warning systems in selected areas has been proposed to decrease damage and the threat to residents (CBCL Limited, 2012).

Accommodation includes accepting temporary inundation of noncritical infrastructure (e.g., flooding of secondary roads where alternative access routes exist for fire or other critical services). Cost-benefit studies can be used to assess the cost of modifying or displacing the road versus accepting occasional closure or repairs for several decades. Improved predictability of extreme events can enable actions such as evacuation of persons at risk and temporary protection of buildings and properties to happen in advance of a major storm.

6.3.4 PROTECTION

Protection consists of a variety of methods to defend coastal assets against the sea (erosion and flooding). It can take different forms, ranging from 'hard' methods, such as dikes, rip-rap, walls, gabions and groynes, to 'soft' or flexible methods, such as beach nourishment, revegetation and dune reprofiling, which allow coastal processes to resume naturally.

Data on the length and type of coastal protection by 'hard methods' tends to be incomplete and commonly outdated for most of the East Coast region (e.g., Bérubé, 1993; Bérubé and Thibault, 1996; Breau, 2000; Dubois et al., 2005; Bernatchez et al., 2008a; Catto, 2012). The exception is Prince Edward Island, where the entire coast was mapped by Davies (2011). Hard-protection approaches have been used for a long time, and estimates of the percentage of coast protected is usually less than 15% within local studies. Rip-rap (i.e., heavy stone or concrete) is by far the most widespread method employed. Other common types of hard protection structures in the East Coast region are seawalls of concrete or wood, bulkheads (i.e., gabions, sheet piling or wood cribs), revetments (i.e., using various materials to cover the coastal slope) and groynes made of stone, concrete blocks or wooden stakes driven in beach (Figure 22). In proximity to ports and harbours, jetties, groynes and breakwaters are the dominant structures and consist mostly of concrete dolosse or tetrapods, or heavy stone (Jennings et al., 2008).

Older homemade defence structures are still found at some locations, but their use is declining in favour of hard engineered structures (Bérubé and Thibault, 1996). Hard-protection measures for coastal defence are used to protect public infrastructure (i.e., harbours, port areas, roads and municipal frontage) and are also used by private landowners to protect their land and property from erosion. The number of individual coastal defence structures far exceeds the

FIGURE 22: Coastal-protection structures commonly used in the East Coast region (*adapted from* Jennings et al., 2008): **a)** riprap, Malagawatch ancestral burial grounds, southwestern Bras d'Or Lake, NS (S. O'Carroll, Geo Littoral Consultants); **b)** seawall, Eel River Bar First Nation, northeastern New Brunswick (D. Bérubé, New Brunswick Department of Energy and Mines): **c)** revetement, Mispec, southwestern New Brunswick (D. Bérubé, New Brunswick Department of Energy and Mines); **d)** bulkhead, Maria, Gaspésie, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–Université du Québec à Rimouski [UQAR]); **e)** groyne, Paspébiac, Gaspésie, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–UQAR); and **f)** breakwater, Pointe-Lebel, north shore of the St. Lawrence estuary, QC (Laboratoire de dynamique et de gestion intégrée des zones côtières–UQAR).

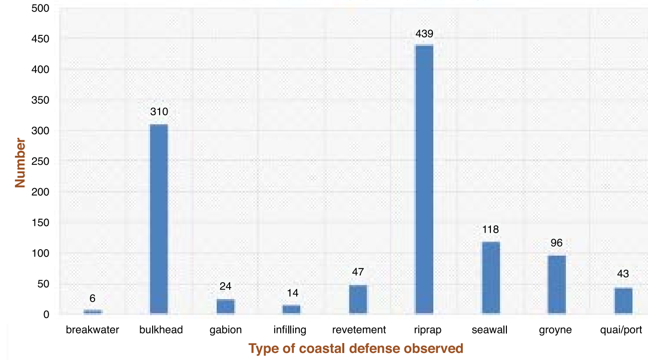

FIGURE 23: Inventory of coastal defence structures along the northern and eastern coasts of New Brunswick (Breau, 2000).

number of ports and small-craft harbours along the northern and eastern coasts of New Brunswick (Figure 23; Breau, 2000). On Quebec's North Shore, only one-third of the 91 km of artificial coasts mapped were attributed to port and harbour activities, with the remainder being public and private coastal protection (Dubois et al., 2005).

The total length of defence structures on the coast steadily increased, sometimes exponentially, during the period covered by aerial photographs. In southeastern New Brunswick, O'Carroll et al. (2006) documented that coastal armouring was 10 times greater in 1971 than in 1944, and 22 times higher in 2001 than it was in 1971. Similar trends have been observed for coastline armouring in the area of Percé (Péninsule de la Gaspésie, QC) and the residential areas surrounding Sept-Îles (Bernatchez and Fraser, 2012). Coastal armouring in the vicinity of Sept-Îles increased the most between the 1970s and the 1990s, and has since slowed considerably.

If hard-protection measures are not properly designed, placed and maintained, they can result in maladaptation: rather than diminishing vulnerability, they can actually worsen the situation, particularly for adjacent landowners. Among the most common negative effects are changes in the local sediment budget, which can result in accelerated erosion downstream, contributing to sand deficit or activating sand transfers. For these reasons, development of new sand-trapping measures such as groynes are highly restricted on crown land in New Brunswick (New Brunswick Department of Natural Resources, 2014). Other localized effects include the lowering, and sometimes the loss, of beaches and flats in front of the seawall (Bernatchez et al., 2008b, 2011; Bernatchez and Fraser, 2012). Lowering of the foreshore increases vulnerability to inundation. During storm events, surges increase the depth of water, allowing higher, more energetic waves to reach the shore. These situations can result in overtopping of protective structures such as dikes and seawalls (Bernatchez et al., 2011).

Hardening of the coastline by rigid, linear, coastal-protection structures can also lead to rapid loss of biodiversity and contribute to coastal squeeze by trapping coastal habitats and ecosystems between the rising sea and landward man-made barriers (Section 4.8). Another disadvantage of hard-protection measures is that they are generally irreversible. Once heavy stone or concrete structures are in place, it can be difficult to change the strategy of coastal protection because removal of the structures can be very expensive and often leaves the coast in an increased state of vulnerability until the equilibrium of the natural state is restored. In instances where coastal infrastructure cannot be removed, properly designed engineering approaches are warranted.

Soft-protection methods have only been used infrequently in the East Coast region. One example is the use of sand from the dredging of fishing harbours by the Quebec Department of Transportation to nourish beaches along roads threatened by erosion on the Îles de la Madeleine (Case Study 5). This method has adequately protected the roads since 2007 with no observed impact on the environment. The sand has the same characteristics as that of the local beach, since it comes from the nearby longshore drift. This reuse of dredged sand is an example of alternatives to hard protective structures. Mixed methods can also be used to reduce the wave energy, such as degradable groynes reloaded with sand (Figure 24), sand-dune–trapping devices, or protection and/or replanting of beach grass (Restore America's Estuaries, 2015).

6.4 IMPLICATIONS AND FUTURE DIRECTIONS

There are considerable opportunities in the East Coast region to increase the capacity for adapting to climate change and implementing effective adaptation measures to address coastal risks. Basic steps include increasing awareness, engaging and empowering stakeholders, reviewing and adjusting legislation and codes of practice where appropriate, enhancing interjurisdictional collaboration, and addressing regional and local differences in adaptive capacity. Adaptation is fundamentally a social process that leads to modification of long-standing habits. Progress has been made. As an example, recently developed guidelines for engineers recognize that the return period of extreme events changes over time.

Most coastal-management practices in the East Coast region were implemented before climate change was recognized as an issue and the concept of climate change adaptation was developed. The most common approaches to address coastal erosion and storm-surge flooding have been the use of hard protection methods and retreat from areas at risk. As a result of changing climate, the East Coast region is facing new challenges and will need to consider new ways of managing the associated risks. Coastal-adaptation researchers and practitioners worldwide have reported on the diverse challenges related to conflicting uses, financial fairness, integration and consultation processes, development, management of uncertainty, perceptions, political will and leadership, and regulatory framework and governance structure.

Examples of innovative ways to address these challenges are emerging. For example, with respect to consultation processes, Quebec has established a series of regional groups that serve as forums for gathering key participants around issues of managing multiple uses in the coastal areas of the estuary and Gulf of St. Lawrence (Ministère du développement durable, de l'Environnement, de la Faune et des Parcs du Québec, 2012). Ultimately, society will have to decide what constitutes sustainable development of the coast. Where cost-benefit analyses have been undertaken, there is evidence that decisions to retreat from the coast, and/or to use soft protection methods, are generally more productive in the long term. Ongoing economic analysis will also contribute to the selection of appropriate adaptation options. Where major infrastructure already exists, or where large populations are already settled in risk areas, the use of hard protection options may be more appropriate.

FIGURE 24: Hybrid living shoreline on the Shubenacadie River, Bay of Fundy, NS, illustrating gabion basket planted with marsh vegetation to reduce erosion scour. *Photo courtesy of V. Leys, August 2015.*

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APPENDIX A

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

Projected relative sea-level changes to 2100 are provided here for 19 locations shown on the accompanying map (Figure A1) for the East Coast region (*after* James et al., 2014, 2015; Section 3.1 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., 2013) and were generated using vertical crustal motion derived from GPS observations.

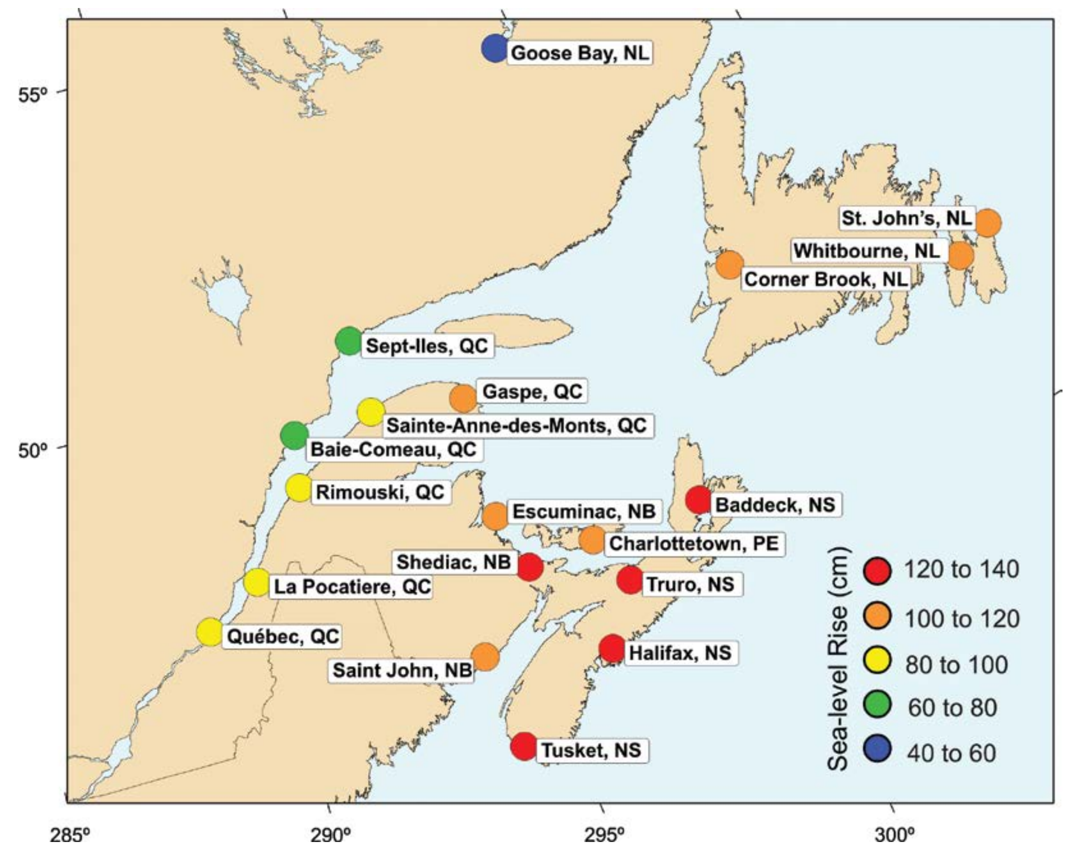

FIGURE A1: Locations for which sea-level projections are provided through the 21st century (Figure A2). Dots are colour coded to indicate the projected sea-level change at 2100 for the 95th percentile of the high-emissions scenario (RCP8.5; *after* James et al., 2014, 2015).

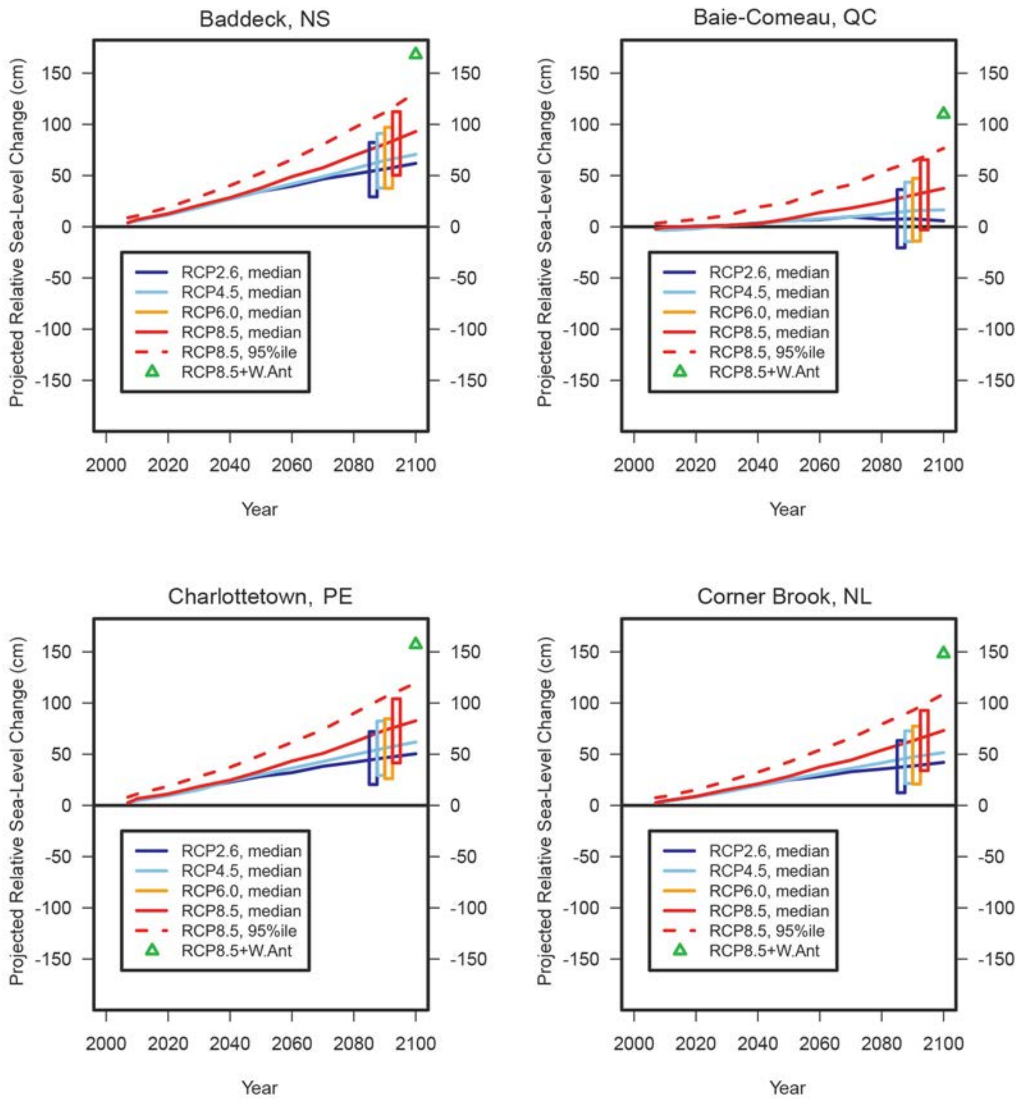

FIGURE A2: Projected relative sea-level changes through the 21st century for selected locations in the East Coast region (*after* James et al., 2014, 2015). RCP2.6 is the explicit emissions-reduction scenario, RCP4.5 is business as usual and RCP8.5 is high emissions. The projected value at 2100 is given for an augmented scenario, in which the West Antarctic Ice Sheet 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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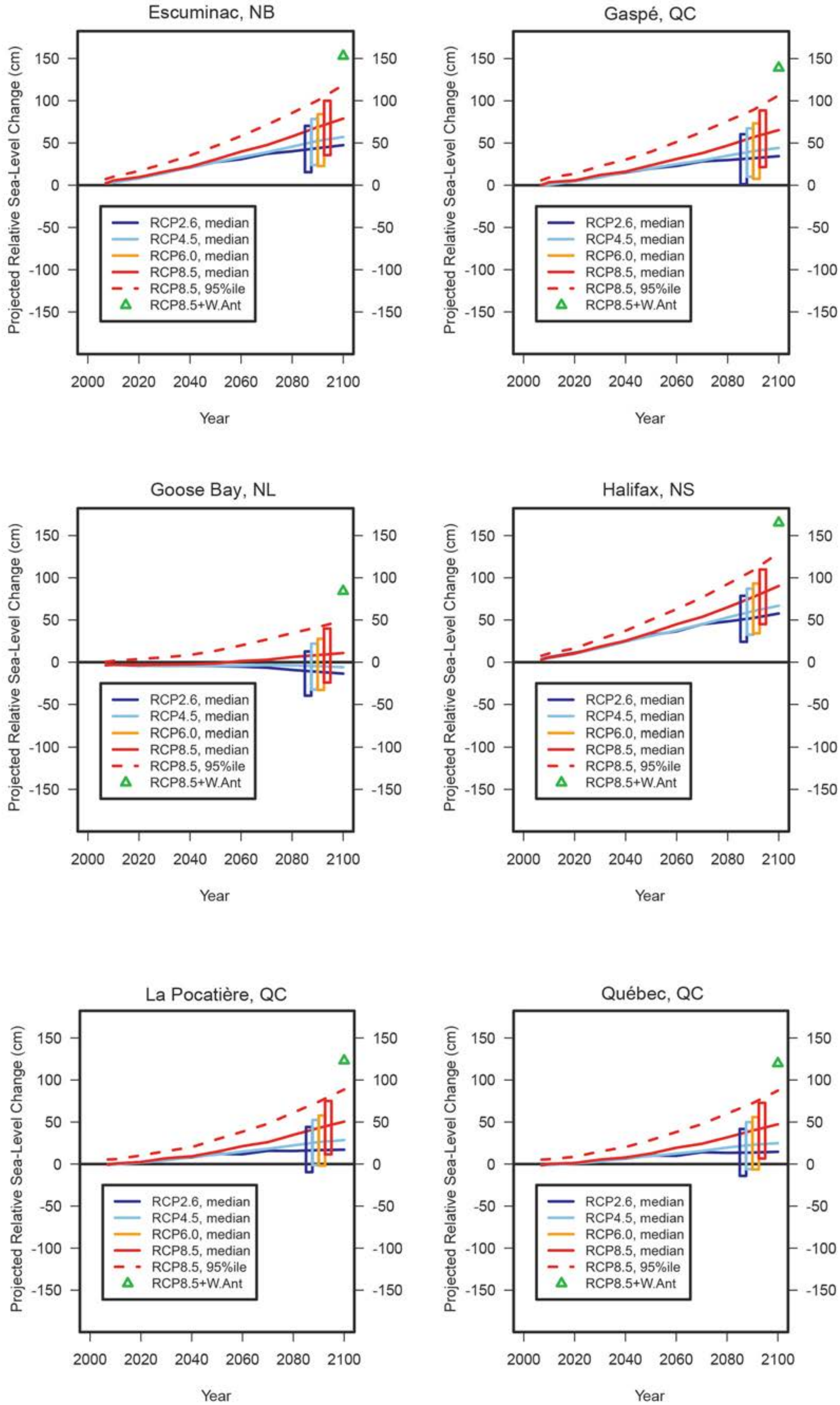

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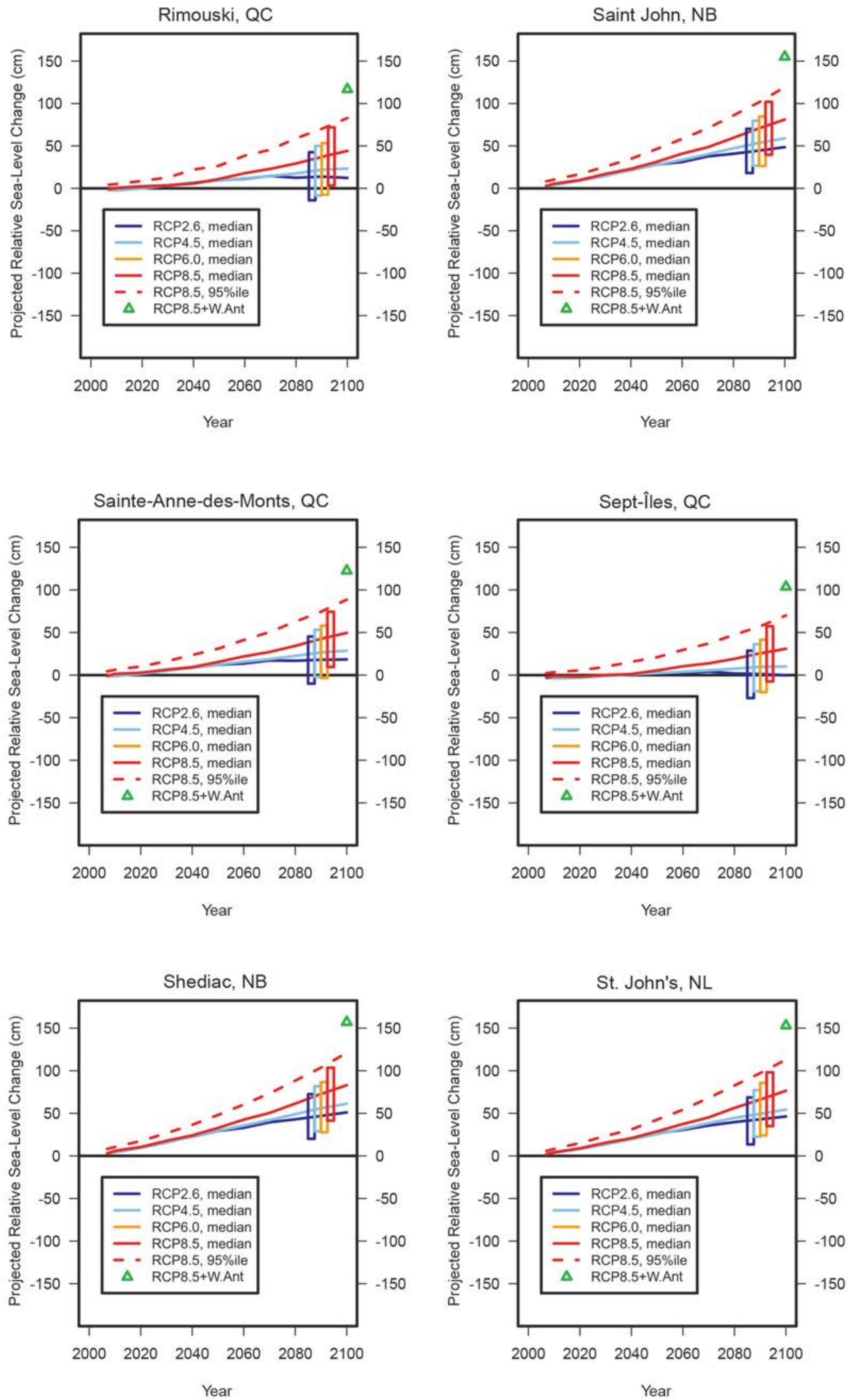

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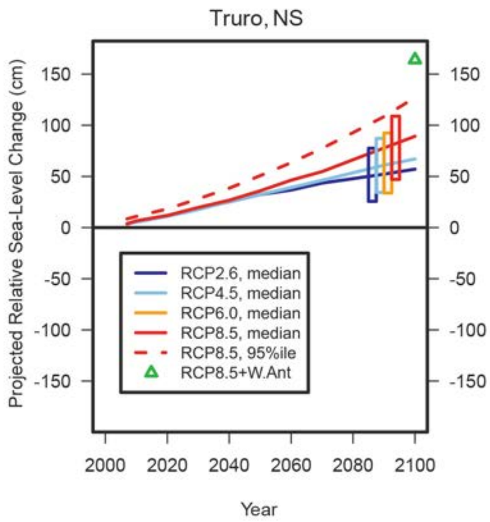
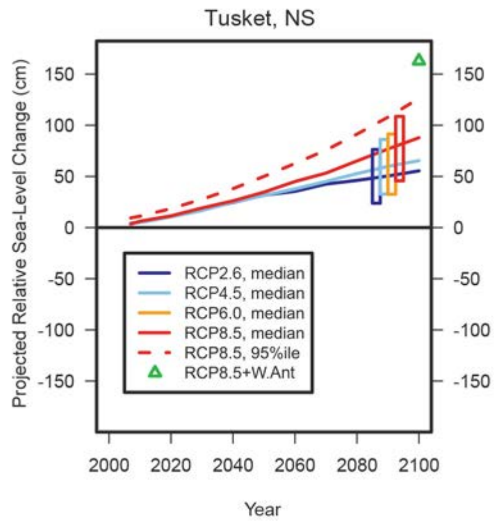
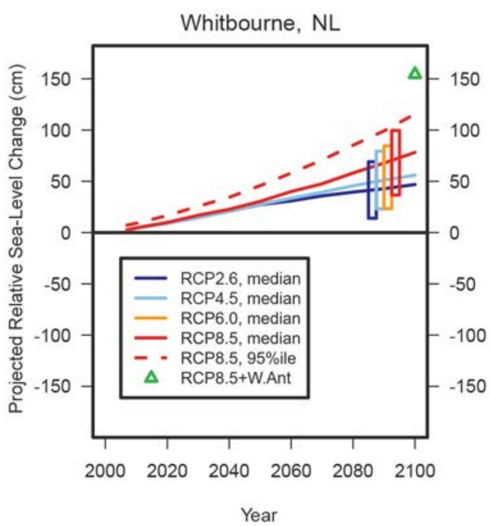

Truro, NS
Projected Relative Sea-Level Change (cm)
150
100
50
0
-50
-100
-150
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant
2000
2020
2040
2060
2080
2100
Year


Tusket, NS
Projected Relative Sea-Level Change (cm)
150
100
50
0
-50
-100
-150
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant
2000
2020
2040
2060
2080
2100
Year


Whitbourne, NL
Projected Relative Sea-Level Change (cm)
150
100
50
0
-50
-100
-150
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant
2000
2020
2040
2060
2080
2100
Year

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-

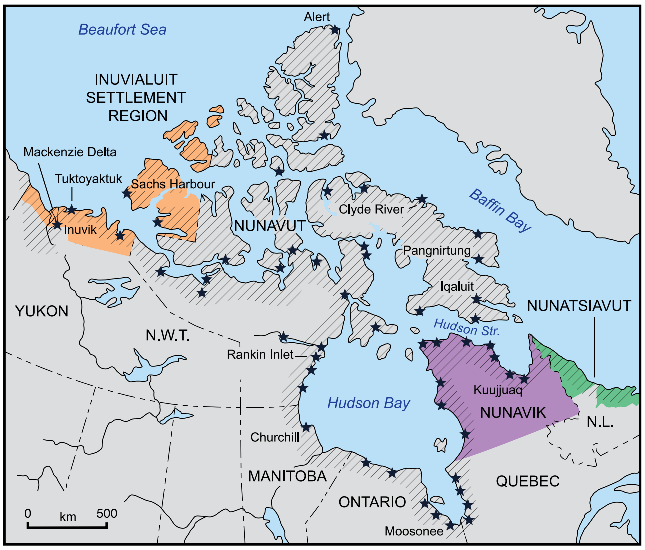

FIGURE 1: Location of the North Coast region. Communities are depicted with small stars. Abbreviation: N.W.T., Northwest Territories and N.L., Newfoundland and Labrador.

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).

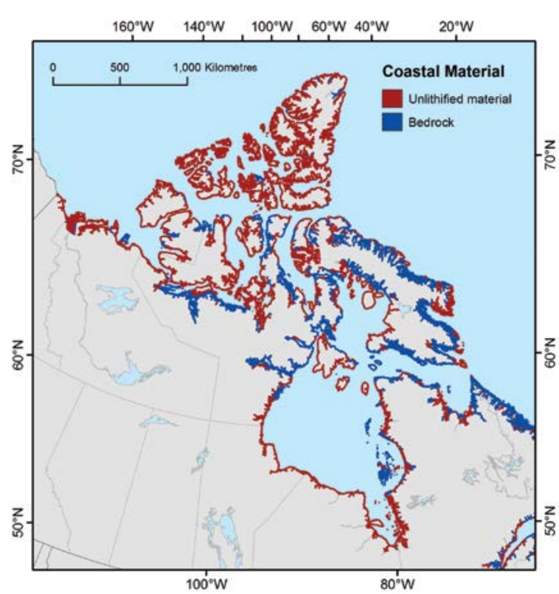

FIGURE 2: Variability of coastal material in the North Coast region (*from* Couture and Manson, 2016).

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).

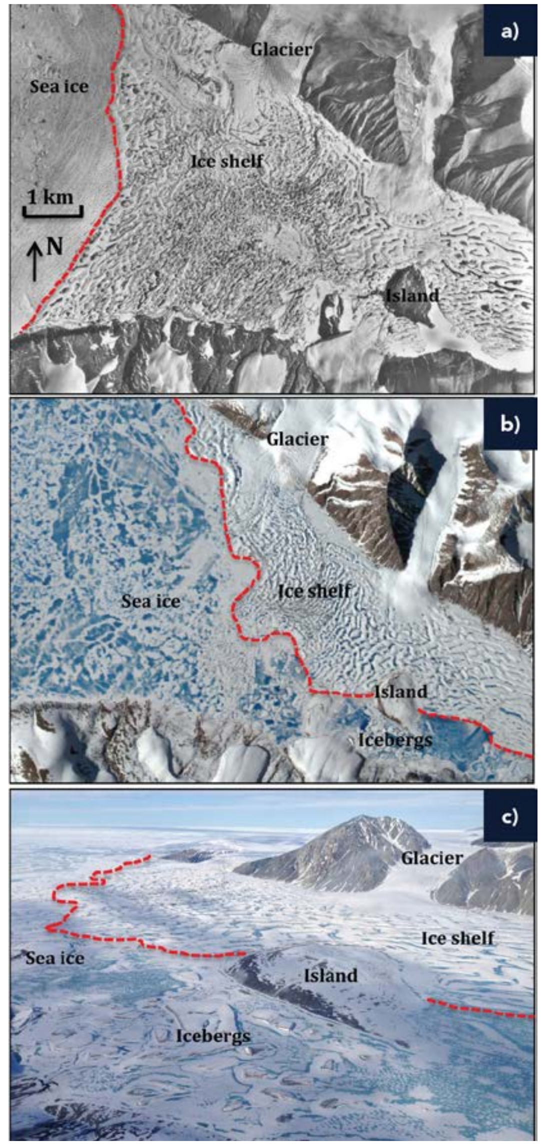

FIGURE 3: Changes in the extent of the Petersen Ice Shelf, Ellesmere Island, between **a)** an aerial photograph from August 13, 1959 (photo A16724-63); **b)** ASTER satellite imagery from July 7 and 11, 2014; and **c)** an oblique photograph from July 13, 2014. Dashed red line marks the boundary between 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

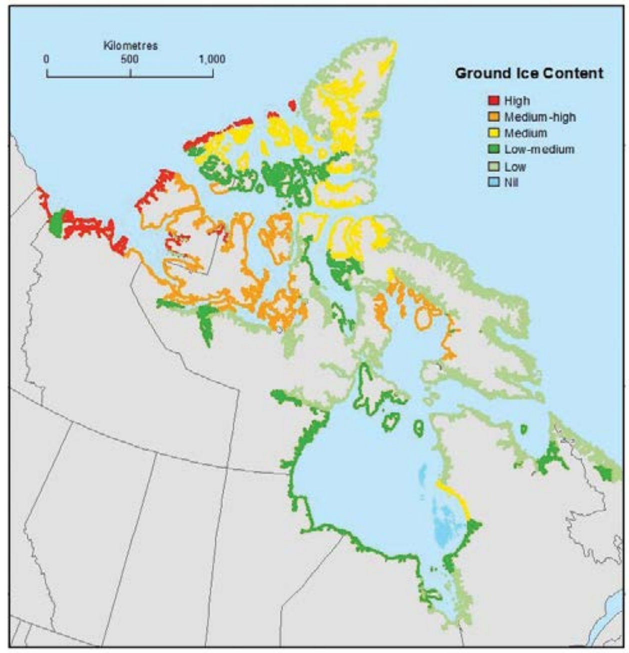

FIGURE 4: Ground-ice volumes in the North Coast region (Couture and Manson, 2016), based on data from Natural Resources Canada (1995). High ground-ice content is >20% by volume, medium is 10–20% and low is <10%.

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).

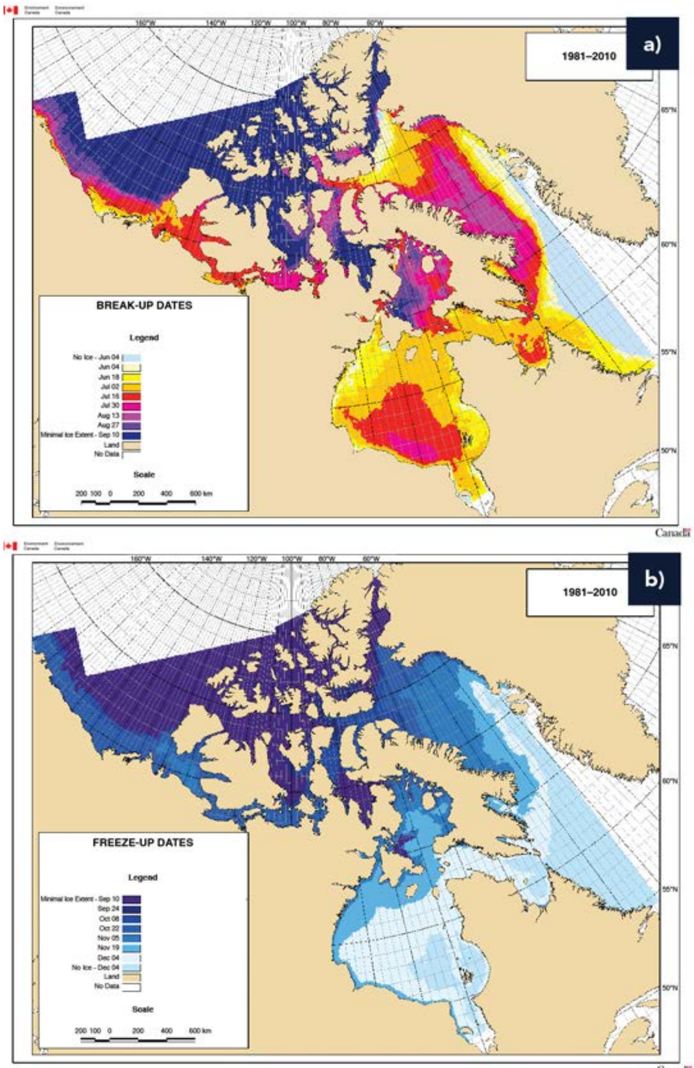

FIGURE 7: Climatic ice atlas 1981–2010 (*from* Environment Canada, no date), showing the extent of sea ice during **a)** the break-up and **b)** freeze periods.

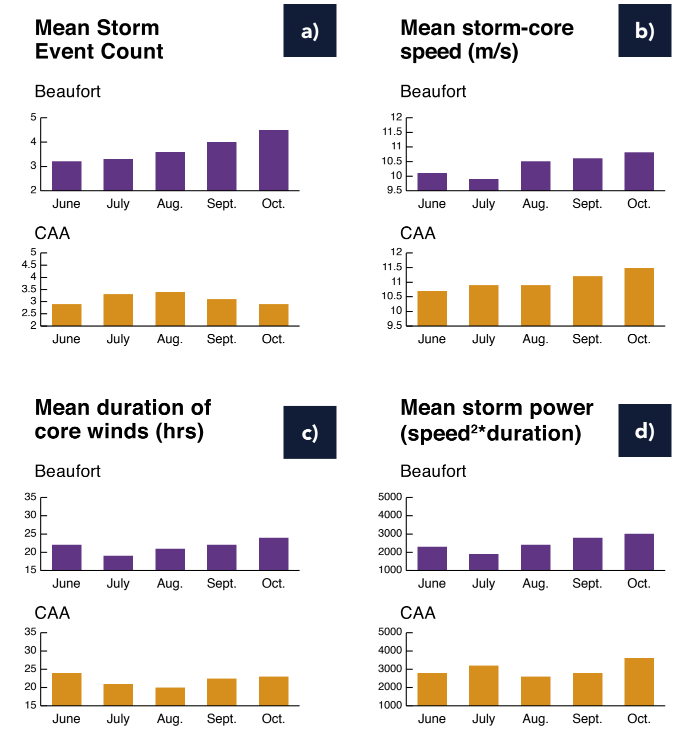

FIGURE 8: Storm statistics for 1950–2000 (*from* Atkinson, 2005), based on data from ground-based stations on the Beaufort Sea coast and the outer margins of the CAA, including **a)** mean storm count per month per sector; **b)** mean core wind speed (upper 50th percentile of all wind speeds); **c)** 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.

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.

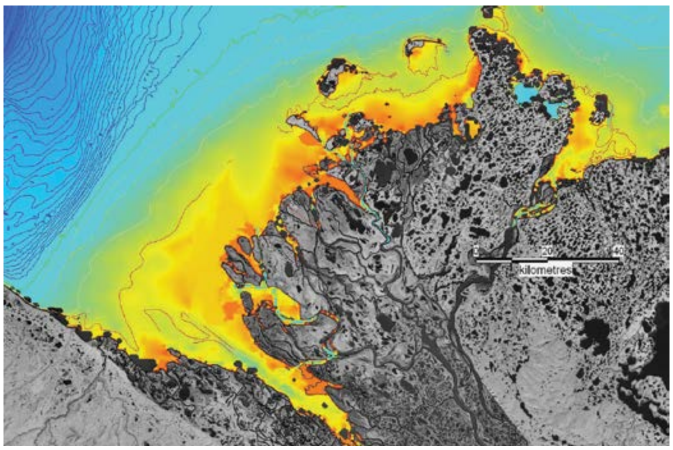

FIGURE 9: Low coastal gradient on the Beaufort Sea shelf along the Mackenzie Delta. The 2 m isobath is indicated in red (*from* Geological Survey of Canada, 2016).

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.

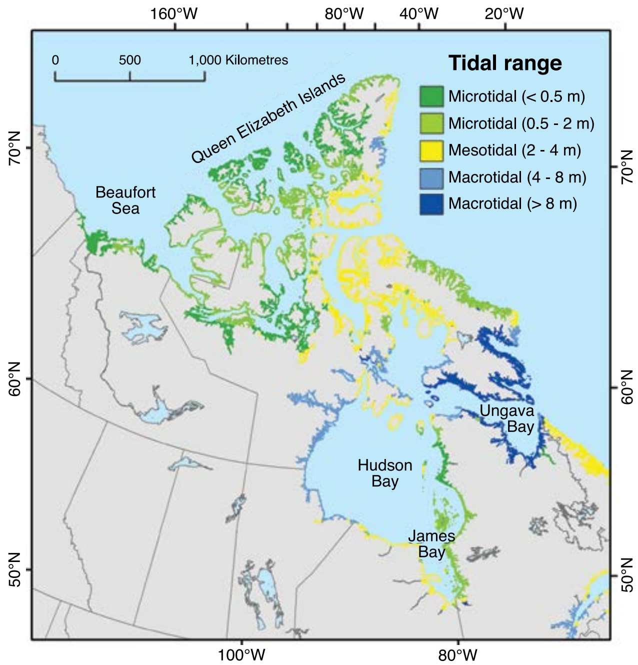

FIGURE 11: Variability in tidal range across the North Coast region (*from* Couture and Manson, 2016). Tides range from <0.5 m along the Beaufort Sea to >13 m in Ungava Bay.

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

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.

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).

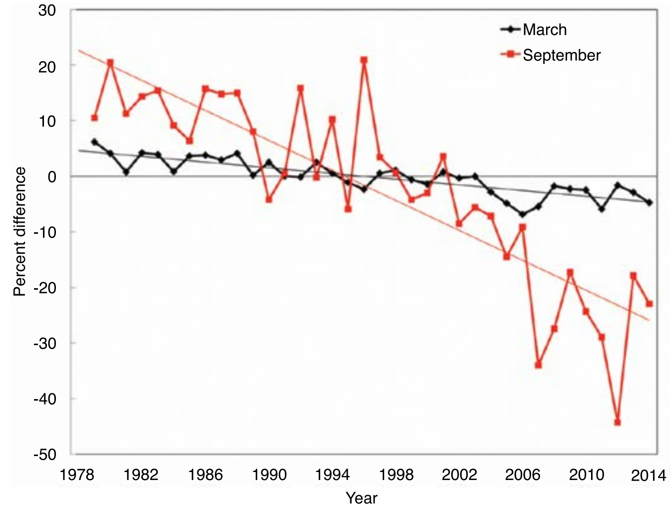

FIGURE 12: Anomalies in Arctic sea-ice extent (relative to the mean values for the period 1981–2010) for the month of maximum ice extent (March, indicated by black line) and the month of minimum ice extent (September, indicated by red line). Source: Perovich et al. (2014).

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).

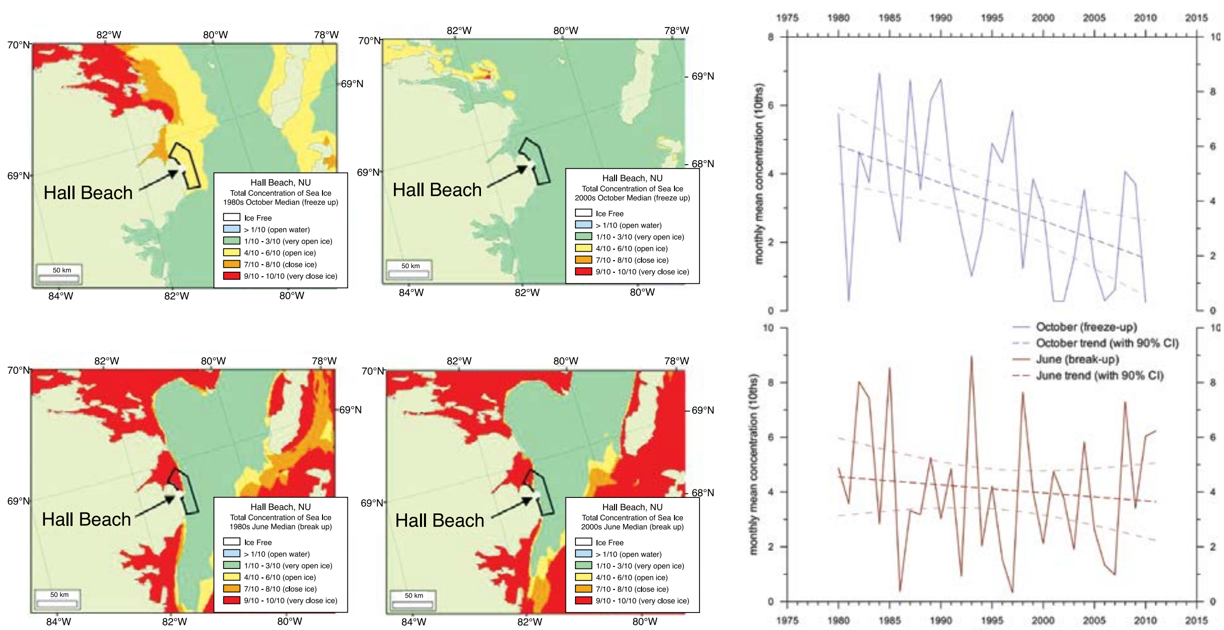

FIGURE 13: Changes in sea-ice concentrations at Hall Beach, NU during freeze-up (October) and break-up (June): **a)** decadal median ice concentrations for October during the 1980s, **b)** decadal median ice concentrations for October during the 2000s, **c)** decadal median ice concentrations for June 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

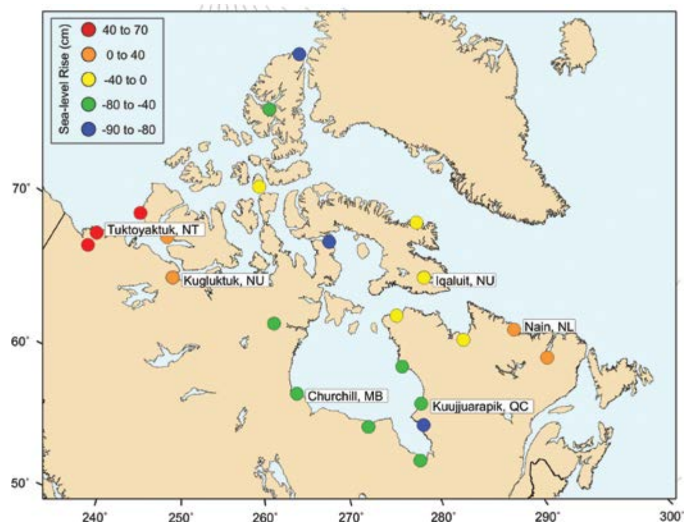

FIGURE 14: Projected median relative sea-level change in 2100 for the high-emissions scenario (RCP8.5; *after* James et al., 2014, 2015). Six labeled locations correspond to those in Figure 15, and projected changes for all sites are presented in Appendix A. See Chapter 2 for a description of scenarios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

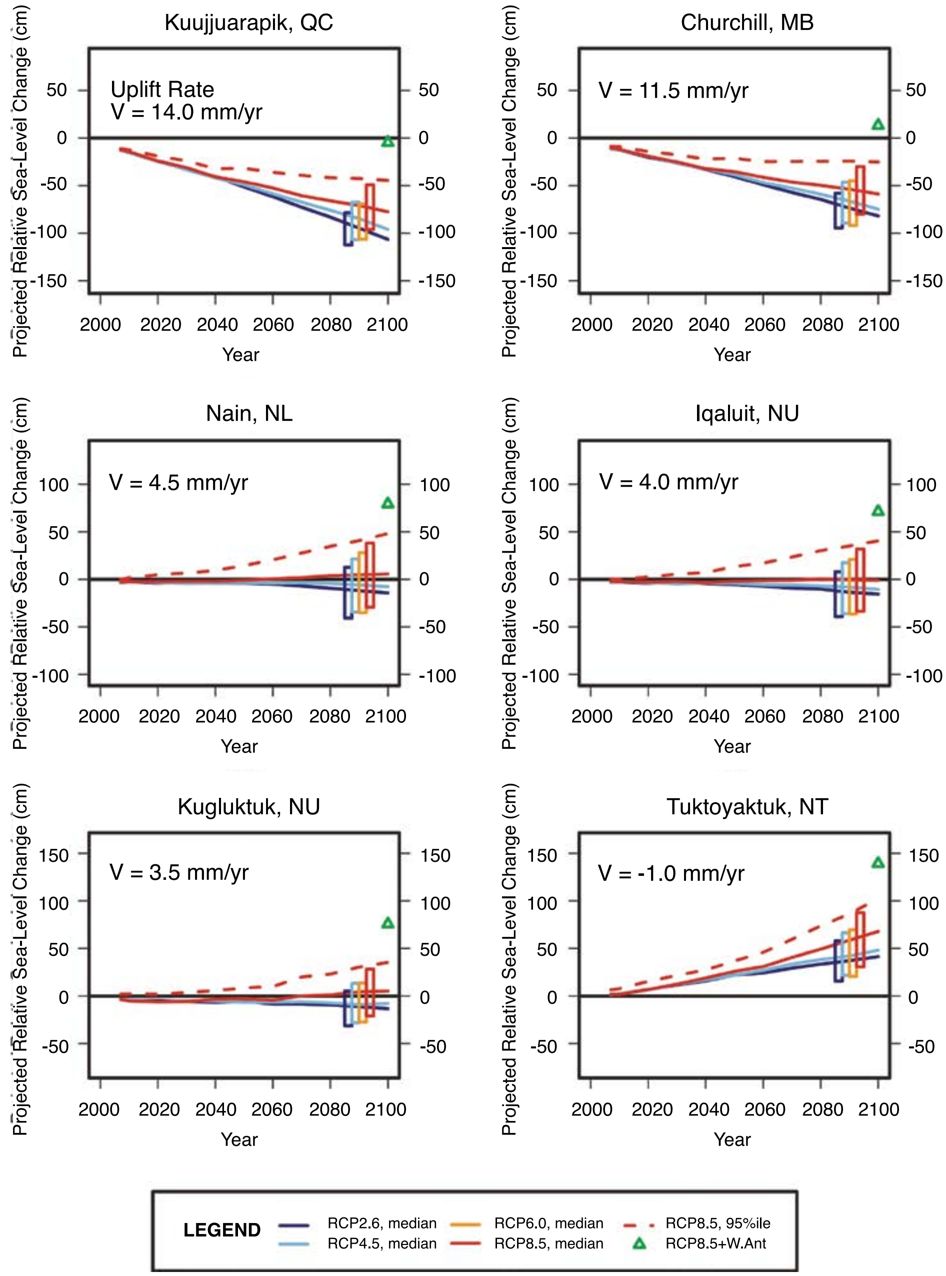

FIGURE 15: Projected relative sea-level change, based on the IPCC Fifth Assessment Report (Church et al., 2013 a, b) and using the vertical (V) crustal motion (uplift rate, given to the nearest 0.5 mm/year, derived from GPS observations) indicated in each panel (James et al., 2014, 2015). Projections 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).

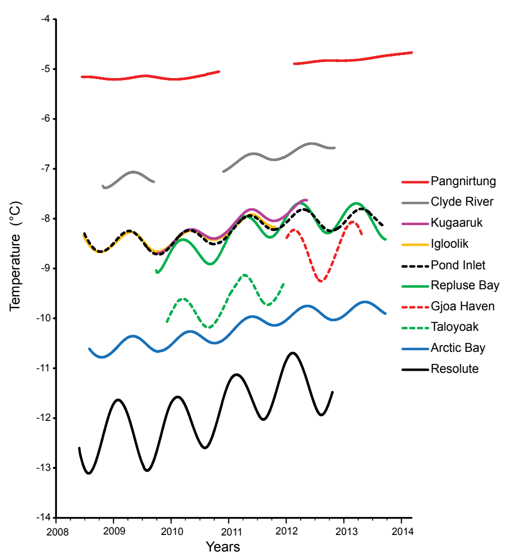

FIGURE 16: Permafrost temperatures at 15 m depth for 10 communities in Nunavut (*from* Ednie and Smith, 2015). Steady increases are seen at all sites during the period of observation, ranging from 0.04°C/year in Igloolik to 0.29°C/year in Resolute. The average increase is 0.15°C/year for all sites.

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 (Nunatsiavut)	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 (Nunatsiavut)	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; Pearce et al., 2010a;

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.

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

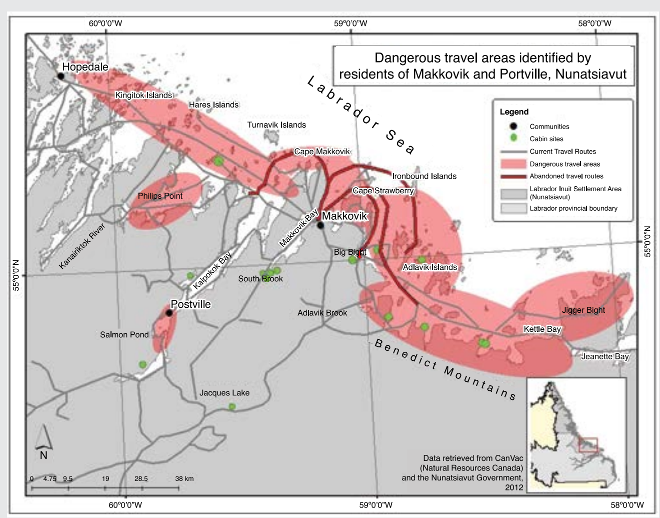

FIGURE 18: Dangerous travel areas (red) identified by residents of Makkovik and Postville, Nunatsiavut, NL (*from* Riedlsperger, 2013). Abandoned sea-ice travel routes are depicted as dark red lines. Inland trails (grey lines) now provide safer and more dependable travel routes.

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.

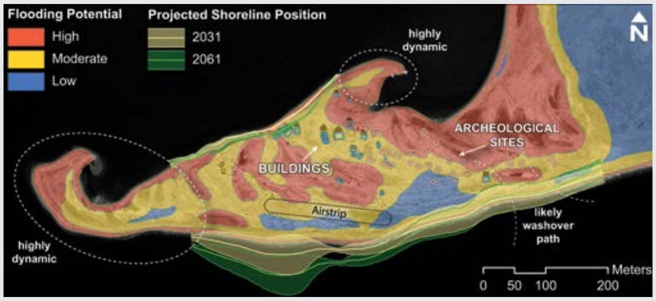

FIGURE 20: Coastal geohazard map of the historical settlement on Herschel Island (*from* B. Radosavljevic et al., 2015). The projected shorelines and potential flooding zones are superimposed on a 2011 satellite image showing the locations of buildings and archeological sites on the spit.

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 additional 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 Transportation 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

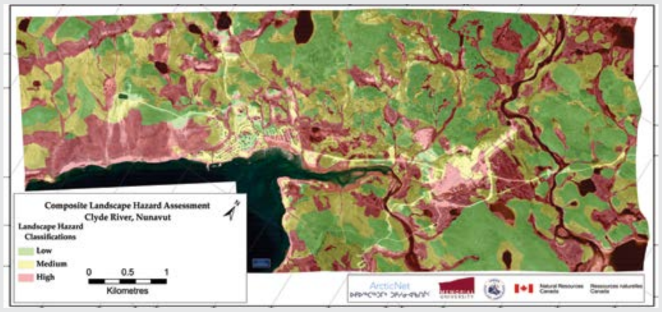

FIGURE 21: Composite landscape-hazard map for Clyde River, NU (*from* Smith et al., 2014).

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.

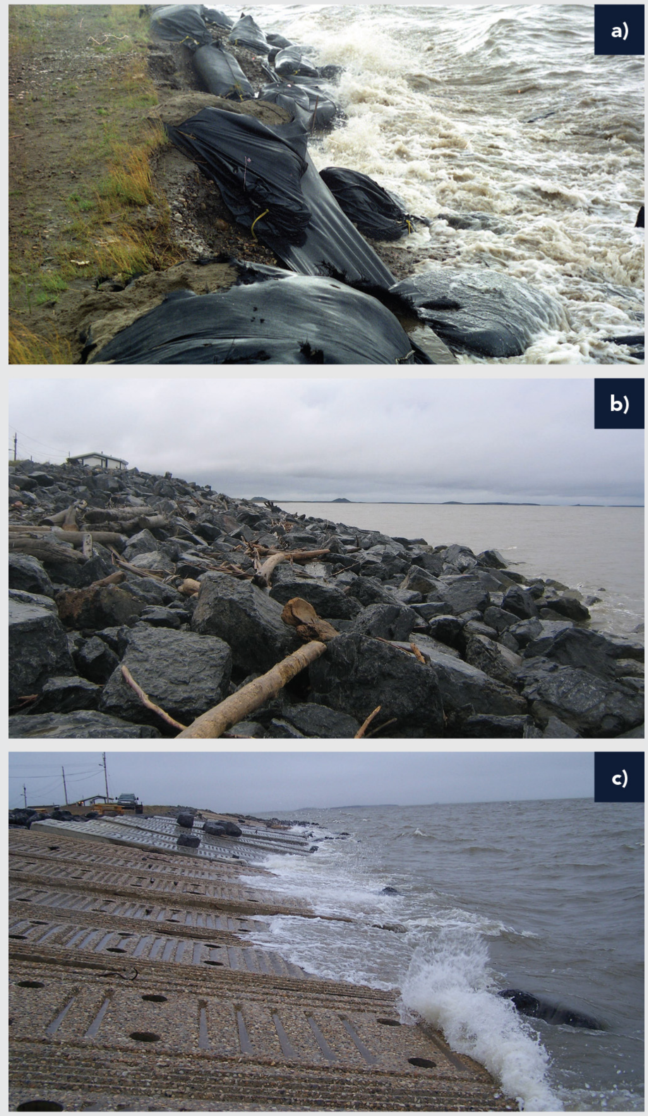

FIGURE 23: Various types of shore-protection measures include **a)** sandbags put in place in 1987, **b)** stone boulders (rip-rap) first used in 1997, and **c)** monolithic concrete slabs that were installed in 1998. *Photos a) and b) courtesy of S. Solomon, and photo c) courtesy of G. Manson.*

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.

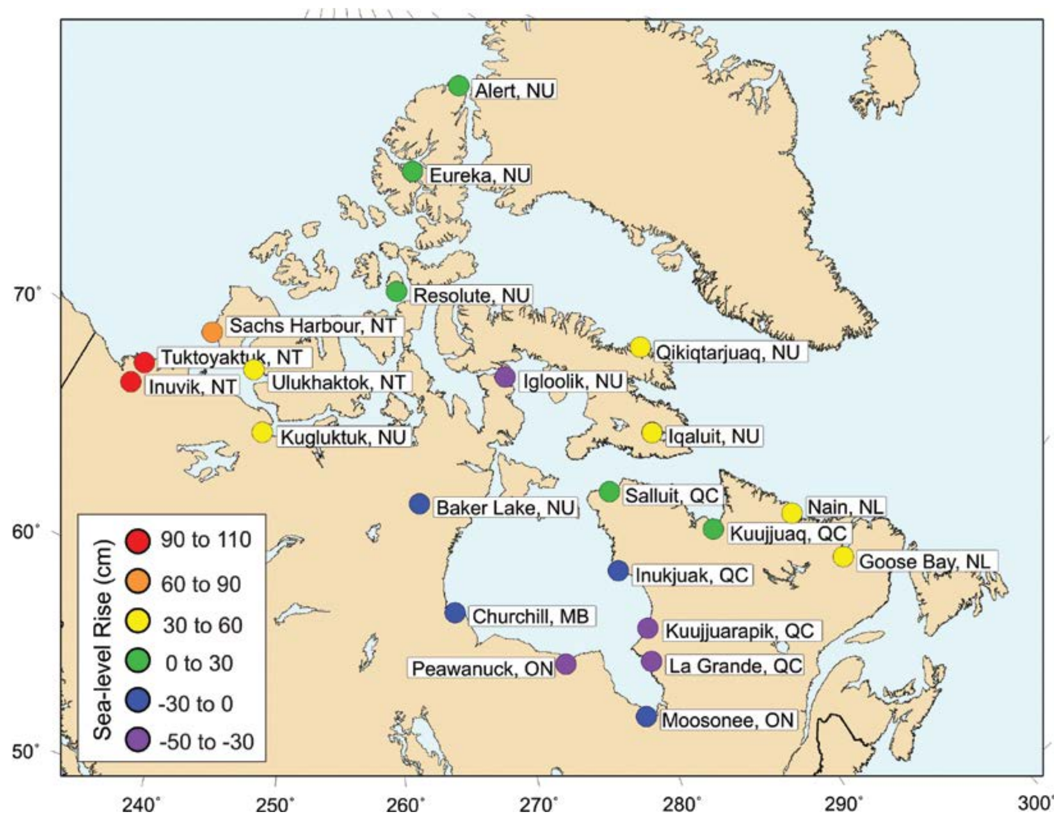

FIGURE A1: Locations for which sea-level projections are provided through the 21st century (Figure A2). Dots are colour coded to indicate the projected sea-level change at 2100 for the 95th percentile of the high-emissions scenario (RCP8.5; *after* James et al., 2014; 2015).

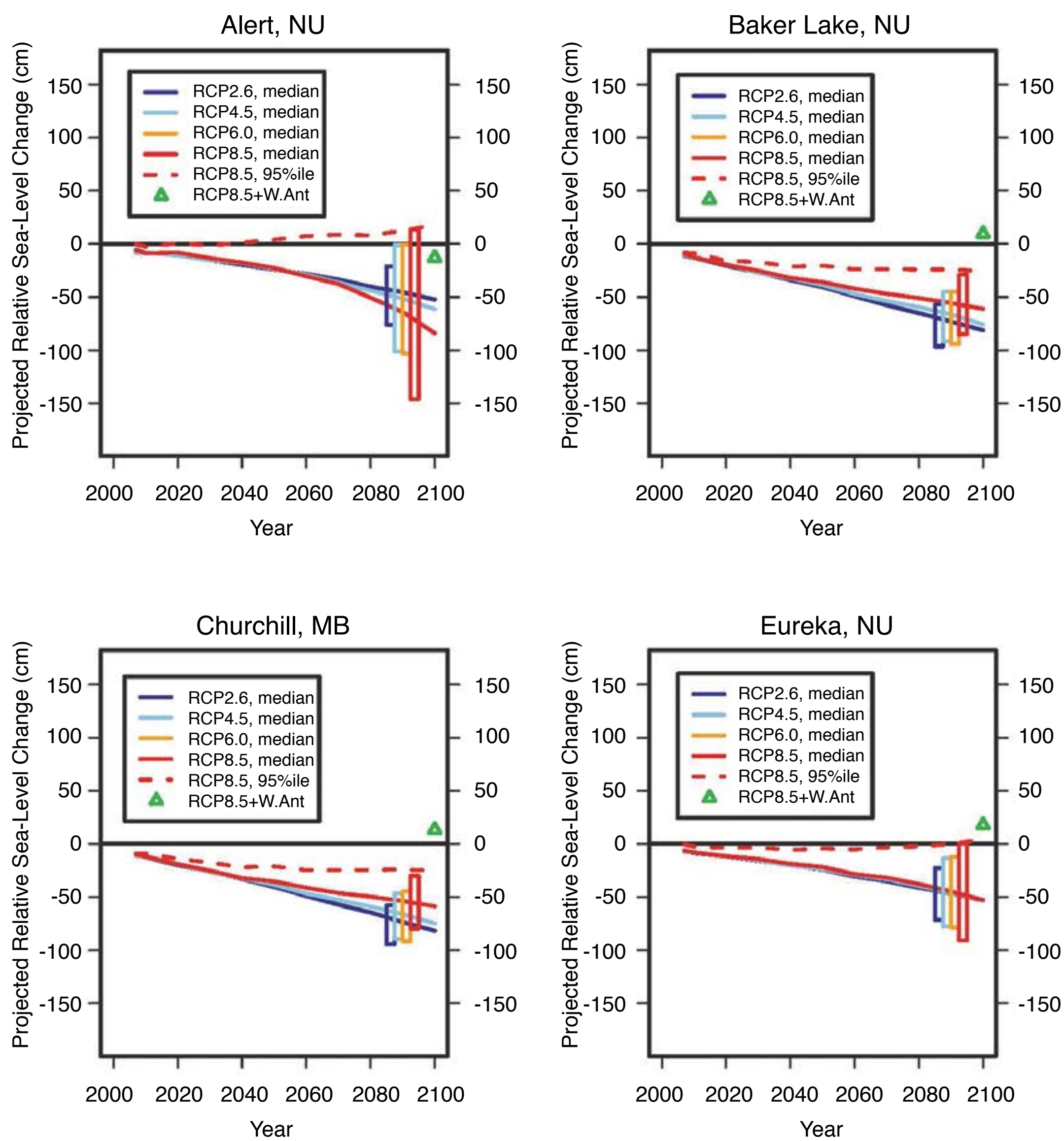

FIGURE A2: Projected relative sea-level changes through the 21st century for selected locations in the North Coast region (*after* James et al., 2014, 2015). RCP2.6 is a low-emissions scenario, RCP4.5 is an intermediate-emissions scenario and RCP8.5 is a high-emissions scenario. The projected value at 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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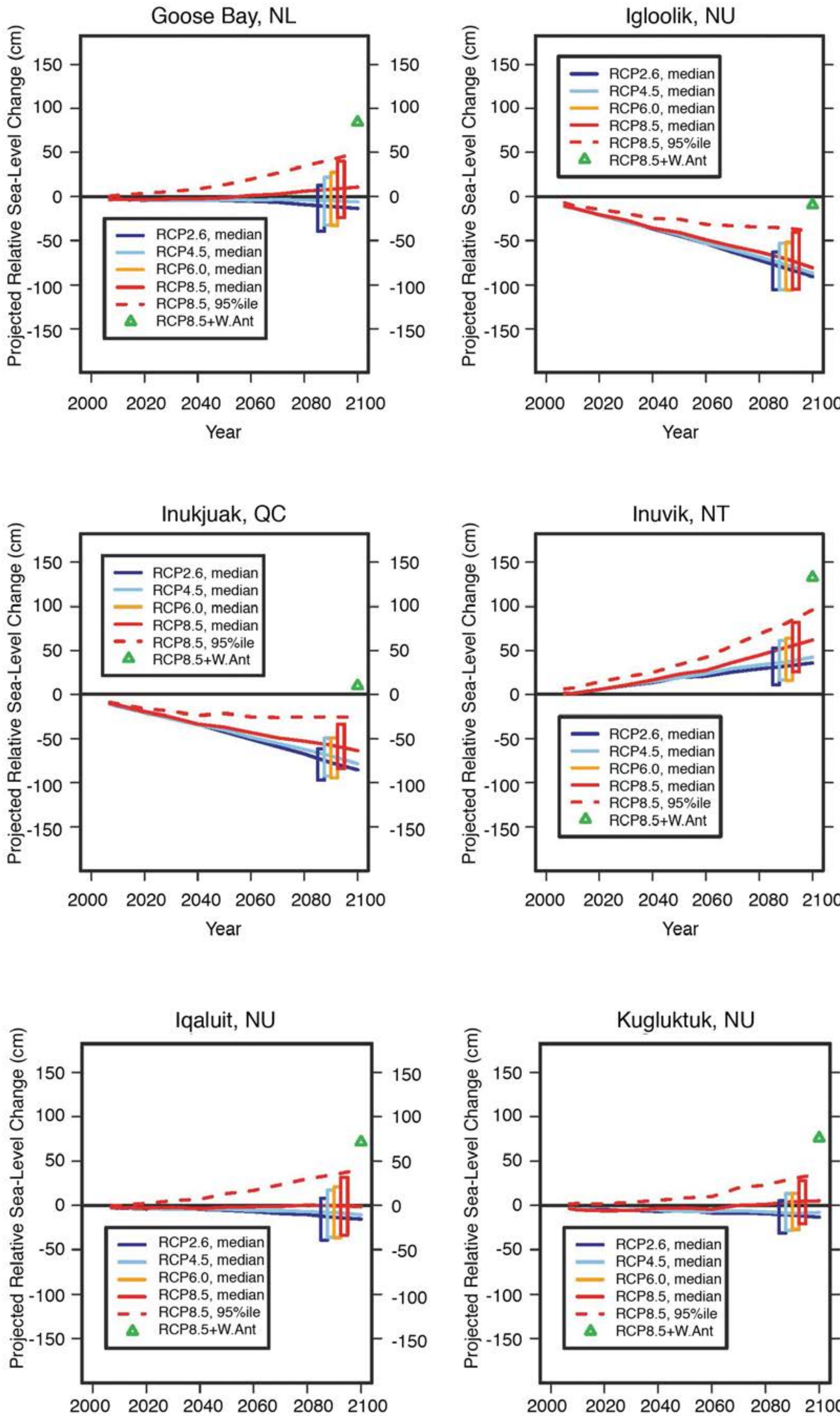

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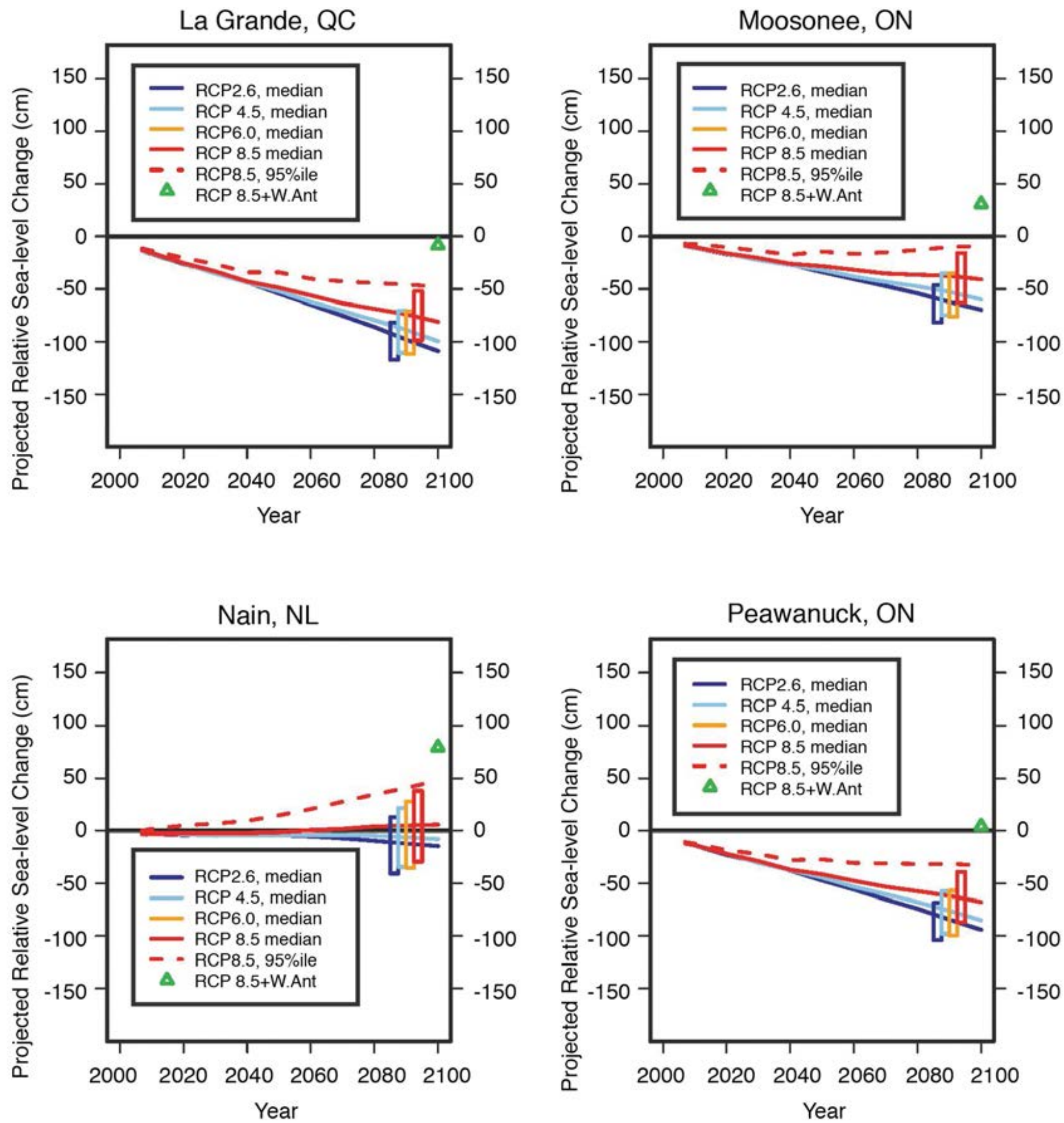

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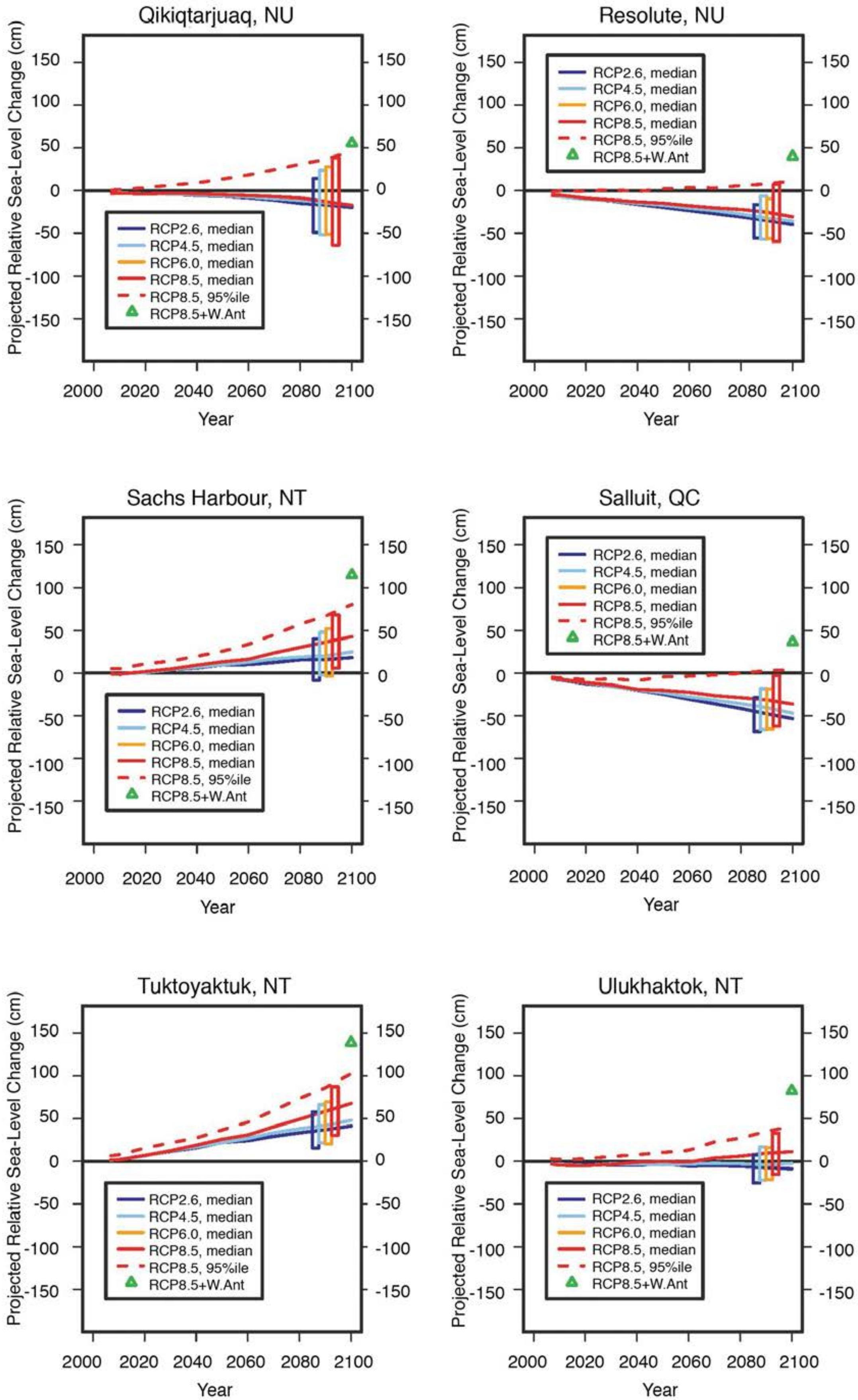
Qikiqtarjuaq, NU
Resolute, NU
Sachs Harbour, NT
Salluit, QC
Tuktoyaktuk, NT
Ulukhaktok, NT
Projected Relative Sea-Level Change (cm)
Year
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant
150
100
50
0
-50
-100
-150
2000
2020
2040
2060
2080
2100

CHAPTER 6: PERSPECTIVES ON CANADA'S WEST COAST REGION

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KEY FINDINGS

Coastal British Columbia is geographically, ecologically and socially diverse. The climate changes anticipated for this region, and their impacts, are similarly varied. Although large urban centres, small rural settlements and First Nations communities will experience climate change in different ways, several key findings are relevant to the region as a whole:

- **Sea-level rise will not affect all areas of the British Columbia coast equally, largely due to differences in vertical land movement.** The largest amounts of relative sea-level rise are projected to occur on the Fraser Lowland, southern Vancouver Island and the north coast. Planning guidance for sea-level rise developed by the British Columbia government provides planning levels that slightly exceed the peak values (95th percentile) of the sea-level projections at 2050. This could be considered a margin of safety that allows for possible additional sea-level rise arising from factors with significant uncertainty, such as contributions from the Antarctic Ice Sheet.
- **Storm-surge flooding presents a greater threat to coastal communities than sea-level rise alone.** Coastal communities are already coping with extreme water levels associated with climate variability (e.g., El Niño/La Niña Southern Oscillation) and storm-surge flooding. The risks associated with these events are expected to increase as sea level rises. Residential, commercial, institutional and municipal property and infrastructure in the region are vulnerable, and communities have begun to take action to reduce the risk through adaptation measures such as shoreline protection.
- **Marine ecosystems will be affected as species move northward in response to warmer water.** Southern species will expand their range northward into British Columbia as the ocean warms, while species that today inhabit the south coast region, including salmon, will also migrate north. In the southern part of the province, warmer ocean-surface temperatures will decrease the habitable range of shellfish and changing ocean acidity will affect their reproductive success. Adaptation in the commercial-fisheries sector will involve shifting the types of species being fished and relocating operations. First Nations, who rely strongly on salmon for cultural uses, often have fewer options for adaptation to changes in distribution and abundance of fish species.
- **Changing precipitation patterns will affect summer water availability and the timing of salmon runs in some watersheds.** Winter precipitation is expected to increase overall, with more falling as rain and less as snow. Less precipitation is expected during the summer and this, combined with reduced snowpack, will decrease the amount of water available for some regions in late summer and autumn. River levels will decrease during this period and water temperature is likely to increase as a result. Increased river temperature would affect the timing of salmon runs because these fish do not enter rivers until water temperatures cool to approximately 15°C.
- **Climate change adaptation is gaining momentum in British Columbia.** Governments have been moving forward on climate change adaptation, particularly regarding sea-level rise and coastal-flooding issues. Notable projects include a cost assessment of upgrading Metro Vancouver's dike system; a risk study for sea-level rise in the Capital Regional District; the City of Vancouver's new Flood Construction Level that considers sea-level rise; the placement of boulders below the low-tide level off the West Vancouver shore to mitigate storm-surge impacts; and the development of a Sea-Level Rise Primer for local governments.

1 INTRODUCTION

Western Canada features more than 27 200 km of coastline, all within the Province of British Columbia (Figure 1). Coastal landscapes range from low-lying deltas to mountainous fiords that host diverse ecosystems, economies and cultures. Climate and weather patterns along Canada's Pacific coast are highly variable, due largely to the region's complex and varied physiography (Section 2; Demarchi, 2011). Much of the British Columbia coastline consists of deeply indented fiords with substantial relief, but the two largest concentrations of population are located on the Fraser Lowland, which includes large regions, such as the Fraser River delta, with elevations near sea level, and on southern Vancouver Island, a region of relatively subdued topography. The major urban areas of the southwestern mainland and southern Vancouver Island give way to smaller communities and remote settlements, many within the traditional territories of numerous First Nations.

FIGURE 1: Geographic extent of the West Coast region.

Although fishing and forestry often feature prominently in discussions about the provincial economy and energy is seen as playing an important role in BC's future, primary industries (agriculture, forestry, fishing, mining and energy) make up only 7.7% of provincial GDP (BC Stats, 2014). British Columbia is also a largely urban province, with about 75% of its population residing within Metro Vancouver (BC Stats, 2013a) on the southwest mainland, and in the Capital Regional District on southern Vancouver Island. The construction and manufacturing industries are equal in size to the primary industries, and service-producing industries overshadow them all, making up 75.5% of provincial GDP (BC Stats, 2014).

The West Coast has two major commercial hubs, Port Metro Vancouver and Vancouver International Airport, which together contribute 6.4% of provincial GDP and generate $34 billion in total annual economic output (Intervistas Consulting Inc., 2009; Vancouver Airport Authority, 2012; Port Metro Vancouver, 2013). These centres of trade, along with the Port of Prince Rupert, link Canada with its trading partners in Asia, making British Columbia the 'Gateway to the Pacific'.

Although the modern provincial economy is diverse, the economies of many coastal communities remain strongly tied to ecosystems—fisheries, forestry and nature tourism. There are more than 170 cities, towns and villages (including unincorporated areas) along the western coast, and many of these are vulnerable to environmental changes that affect the resources and ecosystem services that residents rely upon for their livelihoods. Some of these communities have already experienced stress from the decline of the forestry and fishing industries. The result has been unemployment and economic migration to larger urban centres. People living in coastal communities with cultural ties to specific areas can experience high levels of psychological stress related to ecosystem changes that affect the viability of small, isolated, resource-dependent settlements.

The contrast between globally integrated, wealthy urban centres and resource-dependent rural communities is important for understanding how people perceive, and experience, climate change impacts. Socio-economic differences, such as wealth and the dependence on resources for income, can contribute to varying levels of climate vulnerability (e.g., Adger and Kelly, 1999; Thomas and Twyman, 2005). However, this dichotomy should not be overstated. Northern communities, such as Kitimat and Prince Rupert, play increasingly important roles in the BC export market, and many northern coastal jobs are fully integrated with national and global economies. Therefore, although it is possible to identify differences in regional vulnerability trends, the economic and social diversity of BC communities suggests that a nuanced, community-based approach to adaptation is needed.

Studies linking projected changes in climate to impacts on human activities and health suggest that sea-level rise, changes in the nature, timing and intensity of storms and precipitation events, and the altered distribution of marine species present the greatest concerns in coastal British Columbia. This is reflected in the focus of adaptation work going on in the province. Efforts to understand and address climate change impacts in British Columbia have been underway for more than 25 years (e.g., City of Vancouver, 1990). However, a strong, province-wide focus on adaptation is relatively recent, beginning within the last 10 years. Recognition of the need for adaptation has been accelerating since then.

1.1 SCOPE AND ORGANIZATION OF THIS CHAPTER

This chapter addresses the question "What do we know about climate change in coastal British Columbia and what is being done to adapt?" It presents the current state of knowledge by focusing on areas where there has been the most progress, in terms of both research and work. This includes fisheries, community impacts and responses, and strategically important built environments (e.g., major export hubs). Despite the growing importance of tourism and recreation for coastal economies, less information is available on the impact of climate change on these sectors. By contrast, many coastal local governments, supported by an increasing body of literature on adaptation, have begun to address climate change. These numerous examples allow an assessment of adaptation planning in the region.

While important gaps in understanding are acknowledged, the chapter focuses on what we have learned during the last decade, and in particular the years since the previous assessment of Walker and Sydneysmith (2008). In this way, the chapter profiles the rapid progress of both climate science and of government interest in adaptation.

The chapter first assesses the current state of knowledge regarding the changes in climate anticipated for BC's coastal waters and landscapes, from the Coast Mountains westward. It begins with a review of observed and projected changes in atmospheric, hydrological and oceanographic conditions to the year 2100 (Section 2). Next, it discusses how these changes are expected to affect ecological and human systems along the coast (Sections 3 and 4). The scientific and technical literature does not cover all issues or areas evenly across the West Coast region. For example, sea-level rise and its potential impact on Metro Vancouver have received substantial attention, whereas communities along the north and central coast have received less attention. Recognizing this asymmetry, and in order to broaden the relevance of available information to a coast-wide audience, this chapter places a strong focus on the process of adaptation.

The chapter concludes with a discussion of the state of adaptation in coastal British Columbia. Case studies from a range of coastal municipalities and sectors are provided to illustrate the various approaches to adaptation planning taking place throughout the region.

2 CHANGING REGIONAL CLIMATE

The climate of coastal British Columbia is characterized by relatively dry summers and wet winters, with most storm activity occurring in the winter months (Mesquita et al., 2010). Temperatures are mild and vary little compared to the rest of Canada. Daily mean temperature remains above freezing throughout the year (except at high elevations), and winter and summer mean temperatures rarely differ by more than 15°C.

In contrast to temperature, precipitation shows strong regional and seasonal variability. Average annual precipitation in the region ranges from less than 900 mm on eastern Vancouver Island, the Gulf Islands and eastern Haida Gwaii to more than 3500 mm on western Vancouver Island, with even greater amounts at higher elevations (e.g., more than 5000 mm in the Coastal Mountains of the mainland). Oceanic low-pressure systems dominate in winter, with heavy precipitation arising from the moist, mild air being pushed onto the south and central coast (Demarchi, 2011). In summer, high-pressure systems tend to dominate the region, resulting in drier conditions along much of the coast (Demarchi, 2011).

An important aspect of the regional climate, unique in Canada to the West Coast region, is the phenomenon of 'Atmospheric Rivers' (colloquially referred to as the 'Pineapple Express'). Atmospheric rivers are defined as "long narrow streams of high water vapour concentrations in the atmosphere that move moisture from tropical regions towards the poles across the mid latitudes" (PCIC, 2013a, p. 2). Atmospheric rivers are responsible for the most extreme rainfall events in the West Coast region (e.g., Ralph and Dettinger, 2012). The intense rainfall associated with atmospheric rivers can result in flooding and landslides, and potentially in costly damage to coastal communities (Lancaster et al., 2012; PCIC, 2013a).

The climate of coastal British Columbia shows significant variability at the scale of years and decades, due largely to the important influence of two climate cycles: the El Niño/La Niña Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO; *see also* Chapter 2; Moore et al., 2010). The ENSO has a cyclicity of about 3–5 years. In warm El Niño years, air heated by above-average sea-surface temperatures moves northward from tropical regions into North America, where it remains for several months. The effect of this on the West Coast region is warmer winters with less precipitation. The cold phase, La Niña, brings air cooled by below-normal sea-surface temperatures north from the tropics. This also lasts for several months and leads to colder winters and cooler waters off the coast of BC (e.g., Shabbar et al., 1997; Fleming and Whitfield, 2010).

The other climate cycle, the PDO, is also a warm/cool cycle. However, unlike ENSO, each PDO cycle is measured in decades rather than months, repeating every 40–60 years. Sea-surface temperatures in the north Pacific, which alternate from periods of relative warm to periods of relative cool, drive this cycle. These cyclical changes in ocean temperature affect air temperature in BC because the prevailing winds, influenced by the jet stream, move over north Pacific waters before blowing over the West Coast.

Understanding the strong influence of ENSO and PDO on British Columbia's climate is crucial for understanding climate change in the region. For example, average temperatures in coastal British Columbia are slowly creeping upward, at fractions of a degree per decade (PCIC, 2013b, c). At the same time ENSO and PDO are causing relatively strong fluctuations of several degrees that last from months to years, making it more difficult to discern a climate change signal (*see* Chapter 2).

2.1 TEMPERATURE

Average annual temperatures throughout the West Coast region have increased by 1.3°C during the past century (0.12–0.13°C per decade; PCIC, 2013b, c). This is slightly greater than the increase in global mean surface temperature during the same period (e.g., IPCC, 2013) but less than the average for Canada as a whole (Bush et al., 2014; *see also* Chapter 2). Since 1951, the rate of warming along the West Coast has increased to approximately 0.2°C per decade (Figure 2). Warming has been observed in all seasons; however, since 1951, temperature has increased the fastest during summer (0.22–0.26°C per decade; PCIC, 2013b, c).

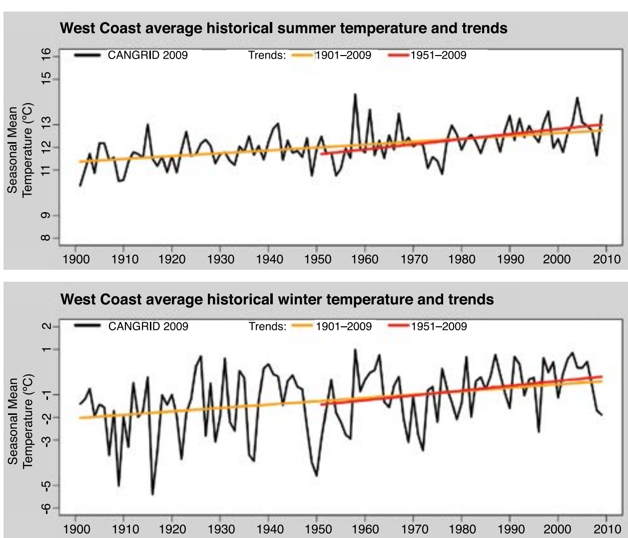

FIGURE 2: Historical temperature trends (1901–2009) for the West Coast region of British Columbia (PCIC, 2013b, c). All trends except winter (1951–2009) are statistically significant at the 95% confidence level. Trends for the south coast, which includes Vancouver, are very similar (PCIC, 2013b).

Projections of future changes in temperature, precipitation and other climate variables are available online at provincial and regional scales from the Pacific Climate Impacts Consortium (www.pacificclimate.org; *see also* www.Plan2Adapt.ca). Temperature projections suggest that warming will continue in all seasons, with the greatest increases in year-over-year temperature continuing to occur during summer. Annual warming of about 1.4°C is projected by the 2050s and 2.3°C by the 2080s (relative to the 1961–1990 average), based on consideration of two Intergovernmental Panel on Climate Change (IPCC) Special Reports on Emissions Scenarios (IPCC, 2000). These increases in temperature are less than those projected for Canada as a whole.

2.2 PRECIPITATION

Trends in average seasonal precipitation have remained stable for the West Coast for the past century. Although records suggest that average precipitation has been increasing during that time, few of these trends are statistically significant (PCIC, 2013b, c). Changes are most likely explained by the high natural variability of precipitation in the region. However, clear signals of the influence of climate change on precipitation may emerge by the 2080s (PCIC, 2013b).

Climate change will likely have little effect on the average amount of precipitation the West Coast region experiences in a given season or year. However, it may affect the timing of precipitation and is likely to alter both its form (rain or snow) and intensity (how much at a time; Whitfield and Taylor, 1998). By the 2080s, average precipitation may increase by roughly 10%, relative to a 1961–1990 baseline, in all seasons except summer, where a 10% decrease is projected (PCIC, 2013b, c). This change would be small relative to historical variability, meaning that the average precipitation levels are expected to remain in line with what the region has experienced during the past century.

Higher winter and springtime temperatures will reduce the percentage of total precipitation occurring as snowfall. By the 2050s, winter snowfall is projected to decrease by about 25% and spring snowfall by about 50% (PCIC, 2013b, c). For the 2080s, the projected reduction in spring snowfall may reach 72% (compared with the 1961–1990 baseline). Less snow and more rain would lead to faster runoff and could contribute to water-scarcity issues because less water will be stored as snow and ice (Section 2.3).

An emerging concern for coastal British Columbia is the potential for more frequent and/or more intense extreme-rainfall events. The West Coast receives 20–25% of its annual precipitation in heavy-rainfall events resulting from atmospheric rivers. The frequency of atmospheric-river events is expected to increase for coastal BC during the period 2041–2070 under a high-emissions scenario

(Cannon et al., work in progress). This would increase the risk of flooding, landslides and sediment loading in drinking-water reservoirs.

Since 2001, British Columbia has experienced at least one flooding event per year caused by extreme weather or precipitation, including a 2009 storm that caused $9 million in damage, and one in 2012 that cost nearly $16 million (PCIC, 2013a). Work is underway to better understand, predict and manage the impacts associated with atmospheric rivers through improved data collection, forecasting and public participation in reporting extreme-rainfall events, the damage they cause and successful adaptation strategies (PCIC, 2013a).

2.3 HYDROLOGY

Projected changes in both temperature and precipitation patterns will result in changes to stream flow in coastal watersheds. Natural climate variability associated with ENSO and PDO will also play a role. As a result, future trends in the distribution and circulation of water within British Columbia's watersheds will be influenced by a combination of long-term climate change and short- to medium-term climate variability.

The distribution and circulation of water in British Columbia's coastal watersheds can be classified into three hydrological regimes: rainfall dominated, snowmelt dominated and hybrid (both rainfall and snowmelt dominated; Wade et al., 2001; Fleming et al., 2007). Climate changes, such as increased temperature and more precipitation falling as rain (rather than snow), threaten to alter the current patterns of water accumulation and discharge. It is not clear what effect climate change will have on rainfall-dominated watersheds, which already exhibit considerable variability. For example, during the period 1976–2005, mean daily, maximum daily and mean annual streamflow has decreased in rainfall-dominated regimes on the south coast but increased on the north coast (Rodenhuis et al., 2009).

A region-wide trend of declining snowpack across BC and western North America has been observed during the past several decades (Mote, 2003; Mote et al., 2005; Rodenhuis et al., 2009; Stewart, 2009). Earlier spring snowmelt and a declining proportion of winter precipitation occurring as snow have contributed to this decline (Stewart et al., 2005; Knowles et al., 2006; Stewart, 2009). Maintaining snowpack is important because this affects the amount of water that is stored for release during the summer and autumn.

Glaciers play a similar role in water storage and have been predominantly in a state of retreat since the mid-18th century as a result of rising temperatures. Glacier surveys throughout the Coast Mountains of BC indicate that the recent rate of glacier loss is nearly double that of previous decades (Schiefer et al., 2007; Bolch et al., 2010). In some basins, this reduced ice cover is associated with decreased summer flows (Moore and Demuth, 2001; Cunderlik and Burn, 2002; Stahl and Moore, 2006). This is consistent with the trend observed throughout western North America of changed timing and seasonality for the flow of snow-melt-dominated rivers (Stewart et al., 2005). Glaciers will continue to retreat as the climate warms. For example, Bridge Glacier, the source of the Bridge River, which provides 6–8% of BC's hydroelectric generating capacity, is expected to lose roughly half of its current area by the end of the century (Stahl et al., 2008).

Long-term trends suggest that coastal BC will experience decreased summer flows in glacier- and snowmelt-dominated watersheds. However, historical streamflow responses suggest that there will continue to be considerable year-to-year regional variability in summer water availability (Fleming et al., 2007). For example, while summer discharge has increased in the glaciated basins of the Stikine and Iskut rivers (Moore et al., 2009), rivers throughout the Fraser basin, including the main stem, have experienced high interannual variability in streamflow in recent decades, particularly during the spring and summer (Déry et al., 2012).

Summer water scarcity is already a concern for some coastal communities, such as those in the Cowichan Valley Regional District and the Sunshine Coast Regional District, and seasonal reductions in potable water supply (e.g., surface-water and groundwater sources) could become a concern for more communities as climate change progresses. Increasing, periodic water scarcity during the summer is anticipated in snowmelt-dominated regimes and, in particular, hybrid rain-snow regimes (Case Study 1).

CASE STUDY 1

PROJECTED HYDROLOGICAL CHANGES IN THE CAMPBELL AND FRASER RIVER WATERSHEDS

(summarized from Schnorbus et al. [2014] and Shrestha et al. [2012]; see these references for more detailed discussion of methodology and results)

The Campbell River and Fraser River watersheds drain into the Strait of Georgia from central Vancouver Island and the lower mainland, respectively (Figure 3). These basins together support a range of ecosystems, including major salmon-spawning grounds.

The Campbell River watershed is a mountainous basin on central Vancouver Island that covers 1755 km^2 and extends to 2200 m above sea level. The basin has a hybrid snowmelt-rainfall runoff regime characteristic of many

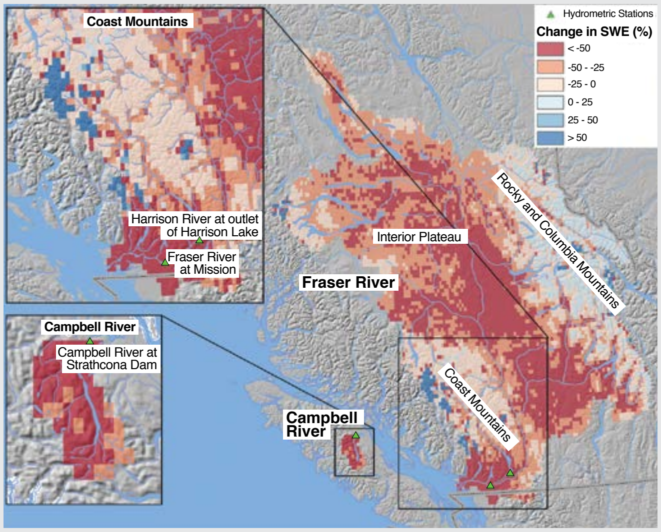

FIGURE 3: Projected mid-century (2041-2070) change in April 1st snow water equivalent (SWE) for the Campbell River and Fraser River basins (Schnorbus et al., 2014). Values are based on the median change from the 1961-1990 period for the A1B scenario (which assumes medium future anthropogenic radiative forcing).

coastal watersheds in BC, with runoff peaks in both fall and spring. The Fraser River system is the largest drainage basin in British Columbia, covering an area of 230 000 km^2. The basin extends to about 4000 m above sea level and has average annual precipitation ranging from 200 to 5000 mm, with areas of higher elevation experiencing greater precipitation. Although much of the Fraser River basin lies in the interior of BC, it supplies the largest pulse of fresh water to the BC coast (Morrison et al., 2012). The majority of the Fraser River basin, including the main stem, is a snowmelt-dominated regime with annual runoff dominated by spring freshet.

Hydrological modelling was used to simulate both a 30-year baseline (1961–1990; or the 1970s) and a future (2041–2070; or the 2050s) hydrological regime in both watersheds. An ensemble of eight global-climate models (GCMs) and three emissions scenarios were used to project changes in regional climate. Statistical downscaling of the GCM output to be compatible with the high spatial resolution of the hydrology model was achieved through bias corrected spatial disaggregation. Data for the Fraser River at Mission and the Campbell River at Strathcona Dam were naturalized to remove the influence of regulation.

Significant changes in winter snow accumulation during the 2050s are projected for both basins (Figure 3). A decrease in snow accumulation is expected throughout the Campbell River basin. A decrease in spring snow cover is anticipated for the Fraser River basin, with the exception of increased snow being projected for parts of the Rocky, Columbia and Coast Mountains.

In addition to warmer temperatures and increased precipitation in all seasons except summer, these changes in snow cover will result in changes to streamflow. In the Fraser River basin, total annual flow is projected to increase under most scenarios. Winter and spring flows should increase, whereas summer and autumn flows could either increase or decrease (Figure 4).

By the 2050s, earlier snowmelt is projected to advance the timing of the annual peak flow for the Fraser River. For example, peak flow could be 14–18 days earlier at Mission and 29–35 days earlier in the Harrison River sub-basin. In the Campbell River watershed, projected changes in mean annual streamflow are negligible, but significant seasonal variation is expected. By the mid-21st century, the Campbell River is projected to change from a hybrid regime to a rainfall-dominated regime, with increases in monthly streamflow from October to April and decreases from May to September (Figure 4).

2.4 SEA LEVEL

Ocean-water levels vary on daily to decadal time scales due to a variety of atmospheric and oceanographic effects, including storm surges induced by low atmospheric pressures and climate-variability cycles, such as ENSO and PDO (e.g., Crawford et al., 1999; Barrie and Conway, 2002; Abeysirigunawardena and Walker, 2008, Section 2; Thomson et al., 2008). During an ENSO or PDO cycle, changes in the density of ocean water brought about by water-temperature changes affect the elevation of the sea surface by tens of centimetres, while the magnitude of a storm surge can reach 1 m (Thomson et al., 2008). Large waves generated by strong winds can exacerbate coastal flooding and erosion during a storm-surge event. In the short term (years), it is this variability in sea levels and waves that will cause coastal flooding. The slow rise in mean sea level over decades described below significantly increases the frequency of extreme water events (*see* Chapter 2).

Over a longer time period, changes in relative sea level across the West Coast region show significant variability. During the past 50 years, for example, sea level rose by 3.1 cm at Victoria and 2.0 cm at Vancouver, but declined by 8.4 cm at Tofino (Bornhold and Thomson, 2013). All three communities are within approximately 220 km of one another. A dominant factor affecting relative sea-level change in British Columbia, as with the rest of Canada, is vertical land motion, but other factors also play a role, as discussed in Chapter 2. Vertical land movements in British Columbia arise from a combination of tectonic activity due to the interactions of the Juan de Fuca and Pacific oceanic

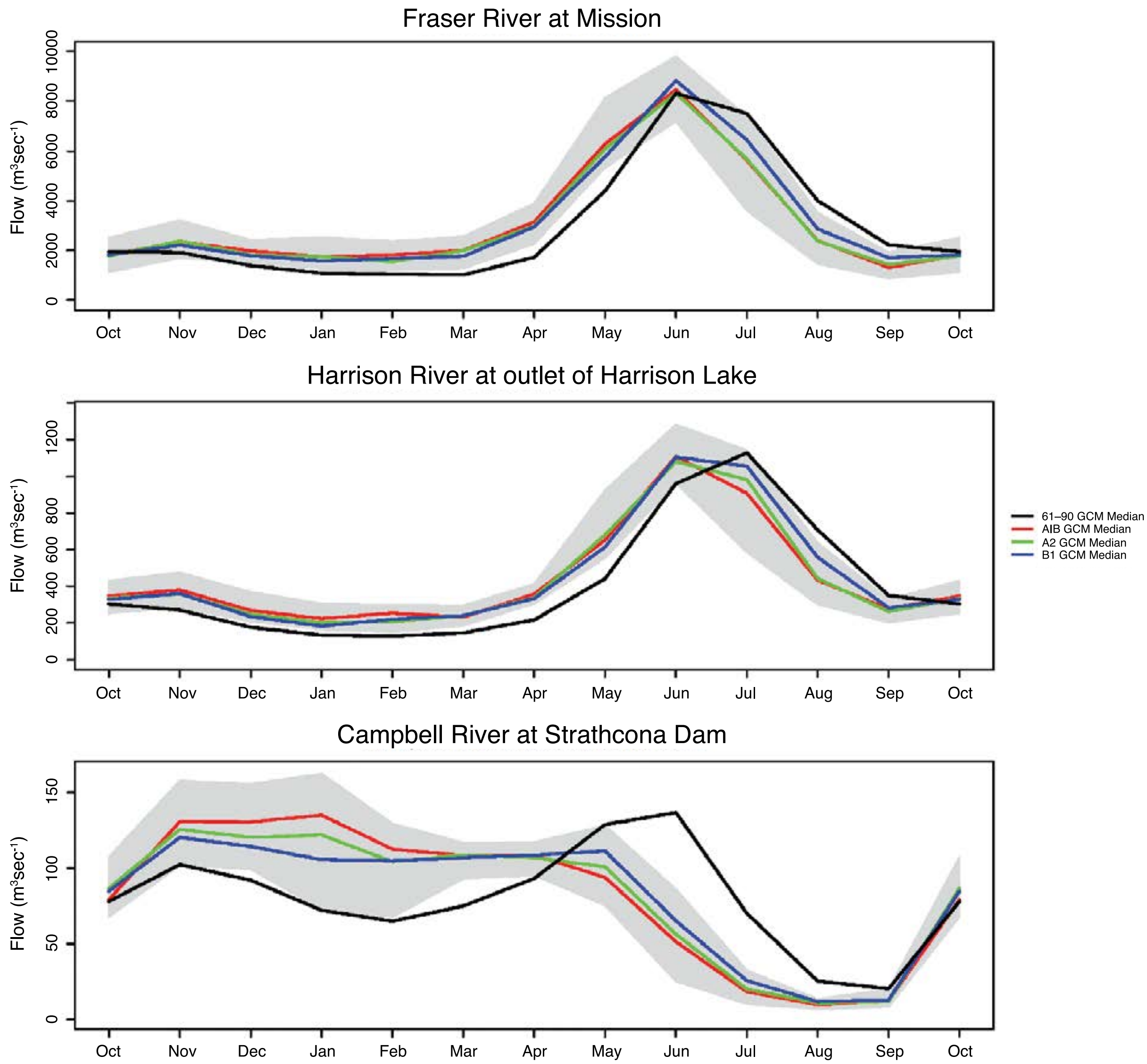

FIGURE 4: Projected change in monthly streamflow for the Fraser River at Mission, the Harrison River at the outlet of Harrison Lake, and the Campbell River at Strathcona Dam. Note that streamflow for the Campbell River represents natural conditions (i.e., absent the effects of flow regulation). Results show median streamflow changes for each scenario (A1B, A2 and B1) and the projection range (grey shading) for 23 individual projections.

plates with the North America plate, the land moving upward in response to the weight removed when the glaciers of the last ice age melted (glacial isostatic adjustment; *see* Chapter 2), and present-day ice-mass changes in the Coast Mountains and the Gulf of Alaska. On the Fraser River delta, sediment compaction contributes to land subsidence (Mazzotti et al., 2009). Global Positioning System (GPS) observations show that the land is rising faster on the west coast of Vancouver Island than at Victoria and Vancouver (Mazzotti et al., 2008), explaining why sea level has been observed to fall at Tofino during the last 50 years but rise at Victoria and Vancouver.

Global mean sea level is expected to rise by 44–74 cm (median values, relative to 1986–2005) by the year 2100 (IPCC, 2013), and larger increases cannot be ruled out (Chapter 2). If the West Antarctic Ice Sheet were to experience accelerated discharge this century due to instability of the marine-based portions, which is a possible but unlikely scenario (IPCC, 2013), global sea level could increase by additional tens of centimetres and surpass one metre.

Projected relative sea-level change in British Columbia coastal waters (Figure 5) exhibits regional variability similar to historical patterns of sea-level change, again primarily due to differences in vertical land motion. Other effects that also contribute to regional variability include the decreased gravitational pull of melting glaciers on nearby ocean waters and changes to ocean currents that affect the topography of the sea surface. Projected median sea-level change at the year 2100 for the high-emissions scenario (RCP8.5) ranges from 50 to 70 cm on southern Vancouver Island, in the region surrounding the City of Vancouver and in northern coastal BC. The remainder of Vancouver Island and the adjacent mainland coast are projected to experience smaller amounts of relative sea-level rise, owing to their larger amounts of land uplift. Despite this regional variability, there is a general trend of projected relative sea-level rise along the West Coast of Canada, although uncertainties are sufficiently large that sea-level fall is possible for some scenarios at communities where land uplift is relatively large.

Sea-level projections through the 21st century are given in Figure 6 for four communities. The relative sea-level projections are smaller at locations with larger amounts of crustal uplift. Also shown are the sea-level allowances developed by the Province of British Columbia to define Flood Construction Levels (Ausenco Sandwell, 2011a, b), based on earlier investigations (Mazzotti et al., 2008; Thomson et al., 2008). The allowance is defined to be 50 cm at 2050 and 100 cm at 2100, and is corrected for local vertical land motion. The BC allowances lie above the projections of the Representative Concentration Pathway (RCP) scenarios but below the highest scenario featuring an augmented sea-level rise contribution from West Antarctica. Thus, they fully account for the range of likely (defined by the IPCC Fifth Assessment Report as 66–100% probability) projected sea-level change and account for a portion of additional, poorly constrained but possible sea-level rise.

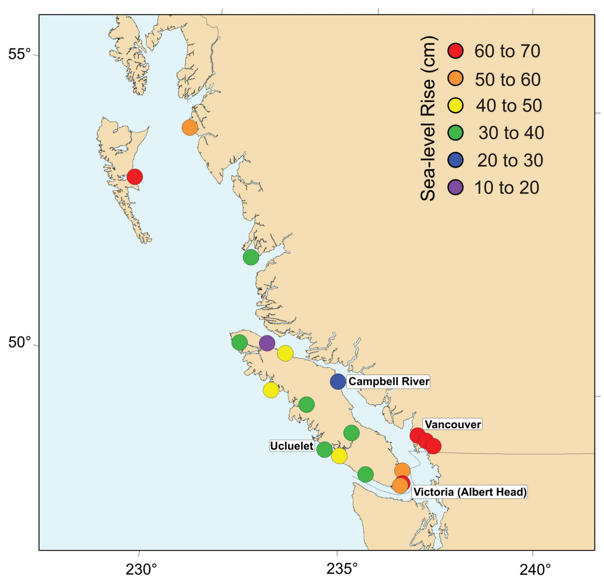

FIGURE 5: Projections of relative sea-level rise for the year 2100 for the median value of the high-emissions scenario (RCP8.5; after James et al., 2014–2015). See Chapter 2 for additional information on sea-level projections. Sea-level projections through the 21st century are given in Figure 6 for the four labelled communities, and projected changes for all sites are presented in Appendix A.

Changes in sea level will present a challenge to many of the roughly 170 coastal communities in British Columbia. For example, approximately 245 000 people in Metro Vancouver live in floodplains at risk from sea-level rise. Important regional and national infrastructure is also at risk. The Port of Metro Vancouver and Vancouver International Airport (YVR), both within several metres of sea level, directly support approximately 71 000 jobs in British Columbia (approximately 221 000 jobs overall) and contribute more than $34 billion in total economic output (Intervistas Consulting Inc., 2009; Vancouver Airport Authority, 2010). Sea-level rise could present challenges to proposed major industrial sites along the north coast, notably in the Kitimat, Prince Rupert and Stewart regions, which are potential energy-export hubs.

Many communities, businesses and local governments, and the Province of British Columbia, recognize the need to better understand and plan for sea-level rise. A more detailed discussion of the risks this presents to coastal communities, and a collection of case studies highlighting adaptation actions already under way, can be found in Section 4 of this chapter.

3 CHANGES TO ECOSYSTEM STRUCTURE AND FUNCTION

Climate change will affect coastal ecosystems in British Columbia. Increased water temperature and changes to ocean acidity, salinity and dissolved oxygen content will together alter ecosystem structure and function. The warm/cool phases of the ENSO and PDO cycles (Section 2) produce short-term changes in water temperatures off the coast of British Columbia and provide a preview of how warmer water may affect coastal ecosystems.

Climate change may have both positive and negative effects on BC's coastal marine biodiversity. For example, an expected increase in upwelling from the California Current (Snyder et al., 2003; Black et al., 2014) could increase the availability of nutrients and lead to higher rates of reproduction for some forms of marine life. However, decreased oxygen and increased acidity (Kleypas et al., 2005; Chan et al., 2008; Ianson, 2008; Widdicombe and Spicer, 2008; Miller et al., 2009) would have negative impacts on other species, particularly shellfish. The most important change may be increased water temperature in both fresh-water (rivers) and marine ecosystems. This could negatively impact salmon by reducing both their reproductive success and the survival chances of salmon fry. Higher water temperatures may also cause a northward shift of the north-south ecological transition zone and, as a result, introduce new species to BC's coastal waters.

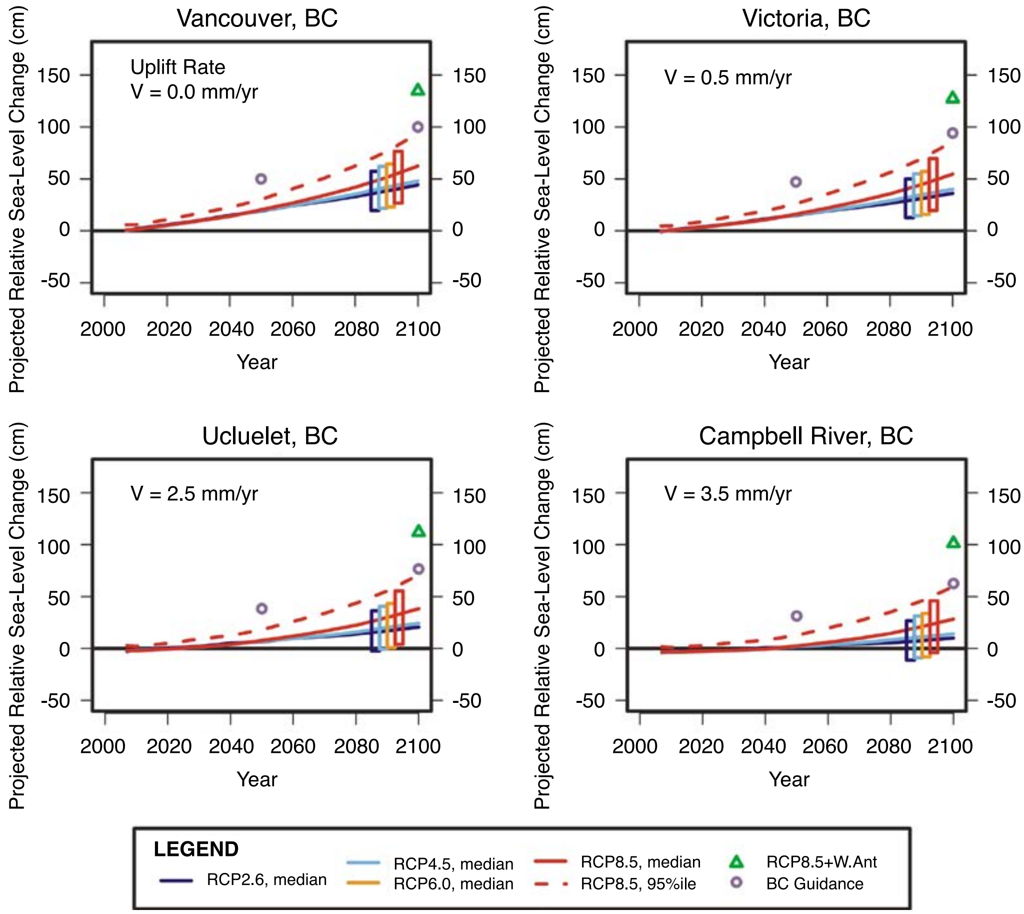

FIGURE 6: Projected relative sea-level change through the 21st century for selected communities in British Columbia (*after* James et al., 2014-2015). RCP2.6 is a low-emissions scenario, RCP6.0 is an intermediate-emissions scenario and RCP8.5 is a high–emissions scenario. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario, an augmented scenario in which West Antarctica 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 dashed red line gives the 95th percentile value for the high-emissions scenario. Vertical land motion is given to the nearest 0.5 mm/year in each panel. The allowance for sea-level rise (BC Guidance) specified by the Government of British Columbia is also given (Ausenco Sandwell, 2011b, c). See Chapter 2 for further explanation of scenarios. Abbreviation: 95%ile, 95th percentile.

3.1 MARINE CONDITIONS: CIRCULATION, ACIDIFICATION AND SALINITY

British Columbia may be particularly vulnerable to ocean acidification, relative to other coastal environments in Canada, over the long term because the north Pacific is already very acidic. If the water were slightly more acidic, it would be termed ‘corrosive’ because calcium carbonate, the building block of shells, would begin to dissolve (Feely et al., 2004). Long-term projections of the risk that increased ocean acidity presents to marine life are not currently possible for the coastal region (Ianson, 2013). This is due, in part, to the fact that processes contributing to ocean acidity can vary region by region and can be hard to predict in expansive areas such as the Strait of Georgia. There are also data limitations related to the highly variable marine circulation (Chavez et al., 2007; Nemcek et al., 2008).

Climate change will influence ocean acidity through changes in temperature, precipitation and streamflow. Climate change can affect nearshore circulation by changing the amount of fresh water that flows into the ocean. As more precipitation falls as rain (rather than as snow) and glaciers and snowpack continue to melt, the fresh-water flow of coastal rivers will increase, particularly in the spring and fall (Section 2.3). Long-term reductions in winter snowpack have already affected the hydrology of the Fraser River (Morrison et al., 2002) by decreasing the volume of water available for release during the summer and, in turn, changing annual patterns of nearshore salinity in the Strait of Georgia. Decreased salinity of surface waters, related to increased regional precipitation (BC Ministry of Environment, 2007; Rodenhuis et al., 2007; Walker and Sydneysmith, 2008) and warming sea-surface temperatures (Freeland et al., 1997; Whitney et al., 2007; Freeland, 2013) result in a decrease in dissolved oxygen.

3.2 FRESH-WATER CONDITIONS: RIVER TEMPERATURE

Water temperatures in the Fraser River have warmed by approximately 1.5°C since the 1950s (Martins et al., 2011) and could increase by an additional 1.9°C by 2100 (Morrison et al., 2002). Such changes to river temperature can negatively impact fish populations, particularly salmon, that are sensitive to river temperature at both ends of their life cycle (spawning salmon do not enter rivers that are too warm, and hatchling mortality is increased by high water temperatures; see Rand et al., 2006; Martins et al., 2011). River temperatures may increase across the province as mean annual air temperature rises and glaciers and snowpack decline. Reduced summer flow in some rivers could also lead to warmer water.

Increased river temperature can have a negative effect on riverine ecosystems and the benefits humans derive from them through its effects on micro-organisms (Farrell and Rose, 1967), amphibians and other poikilotherms (i.e., animals whose body temperatures fluctuate; Fry, 1967), fish (Elliot, 1994; Rand et al., 2006; Martins et al., 2011), insects (Ward, 1992), water quality (Morrill et al., 2005), and businesses and recreation (McMichael and Kaya, 1991). Although river temperature will be affected by climate change, there are many other human-driven factors that can influence this, and research is beginning to further our understanding of these non-climate drivers (Webb et al., 2008).

3.3 MARINE ECOLOGICAL CHANGES

Climate change will impact marine ecology in coastal British Columbia by altering the vertical, shoreward (Brodeur et al., 2006) and latitudinal (Cheung et al., 2011) distribution of species. Although distributional changes will be complex (Schiel et al., 2004), there is a general trend of poleward movement of species in the northeastern Pacific (Brodeur et al., 2003; Zacherl et al., 2003; Brodeur et al., 2005, 2006; Trudel et al., 2006; Wing, 2006; Orsi et al., 2007; Rogers-Bennett, 2007; Harding et al., 2011). An almost 300 km shift in the normal range of 20 species is expected from 2005 to 2055 (Cheung et al., work in progress). This is based on observations of the changing ranges of species both over decades and during warm/cool ENSO cycles (Orsi et al., 2007). For example, species rarely seen in coastal British Columbia were documented during the 1982–1983 El Niño (Fulton, 1985; Okey et al., 2012) and have been periodically observed more recently as well (Brodeur et al., 2006; Trudel et al., 2006; Wing, 2006). This resulted in temporary increases in biodiversity and was a function of climate variation, not climate change. However, as waters warm and the ecological transition zone marking the northerly range of many species not endemic to British Columbia moves northward, such occurrences may become more common.

Changing environmental conditions and proximity to an ecological transition zone may have shaped the development of a biota in the West Coast region that is relatively resilient and responsive to climate and oceanographic change. As climate change promotes an overlap of northern and southern transition zones, the associated increase in an already highly biodiverse region could help build ecological resilience (Okey et al., 2014). However, some species, including Pacific salmon, sardines, anchovies and Pacific hake (e.g., Robinson and Ware, 1999; Ware and Thomson, 2000; Wright et al., 2005), are extremely sensitive to changes in oceanographic conditions and may be negatively impacted. Variations in oceanic conditions may induce dramatic shifts in distribution and abundance of such short-lived species (i.e., 'boom and bust' cycles) but not of longer lived ones. This is because long-lived species that have little reproductive success during periods of environmental stress may survive to produce additional cohorts when conditions improve, whereas short-lived ones cannot.

Climate change is expected to become the dominant influence on marine conditions in the north Pacific during the next several decades (Overland and Wang, 2007). Long-term reorganizations of coastal species may include the separation in space or time of co-evolved species. For example, the timing of Cassin's and Rhinoceros auklet nestlings (a seabird) was historically aligned with the population peak of their prey, the copepod Neocalanus cristatus. As ocean temperature increased throughout the 1990s, the population peak of Neocalanus began to occur earlier in the year (Bertram, 2001). This caused a mismatch between the peak food demand of auklets and the population peak of a critical food source (Hipfner, 2008; Borstad et al., 2011). This example may foreshadow broader productivity-related ecological changes in Canada's Pacific because of the sensitivity of other key food sources and primary producers, such as plankton, to climate variability and change (Mackas et al., 1998; Bertram, 2001; Mackas et al., 2007; Batten and Mackas, 2009).

4 CLIMATE CHANGE EFFECTS ON SECTORS AND COMMUNITIES

Roughly four out of five British Columbians live in coastal cities, towns and villages (BC Stats, 2013a). Millions of people and billions of dollars in goods arrive each year at the airports, ports and ferry terminals that line the province's shores. The ocean is within metres of this critical infrastructure and, as sea level rises, so does the risk of flooding.

The variety of challenges climate change presents to this region's residents and industries is a product of their exposure to hazards (e.g., proximity to the ocean and elevation) and their capacity to adapt to the risks this presents (e.g., knowledge of the hazards and possessing the resources to respond).

There is a variety of potential climate change impacts on coastal communities and businesses, including sea-level rise, changes in storm frequency and intensity, and changing ecosystems. As sea level rises, the height of waves relative to the shoreline will increase due to deeper water and, with it, the destructive potential of higher waves during positive storm surges. New wave dynamics will also affect sediment resuspension and transport rates, and have the potential to reintroduce toxic materials, such as heavy metals, that have accumulated on the sea floor (Eggleton and Thomas, 2004; Kalnejais et al., 2007–2010; Roberts, 2012). Coastal settlements face increasing risk of land loss, infrastructure damage and impacts to the natural-resource and tourism industries (Klein and Nicholls, 1999; Craig-Smith et al., 2006). The general risks presented to different regions of the West Coast are summarized below:

Lower Mainland: The Lower Mainland has the largest population in the West Coast region, with nearly 61% of British Columbians and 75% of coastal residents (BC Stats, 2013b). It is also the fastest growing subregion in the province, with 1.6% annual growth projected for the next two decades (BC Stats, 2013b). Rapid development, urban densification and increased international trade through gateways located in low-lying areas exposed to sea-level rise and storm-surge flooding are a concern in this region. A 1 m rise in sea level could inundate more than 15 000 hectares of agricultural and 4 600 hectares of urban lands in the Lower Mainland (Yin, 2001). The estimated costs of raising the dikes to protect these exposed areas are in the order of $9.5 billion for Metro Vancouver (Delcan, 2012). As discussed in subsequent case studies (Section 4.2.2), Metro Vancouver and its member local governments are actively working to plan for adaptation to sea-level rise. Case studies in Section 4.3 examine two main economic hubs, Port Metro Vancouver and Vancouver International Airport, both of which have demonstrated awareness of the potential consequences of sea-level rise and are working with neighbouring municipalities to identify potential solutions.

Vancouver Island: On Vancouver Island, the Capital Regional District (CRD), comprising 13 local governments (including the provincial capital), is the province's second most populous region. The CRD does not face the same exposure to sea-level rise as Metro Vancouver given its slightly higher elevation and smaller population, but climate change nonetheless remains a concern. Sea-level rise will affect low-lying areas, including Victoria's Inner Harbour (an important source of tourism revenue) and Canadian Forces Base Esquimalt (the home of Canada's Pacific Fleet). Summer water shortages due to drought are the greatest near-term climate change–related concern in the CRD, which receives roughly half the annual precipitation of the Lower Mainland. The CRD is aware that climate change presents challenges and has begun adaptation planning (e.g., Capital Regional District, 2012).

Sea-level rise, storms and storm-surge flooding are a concern throughout Vancouver Island, with the effects of storm surges particularly pronounced where the coast is exposed to long stretches of open water. Potential disruptions to transportation networks, such as ferry services, from storms or damage to wharves is a concern for many of the small communities in this area.

North and Central Coast: Small communities along British Columbia's north and central coast have experienced significant social and economic disruption during the past two decades as a result of such non-climate factors as the decline of the regional fishing and forestry industries (e.g., Matthews, 2003; Young, 2006). Both the timber processing and fishing industries are now centralized and many jobs have moved to the Lower Mainland. For example, employment in the capture fishery is less than 25% of what it was 20 years ago (with estimated employment at 1400 in 2011; Stroomer and Wilson, 2013), and centralization of many of the remaining jobs has left relatively few fishers and fish processors in outlying areas.

In contrast to the decline of primary renewable industries, recent interest in energy development and shipping is promoting growth in some communities on BC's north coast, notably Kitimat and Prince Rupert. In these communities, climate change impacts of concern relate to increased storminess, which can potentially affect coastal export terminals and create hazardous conditions for shipping. Expansion of economic activity along the north coast is perhaps the most significant development since the last climate impacts and adaptation assessment for British Columbia (Walker and Sydneysmith, 2008).

Increased storminess is a concern for communities of the central coast. The one road connection to the region, Highway 20, can be washed out during major storms associated with atmospheric rivers, as demonstrated by the Bella Coola flood of September 2010. Flooding can damage property, infrastructure and habitat, and present a threat to human health and safety. Communities in this region are relatively isolated and access to other communities may be temporarily cut off during storms.

The remainder of this section begins by focusing on climate change implications for fisheries. It outlines how the sector is changing, and reviews potential challenges and strategies for adaptation. This discussion is followed by a review of potential community impacts, supported by a suite of case studies that illustrates the current state of adaptation in the region.

4.1 FISHERIES

> *Fishermen do not fish only from individual boats; it is fair to say that they also fish from communities. This is perhaps what most distinguishes the world of work in rural communities from the types of industrial and factory work found in larger centres… In agriculture and fishing communities, however the separation of work from community and family life makes no sense and is generally impossible… It is impossible to study the nature of work without being involved, ipso facto, in a study of community and family life. (Matthews, 1993)*

Fisheries have been an integral part of the social fabric of coastal communities in British Columbia for generations. Place-based fisheries are not just an economic sector but can also be an important part of social life. Fisheries, particularly salmon, are an important source of identity for both Aboriginal and non-Aboriginal British Columbians. For example, salmon play a particularly important role in First Nations communities by supporting cultural activities and providing food security.

Although the social importance of fish remains high, their economic contribution has been declining since the early 1990s (Box 1). Fisheries support approximately 14 000 jobs in British Columbia, down 30% from the nearly 21 000 jobs available 25 years ago (Stroomer and Wilson, 2013). The economic contribution of fisheries, measured by contribution to GDP (all sectors), decreased by 28.8% during the same period (Figure 7). The capture fishery led this decline, with smaller reductions in the real GDP output of the fish-processing and sport-fishing industries. The commercial-culture sector is the only fishery that has grown during this period.

The economic decline of the fishery sector is particularly severe compared to other goods-processing industries, which have increased by 41% over the past two decades (Figure 8). The BC economy grew by 72% during this time, led by the service-producing sector, which expanded by 85%.

4.1.1 CLIMATE IMPACTS

Changing marine conditions, including temperature, oxygen content and other biogeochemical properties, are currently affecting fisheries in British Columbia (Cheung et al., 2012). These changes are expected to continue and affect many species of fish (Section 3; Cheung et al., 2013). Changes in water temperature appear to have the strongest influence on fish. These well-known and quantifiable changes (Pauly, 2010) have affected species distribution, abundance, metabolism, growth and fecundity (reproductive success). For example, global-catch data from 1970 to 2006 show that commercial catches from Canada's West

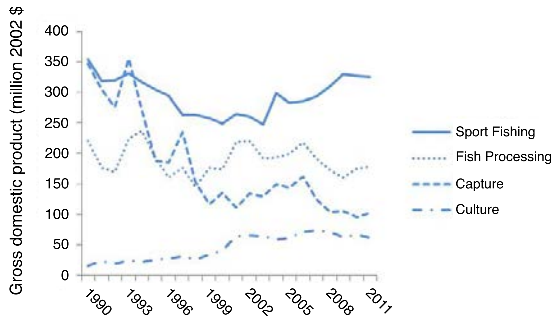

FIGURE 7: Real gross domestic product (GDP) by sector in British Columbia, 1990–2011 (Stroomer and Wilson, 2013).

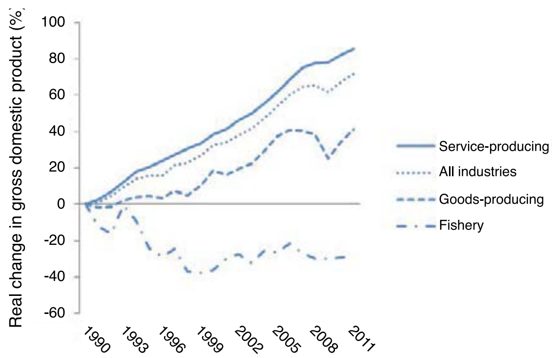

FIGURE 8: Real change in gross domestic product (GDP) by sector (Stroomer and Wilson, 2013).

Coast region were increasingly dominated by warm-water species (Cheung et al., 2013). Such changes, after accounting for fishing effects and large-scale oceanographic variability, are strongly related to ocean warming.

Climate variability has historically played a strong role in Pacific fish stocks (e.g., Finney et al., 2002), primarily associated with natural climate oscillations, such as ENSO and PDO (*see* Chapter 2; Powell and Xu, 2011). However, as the climate shifts during the next century, changing conditions are likely to influence the distribution and abundance of marine species, with significant ecological implications (Beaugrand et al., 2002, 2008; Brierley and Kingsford, 2009; Cheung et al., 2009, 2010, 2013; Blanchard et al., 2012). For example, records show a more rapid decline of eulachon (smelt; *Thaleichthys pacificus*) in southern rivers along the Pacific coast relative to changes in populations encountered in rivers farther north (Moody and Pitcher, 2010), and there are reports of increasing occurrences of previously rare warm-water species, such as the Humboldt squid (*Dosidicus gigas*; Cosgrove, 2005; The Canadian Press, 2009) and increasing biomass of 'California' sardine (*Sardinops sagax*; Ishimura et al., 2012, 2013).

BOX 1

BC FISHERIES SECTOR

The British Columbia fisheries sector generated total revenue of $2.2 billion in 2011, representing a contribution of $667 million to provincial GDP and paying $338 million in wages (Stroomer and Wilson, 2013). Of this, recreational fishing accounted for 60% of employment and nearly half of the GDP generated by the sector (Table 1).

TABLE 1: BC fisheries industry overview, based on 2011 data (Stroomer and Wilson, 2013).

Fishery type	Labour force	Estimated contribution to GDP (million $)	% change in GDP, 1990–2011	Important species
Commercial capture	1 400	102.3	-70.5	Pacific salmon, herring, groundfish (e.g., halibut), shellfish (e.g., clams, crabs)
Commercial culture	1 700	61.9	298.1	Atlantic salmon, shellfish (clams, oysters, mussels)
Recreational	8 400	325.7	-8	Chinook, sockeye and coho salmon, halibut, trout
Seafood processing	2 400	177.5	-19.6	Pacific and Atlantic salmon, herring, groundfish
Total	13 900	667.4	-28.8	–

There is also evidence that salmon stocks are moving poleward in response to increasing ocean and river temperature (e.g., Moody and Pitcher, 2010). In southern British Columbia, a broad regional decline in sockeye populations has been recorded (DFO, 2011b; Irvine and Crawford, 2012, Peterman and Dorner, 2012), and there is reasonable confidence that sockeye production in the Fraser River is, and will continue to be, negatively affected by warming temperatures that impact marine and fresh-water populations at both adult and juvenile stages (MacDonald et al., 2000; Hyatt et al., 2003; Crossin et al., 2008; Hinch and Martins, 2011; McKinnell et al., 2011; Peterman and Dorner, 2011). Changes in water temperature can also affect the upriver migration and survival of salmon during the fresh-water stages of their life cycle (Welch et al., 1998; Cooke et al., 2004; Irvine and Fukuwaka, 2011; Rogers and Schindler, 2011; Selbie et al., 2011).

As glaciers decline, reduced river flow and related changes to water quality and temperature in glacier-fed watersheds may impact coho salmon, whose spawning patterns are linked to riverine discharge (Bryant, 2009). Warmer rivers can also delay sockeye entry into spawning grounds in the autumn and may trigger an earlier migration of riverine juveniles to the ocean, when coastal marine food resources are low (Bryant, 2009). Projections under different river-temperature scenarios have shown the potential for increasingly earlier timing of spawning runs (Reed et al., 2011).

While it is possible that southerly salmon populations may display some adaptation to warmer river temperatures, current evidence (e.g., the fate of California salmon populations; Katz et al., 2013) suggests an overall northward shift of relative population abundance and continued stress on stocks. Throughout the West Coast region, climate change represents a threat to small salmon stocks or those with unique habitat requirements (Bryant, 2009). Northern regions of the province will likely see neutral or positive outcomes for salmon (Peterman and Dorner, 2011), although this may last only a few decades.

4.1.2 IMPACTS ON FISHERY TYPES

COMMERCIAL CULTURE FISHERY

The commercial culture fishery is the fastest growing sector of the four BC fisheries examined here, increasing nearly 300% during the period 1990–2011, with most growth occurring between 1999 and 2007. Salmon represent the largest contribution to GDP in this sector, making up 86.7% of the total, while shellfish make up the remaining 13.3% (Stroomer and Wilson, 2013).[1]

Ocean acidification is a major challenge for economically important, heavily calcified shellfish like abalone (Crim et al., 2011), oysters (Kurihara et al., 2007), mussels (Melzner et al., 2011), clams (Ries et al., 2009) and sea urchins (Reuter et al., 2011). The wholesale value of the BC shellfish fishery (culture and capture) was $224.9 million in 2010 (BC Ministry of Agriculture, 2011). The effects of low-pH water have recently become important in BC aquaculture facilities, where entire

1 Salmon contributed $58.5 million to GDP, while shellfish contributed $9 million in 2011. However, the total contribution to this sector is only $61.9 million due to a loss of $5.9 million from other species.

cohorts of larvae have been lost when upwelling brings corrosive water up to the depth of a facility's intake pipes (R. Saunders, pers. com., 2014). The impact on the industry could run into the millions of dollars per year but is difficult to forecast due a scarcity of monitoring data.

Climate change may also impact the shellfish culture fishery via temperature-influenced zonation changes, forcing farmed organisms into deeper water. The upper limit of some predators, whose habitat is not likely to be affected, represents the limit of this downward vertical migration. As a result, the habitat range of shellfish gets squeezed. Potential impacts include difficulties in securing larvae and seedlings, whose health and productivity will be affected by both increasing acidity and disruption of temperatures (Huppert et al., 2009). Shellfish-culture fisheries may be able to adapt by moving operations farther north to colder waters, to avoid this temperature-predator squeeze.

COMMERCIAL CAPTURE FISHERY

The commercial capture sector has experienced a 70.5% decline in real GDP since 1990. The number of the jobs in the sector has decreased by 78.8% during the same period. Most of the decline in the capture fishery occurred during the 1990s (Figure 7), due in part to the reduction of many salmon subpopulations and a precautionary policy approach. The economic contribution of salmon declined by 82.5% over the period 1990–2011. In 1990, salmon accounted for 55.3% of the total value of the capture fishery in BC. By 2011, this proportion was reduced to 13.4% (Table 2).

Salmon no longer dominate this sector but are now one of several important catch species (Table 2) that also include halibut, geoducks and clams, and prawns and shrimp, demonstrating the adaptability of the sector. Groundfish (which include halibut, sablefish, hake and rockfish) are now the largest part of the BC capture fishery, making up 39% of the total value. The fastest growing species by economic importance is tuna, whose contribution to the sector was negligible 20 years ago but whose landed catch has since increased by nearly 35 times (Table 2).

It is important to note that groundfish catch alone is not likely to return the BC capture fishery to the values seen in the early 1990s. This is due to their longer reproductive lifecycles. For example, it takes halibut 2–3 times longer than salmon to reach sexual maturity (8–12 years). Halibut can also live 10 times as long as salmon, more than 50 years (Forsberg, 2013), and their reproductive potential increases with the size of the fish, meaning that the capture of large fish has a higher impact on replacement.

As the distribution of species along the west coast of North America shifts northward in response to changing climate, new species will become accessible and the availability of current species will change, presenting potential opportunities for fishers in British Columbia. It is also possible that such changes could create issues for the transboundary management of species that migrate between Canadian and United States waters. Collaborative management of emerging, economically important international stocks may become an important consideration for adaptation to changing fish distributions along the west coast of North America (Case Study 2).

TABLE 2: Changing composition of the capture fishery in British Columbia, 1990–2011 (Stroomer and Wilson, 2013). 'Proportion of total value' is the proportion (in %) that each species contributes to the real gross domestic product (GDP) of the wild-capture fishery.

Species	Proportion of total value, 2011 (%)	Proportion of total value, 1990 (%)	Change in real GDP from 1990 (%)
Salmon	13.4	55.3	-82.5
Halibut	13.2	4.4	116.1
Geoducks & clams	12.4	3.4	166.3
Prawns & shrimp	11.9	2.0	327.1
Crab	9.4	2.0	249.5
Tuna	8.3	0.2	3487.5
Sablefish	7.9	4.1	40.2
Rockfish	7.5	3.3	67.7
Other groundfish	5.5	3.9	1.1
Hake	4.8	2.7	28.9
Other (non-groundfish)	4.6	1.7	98.7
Herring	1.1	17.1	-95.3
Total	–	–	-27.6
All groundfish	39.0	18.4	53.3

CASE STUDY 2

TRANSBOUNDARY FISHERIES: THE CASE OF PACIFIC SARDINE

A country's exclusive right to manage and conserve fishery resources within its Exclusive Economic Zone (EEZ) was granted by the 1982 United Nations Convention on the Law of the Sea (UNCLOS). Although such rights legally rest with individual coastal countries, significant challenges can arise when it comes to the conservation and management of transboundary fish stocks (i.e., those whose distribution or migration extends over more than one country's EEZ (United Nations, 1982). In these cases, unilateral attempts to conserve and manage a transboundary fish stock usually lead to dissipation of the economic benefits and increasing risk of resource depletion (Miller et al., 2004; Munro, 2007). Non–co-operation management leads to what has been described as the "tragedy of free for all fishing" (Sumaila, 2013) because it results in inferior economic and ecological outcomes compared to co-operative solutions (Herrick et al., 2006; Bailey et al., 2010). However, there are a number of fisheries in the world where the co-operative conservation and management of a shared stock has been successfully negotiated among a limited number of countries (Clark, 1990; Sumaila, 1999).

The Pacific sardine (*Sardinops sagax*) is a transboundary fish stock that is presently fished exclusively by Canada, the United States and Mexico without a co-operative agreement (Ishimura et al., 2012). The Pacific sardine is a small pelagic schooling fish whose abundance and distribution within the California Current Ecosystem (CCE) are greatly influenced by climate variability (Hill et al., 2006) and are therefore sensitive to climate change. During the 20th century, the northern stock of this fish exhibited extreme fluctuations in its abundance and distribution, which have been attributed largely to climate variability inherent in the CCE (Norton and Mason, 2005; Herrick et al., 2006). By the 1970s, a cold regime shift in the CCE and overfishing resulted in the collapse of the stock, closure of the fishery and an 'endangered' species listing in Canada. In the 1980s, a warm regime shift, combined with conservation measures in California, saw the sardine population rebound to traditional levels and the fishery was reopened in the mid-1980s.

SPORT (RECREATIONAL) FISHERY

Sport fishing is the largest contributor to provincial GDP of all the fishery sectors, and is divided between saltwater (approximately 60%) and fresh-water (approximately 40%) fisheries. The number of tidal (saltwater) anglers has grown from roughly 145 000 in the year 2000 to 166 000 in 2010, while fresh-water angling held steady at approximately 236 000 during the same period (DFO, 2011a). The revenue derived by this sector is largely from the process of fishing, not the fish themselves. Because of this, there is overlap between the GDP contribution allocated to the sport fishery and the tourism industry. Therefore, any discussion about the potential impact of climate change on the sport fishery must extend beyond the availability and distribution of the fish themselves and include the accessibility and cost of sport-fishing opportunities.

Pacific salmon is a major source of income for the sport-fishing industry. Both local anglers and tourists pursue these fish, with the majority of fishing efforts occurring in the southern part of the province. It is possible that there would be a considerable impact on this sector if a northern distributional shift in salmon were to affect salmon numbers along the south coast. This is because of the reduced accessibility of north coast–based fishing charters and a potential reduction in expenditure on salmon-fishing gear in the southern part of the province.

FIRST NATIONS FISHERIES

Empirical data on First Nations fisheries is limited, outside of a small number of community studies (e.g., Weinstein and Morrell, 1994; Jacob et al., 2010), and little of the information is available in the public domain. Data are scarce on the species harvested and catch levels, the distribution and use of these catches, the needs and projected changing needs of communities, and the in-kind contribution of these fisheries to local livelihoods.

There are two principal categories of First Nations fisheries: subsistence (i.e., food or traditional) and commercial. The available data suggest that subsistence fisheries account for approximately 1% of the total marine catches in the Pacific region (Campbell et al., 2014). However, the true value of these fisheries far exceeds that which can be represented by measures such as contribution to GDP and revenue. As in the Arctic, subsistence fisheries serve to strengthen community resilience to environmental changes (e.g., Nuttall, 2001; Smit and Wandel, 2006) and are of great cultural importance, as they strengthen and build familial and social ties (Wenzel, 1991; Weinstein and Morrell, 1994; Berkes and Jolly, 2002; Lee, 2002).

Subsistence catches account for a significant proportion of in-kind income (up to one-third) for First Nations along North America's northwest coast (Vadeboncoeur and Chan, work in progress). The loss of access to traditional/wild foods has been related to both increased costs in healthcare due to dietary changes (typically the adoption of more nutritionally deficient diets) and the social-psychological stress resulting from relocation that can accompany the loss of an important part of livelihood (e.g., Callaway, 1995; Bjerregaard and Young, 1999; McGrath-Hanna et al., 2003; Arctic Climate Impact Assessment Secretariat, 2005).

The BC Assembly of First Nations has identified steps to maintain the viability of First Nations commercial fisheries, which often lack the spatial mobility of commercial fleets. The boats used for this fishery tend to be much smaller than those of large-scale commercial operations, thus limiting their range. Strategies for management of First Nations fisheries include, for example, ecosystem-based management of aquatic resources, habitat conservation and negotiations regarding fish allocation.

Both categories of First Nations fisheries, particularly those in southern BC, may be heavily impacted as distributions of abundance of species such as salmon, herring and eulachon shift northward. Changes to the timing and abundance of salmon runs can also present challenges to First Nations fishers, whose cultural activities and fish-preservation methods can be sensitive to such changes (Jacob et al., 2010). Ongoing negotiations between First Nations and the federal government may help address this problem by gradually shifting some fisheries from non-Aboriginal commercial operations to First Nations control (McRae and Pearse, 2004; BC Assembly of First Nations, 2007). Efforts are underway to understand First Nations vulnerability to climate change, and strategies for adaptation are being explored (Box 2).

4.2 COMMUNITY IMPACTS AND RESPONSES

Sea-level rise presents a long-term threat by increasing the risk of coastal flooding. However, it also increases the potential impact of storm-surge flooding (e.g., damage to nearshore infrastructure) because deeper nearshore water raises the height and energy of waves as they strike coastal structures. The extent of storm-surge flooding is related to wind speed and duration, length of fetch (how long waves can travel uninterrupted before breaking on the shore) and atmospheric pressure (*see* Chapter 2). Therefore, although sea-level rise itself presents risks, it is the combination of extreme high water levels associated with storms that has the greatest destructive potential.

The human and economic costs of extreme weather have been increasing in British Columbia over the past 40 years (Table 3; Public Safety Canada, 2013). This trend is expected to continue as the frequency and/or intensity of extreme weather events, such atmospheric rivers, increases.

4.2.1 THE DEVELOPED COAST

Recent efforts to prepare shorelines for the impacts of climate change have concentrated predominantly on sea-level rise. Other phenomena, such as atmospheric rivers, are associated with hazards such as overland flooding that can damage roads, dikes and private property, but an understanding of the severity and distribution of the associated risks is less developed. Therefore this section focuses primarily on sea-level rise.

BOX 2

CLIMATE CHANGE ADAPTATION IN FIRST NATIONS COASTAL COMMUNITIES IN BRITISH COLUMBIA

Climate change impacts are already affecting Aboriginal communities across Canada. The Climate Change Adaptation Program of Aboriginal Affairs and Northern Development Canada (AANDC) supports development of community-relevant information and tools for Aboriginal communities, governments and organizations to assess vulnerabilities to climate change and to develop adaptation plans. The program focuses on building capacity and addressing impacts related to coastal erosion, sea-level rise, drinking-water quality and quantity, extreme weather events, food security and emergency management.

Participants in the program include some BC First Nations coastal communities. For example, the Hartley Bay Band Council and Semiahmoo First Nation have carried out climate change vulnerability assessments and adaptation planning using a holistic approach that considers changes in both biophysical and socio-cultural environments. The Hartley Bay Band Council (Gitga'at territory, located on the northwest British Columbia coast) identified future changes in marine and terrestrial species as a key factor affecting the availability of traditional food. The Semiahmoo First Nation (southwestern British Colombia coast) assessed infrastructure vulnerability and the community's capacity to face these challenges. The assessment focused specifically on their water supply and distribution system, sewage system, road access and risk of flooding. The Semiahmoo First Nation has proposed specific adaptation actions that can address the key vulnerabilities identified.

TABLE 3: Forty years of extreme meteorological events in British Columbia (Public Safety Canada, 2013). Meteorological events include avalanches, cold events, droughts, floods, geomagnetic storms, heat events, storm surge, storms, severe thunderstorms, tornados, wildfires and winter storms.

Years	Average disaster events*per year	Average threshold events** per year	Normalized total cost per year of threshold events (millions of 2010 $)	Fatalities per year	Persons evacuated per year
1970–1980	1.3	0.6	29.9	2.5	345
1981–1990	1.5	0.5	14.3	4.6	64
1991–2000	2.5	1.1	42.7	1.5	2296
2001–2012	2.3	0.8	54	14	4899

* those recorded as 'meteorological disasters' in British Columbia by the Canadian Disaster Database
** those where damages exceeded $1 million 2010 dollars

There are several approaches to coastal protection for communities to consider and, given the relatively slow onset of sea-level rise, there is an opportunity for adaptation to be integrated into existing long-term infrastructure and community plans. Adaptation options are generally divided into five categories (*see* Chapter 3) that focus predominantly on options to deal with changes in the physical environment:

- protection (e.g., hard protection measures, such as sea dikes or seawalls, and soft protection measures, such as beach nourishment and revegetation of the nearshore)
- accommodation (e.g., elevated buildings, provision of alternative transportation routes)
- avoidance/retreat (e.g., removing high-risk structures and preventing new construction in flood-risk areas)
- no active intervention (e.g., a decision not to act following the review of available information)
- emergency preparedness (e.g., early-warning systems, evacuation preparedness, disaster response)

Hard protection measures are often expensive. However, there is evidence that the cost of adaptation will be less than the cost of inaction. For example, upgrading dikes in Metro Vancouver to protect the community from a 1 m rise in sea level is expected to cost about $9.5 billion (Delcan, 2012) but will protect an estimated $33 billion of assets exposed in the City of Vancouver alone (Hallegatte et al., 2013). In many cases, soft armouring measures may be less expensive than hard armouring, and may deliver similar protective benefits. For example, the City of West Vancouver undertook a pilot project of positioning boulders below the low-tide mark that is having success mitigating wave impacts (Section 4.2.2).

Accommodation responses seek to lower the risk of hazards while there is continued human use of infrastructure, lands and waters. Generally, accommodation allows for occasional, short-term impacts (e.g., impacts from storm events or seasonal flooding), and is an appropriate response when the practicality of protecting coastal assets is outweighed by the cost and/or the effectiveness would be limited to a relatively short period of time. Accommodation responses on the coast can utilize a range of actions, such as protection of local salt marshes or restricted use of designated areas.

Avoid-and-retreat measures include approaches such as designating hazard zones where construction is prohibited, and property buybacks in at-risk areas.

While the decision not to move forward with adaptation (do nothing) can be a valid option (e.g., when there is inadequate information or where the data do not indicate a hazard), it is recommended that such decisions be revisited as new information becomes available.

Each community will have unique needs and the range of appropriate measures must be considered on a case-by-case basis, considering both climatic and non-climatic factors. Proactive planning is important because the costs of adaptation can be reduced when adaptation is integrated with other ongoing operations, such as infrastructure maintenance schedules. For example, it is cheaper to move a sewer line when the pipes reach the end of their serviceable life than to remove or decommission it while it is still working well. Most adaptation plans will involve a number of initiatives from one or more of the categories of options, selected to respond to a range of local vulnerabilities and risks, which will change over time.

The type of coastal-protection infrastructure a community may select can have a marked impact on nearshore ecosystems. Hard-protection measures can cause coastal squeeze (*see* Chapter 3) and alter marine habitats as a result of changes to wave energy and local currents (e.g., Dugan et al., 2008; Dawson et al., 2009; Bulleri and Chapman, 2010). Alternatively, some forms of adaptation can facilitate ecological integrity, including efforts that reduce the use of hard armouring. The protection of existing natural coastal geomorphological features and habitats (Katsanevakis et al., 2011), and the application of principles for ecological conservation, can help reduce the impacts from both storm events and sea-level rise (e.g., Borsje et al., 2011).

Heavy precipitation events, such as those associated with atmospheric rivers, present challenges to adaptation planning in many coastal communities. This is because the structures built to reduce the impacts of coastal floods (e.g., dikes) could affect the functioning of storm-water management infrastructure. For example, dikes could present a problem for gravity-based drainage systems whose outflows have become submerged, allowing water to back up and accumulate on the landward side. The potential for more intense precipitation events may require increased pumping capacity, wider collection pipes and the relocation of storm-water discharge pipes.

A variety of guidance materials for adaptation to sea-level rise is available to local governments (e.g., Plan2Adapt, Climate Action Tool), who also have the authority to regulate exposure to flood risk through bylaws (BC Ministry of Environment, 2004). Alliances between local governments and other organizations, particularly universities and NGOs, have helped municipalities access scientific and technical expertise to better inform their adaptation planning.

Adaptation efforts can yield tangible benefits, such as increased wildlife habitat and enhanced biodiversity. The identification of benefits is important because these can be weighed against both the costs and the concerns of local residents who may have strong emotional attachments to particular features within their communities, as in the case of adaptation planning in Qualicum Beach (Section 4.2.2).

4.2.2 COMMUNITY CASE STUDIES OF ADAPTATION

This section highlights a range of approaches taken by communities across coastal BC (Figure 9) to adapt to climate change. The case studies are listed alphabetically and are followed by a summary of lessons learned.

FIGURE 9: Locations of community case studies.

CASE STUDY 3

CAPITAL REGIONAL DISTRICT: REGIONAL GOVERNMENT PLANNING FOR SEA-LEVEL RISE

(Nikki Elliot, Manager, Climate Action Program, Capital Regional District)

Located on the southern tip of Vancouver Island, the Capital Regional District (CRD) is the regional government for 13 municipalities and 3 electoral areas, including the provincial capital, Victoria. Storm-surge flooding is already a risk in the CRD (Figure 10). The potential for flooding of residential, commercial, institutional and municipal property and infrastructure in the CRD is expected to increase with sea-level rise. To reduce climate-related risks and vulnerabilities, the CRD Climate Action Program is leading a project that will better inform its member municipalities and other stakeholders on the implications of rising sea levels.

The CRD Climate Action Program was established through bylaw in 2008 and serves municipalities by acting as a resource, hub and facilitator on both climate change mitigation and adaptation issues. Working in partnership with public, private and nonprofit sectors, the Climate Action Program supports shifts in policy, planning, infrastructure and behaviour that are required to create a resilient and low-carbon region.

In late 2013, the CRD initiated a Coastal Sea-Level Rise Risk Assessment project as a first step to understanding the implications of sea-level rise within the capital region. The primary task of this project was to identify and map areas that are potentially vulnerable to sea-level rise. Mapping was based on the Province of British Columbia's *Coastal Floodplain Mapping—Guidelines and Specifications Report* (June 2011). Analysis focused on 24 areas that were selected because of the relatively high levels of expected future inundation and/or the location of key community assets. An assessment of the public and private assets in these areas was then undertaken to help local governments understand the potential economic risks of coastal flooding.

This project provided the CRD and its municipalities with:

- mapping showing potential inundation levels in each focus area;
- analysis of the expected depth of inundations;
- the area and percentage of key land uses in the focus areas;
- a summary of the public infrastructure and assets in the focus areas;
- the total value of private and public infrastructure and buildings in the focus areas;

FIGURE 10: December 2010 storm surge in the Capital Regional District. *Photo courtesy of the District of Saanich.*

- a description of the physical characteristics of the coastline in the focus areas; and
- three case studies on the potential disruption costs of sea-level rise (business area, residential area and transportation corridor).

This information provides municipalities with data at a spatial scale fine enough to allow the impacts of climate changes to be easily understood at the local level.

Based on the results of the Coastal Sea-Level Rise Risk Assessment project, the CRD Climate Action Program and their partners are engaged in a project to collect, evaluate and share potential planning, regulatory and structural approaches to address sea-level rise with municipal staff across the region.

CASE STUDY 4

CITY OF COURTENAY: CROSS-SCALE CO-ORDINATION FOR COASTAL-FLOOD MANAGEMENT

(Allan Gornal, Climate Action Analyst; Nancy Hofer, Environmental Planner; and Craig Armstrong, Professional Engineer, City of Courtenay)

The City of Courtenay, like other communities on the east coast of Vancouver Island, is addressing increased flood risk in the face of climate change. Major flooding of the Courtenay and Tsolum rivers in November 2009 and January 2010 disrupted transportation and emergency-response capacity, motivating the city to act (Figure 11).

FIGURE 11: Courtenay River flood, 2010. *Photo courtesy of the City of Courtenay.*

Adaptation planning began following the city's successful application to the BC Flood Protection Program. This funding was used for:

- updating of floodplain mapping;
- development of a hydraulic model to predict flood elevations for various environmental scenarios;
- investigation of flood-mitigation options (both hard and soft approaches);
- overall development of an integrated flood management study; and
- design and construction of flood protection works.

Two climate change impact scenarios were considered. The first assumed a 1 m sea-level rise by 2100, following the Guidelines for Management of Coastal Flood Hazard Land Use (Arlington Group et al., 2013) and a 15% increase in peak river flows by 2100, based on the flood hazard guidelines of the BC Association of Professional Engineers and Geoscientists (Association of Professional Engineers and Geoscientists of British Columbia, 2012). The second scenario considered changes between 2100 and 2200, and included an additional 1 m increase in sea level and an additional 15% increase in peak river flows.

Analysis of these scenarios informed an integrated flood management study (City of Courtenay, 2014), which presented a series of flood-mitigation options. The study included options for both hard armouring (e.g., dikes and floodwalls), improved infrastructure (e.g., overland systems to disperse flood waters and increase retention areas) and accommodations and avoid/retreat approaches, such as rezoning, amendment of flood-control levels to account for the risks presented by rising sea level and limiting development in areas identified as being at risk. Approaches to planning and flood management will likely involve a combination of these options, following consultation with the community.

Ongoing work includes the development of the K'ómoks Estuary Management Plan, which will provide a policy framework for the multiple jurisdictions bordering the estuary (including the K'ómoks First Nation, Comox Valley Regional District, City of Courtenay, Town of Comox, Fisheries and Oceans Canada and other authorities). The objectives of the plan are to establish short- and long-term guidelines for human activities in the estuary; to reduce or prevent negative impacts of human development and/or activities on water quality and aquatic and terrestrial ecosystems; and to restore degraded habitat and protect existing habitat. The plan provides policy guidance for numerous activities within the estuary, including the protection of cultural heritage and water quality; wildlife management; the use of recreation and greenways; and guidelines for urban development, navigation and dredging, log storage and handling, agriculture and aquaculture. The plan is an important component of an integrated flood-management strategy that will highlight the potential effects of land-use change for both the community and local ecosystems, and will facilitate the cross-scale co-ordination needed for the successful management of a floodplain that crosses local-government boundaries.

Elements of the plan that help to address the impacts of climate change include:

- co-ordinated floodplain mapping and management bylaws amongst all local-government jurisdictions that account for potential sea-level changes;
- consistent setbacks in zoning bylaws; and
- consistent Development Permit Area guidelines regarding site and building design relative to setbacks and buffers.

CASE STUDY 5

CORPORATION OF DELTA: DEALING WITH UNCERTAINTY

(Angela Danyluk, Senior Environmental Officer, Corporation of Delta)

Delta is a low-lying coastal community of approximately 100 000 people located on the Fraser River estuary (Figure 12). This ecologically important area forms part of the Pacific Flyway, a conservation area that provides habitat for millions of overwintering songbirds, waterfowl and raptors. It consists of an expansive intertidal zone, comprising wetlands, eelgrass meadows and farmlands, that supports marine invertebrates and coastal salmon populations (Hill et al., 2013); and Burns Bog, a protected area containing a rare raised peat bog of high ecological and cultural significance.

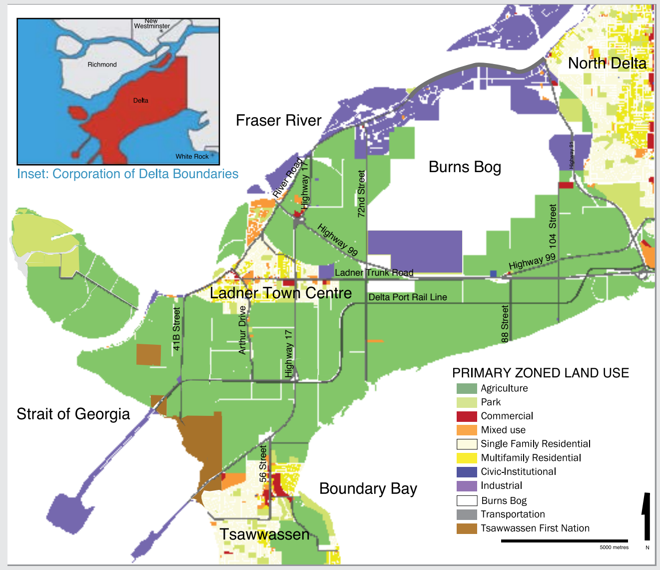

FIGURE 12: Land-use map of the Corporation of Delta created by the Collaborative for Advanced Landscape Planning (CALP) at the University of British Columbia. Image credit for map: G. Canete. Image source for inset map: http://en.wikipedia.org/wiki/File:GVRD_Delta.svg.

The aquatic ecosystems surrounding this community may be somewhat resilient to climate change because important species such as eelgrass will likely shift landward as sea-level rises. Local marshlands and mud flats could be eroded and decrease in area, but new accretion processes may offset these changes (Hill et al., 2013). Overland flooding presents a major hazard to the human community. Roughly 35 000 residents are considered acutely vulnerable to flooding, as are approximately 9 400 hectares of farmland (BC Agriculture and Food, 2013b) and major infrastructure installations, including marine terminals (Roberts Bank coal and container terminals), the rail lines serving these terminals and BC Ferries' busiest terminal, Tsawwassen.

Two major causeways that extend over Roberts Bank, a large undersea bank that provides habitat for salmon during their early life stages, fall within the jurisdiction of the Corporation of Delta. The first causeway supports a rail link to Canada's largest coal export hub—the Westshore Terminal. The second causeway connects to the Tsawwassen Terminal of BC Ferries. The ferry terminal handles roughly 8 million passenger trips per year on routes to Victoria, Nanaimo and the Gulf Islands. These causeways and their associated transportation facilities, along with a network of protective dikes and the nearshore built environment, represent the existing infrastructure in Delta most directly exposed to threats from sea-level rise and storm events. The Tsawwassen Commons, a major commercial and residential development project located between the two causeways on lands owned by the Tsawwassen First Nation, is under construction and will also be at risk. Waves will become more powerful as sea-level rise causes deeper water over Roberts Bank, putting greater stress on coastal infrastructure and ecosystems. Planning for these impacts has been a collaborative process, with local stakeholders involved throughout (Hill et al., 2013).

Following work to identify potential physical hazards of climate change (Hill et al., 2013), the Corporation of Delta partnered with the Collaborative for Advanced Landscape Planning (CALP) at the University of British Columbia to facilitate engagement with the public. Using local climate change projections and current land-use data, CALP mapped anticipated physical changes (Figure 13) and produced visualizations to assist in the identification of adaptation options, based on a range of future scenarios (Figure 14). Because the visualizations used local data, they clearly conveyed the range of social, environmental and economic impacts facing the community and its infrastructure. Sharing results with staff and citizens stimulated discussion about community values, opportunities and solutions in response to the impacts of climate change, thereby increasing awareness and capacity.

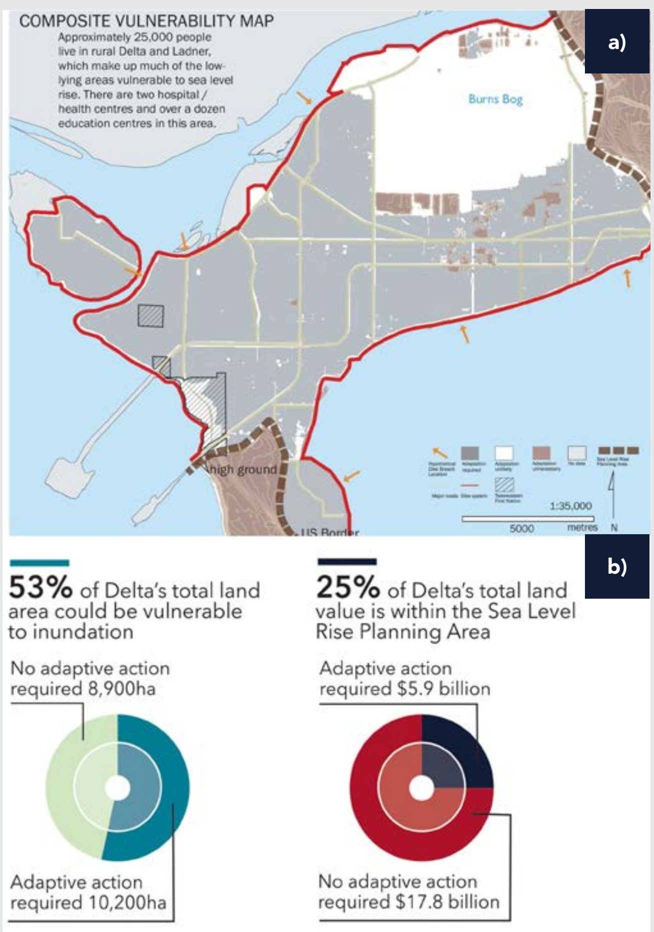

FIGURE 13: Composite vulnerability map in the Corporation of Delta (Barron et al., 2012).

Delta's improved understanding of the potential effects of a changing climate contributed to its selection as one of three agricultural climate change adaptation pilot projects (BC Agriculture and Food, 2013a). In partnership with farmers, the provincial government and the federal government, Delta is now working to implement recommended actions. Corporation staff are also developing an adaptation strategy (through the Building Adaptive & Resilient Communities [BARC] Program of ICLEI Canada) to protect the community from flood hazards, promote agricultural resilience, enhance natural-area and urban-forest resilience, and ensure the health and safety of residents.

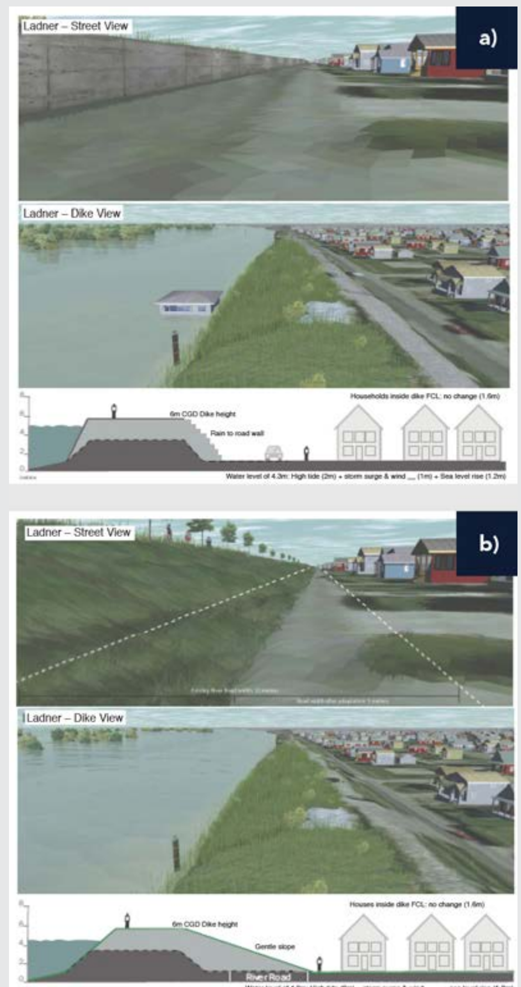

FIGURE 14: Visual models of potential adaptation options. Images are of Ladner (part of the Corporation of Delta) with a larger dike and berm in 2100 with 1.2 m of sea-level rise. The dike has been built up accordingly, and the images show two design options: **a)** a steep concrete-reinforced wall that would maintain the current right-of-way for River Road; and **b)** a conventional design that would take up half of one of the main roads. Source: Corporation of Delta. Created by Collaborative for Advanced Landscape Planning (CALP), University of British Columbia.

CASE STUDY 6

TOWN OF GIBSONS: ADAPTATION PLANNING IN COLLABORATION WITH A UNIVERSITY

(Michael Epp, [former] Director of Planning, Town of Gibsons; [currently] Planner, City of North Vancouver)

Residents and leaders of Gibsons, a town of 4400 people on BC's Sunshine Coast (Figure 15), have a history of proactive action to address environmental issues. However, when the town initiated community conversations about climate change in 2009, it was considered secondary to other concerns, such as municipal finances, infrastructure and development. The impact of recent extreme weather events has since changed this impression. Severe drought in the summer of 2012 threatened water supplies and an unusually high king tide (the highest tides of the year, which occur near both the summer and winter solstices) in December of the same year sparked recognition that sea-level rise is an issue of immediate concern. The town has determined that, over the next several decades, new construction will need to consider future sea levels and that municipal infrastructure must be relocated where appropriate.

In 2011, the Town of Gibsons became a community partner in a University Community Research Alliance project that aimed to advance adaptation planning for climate change in coastal communities. As a result of this partnership, the town now has a model of the potential extent of flooding associated with sea-level rise (Figure 16). Existing land, property and LiDAR data were combined with estimates of sea-level rise by 2100 to provide a model of the potential extent of coastal flooding and the cost of damaged assets. Estimates of the financial impacts of flooding associated with sea-level rise and storm surges start at $20 million.

FIGURE 15: Gibsons harbor from the air. *Photo courtesy of the Town of Gibsons.*

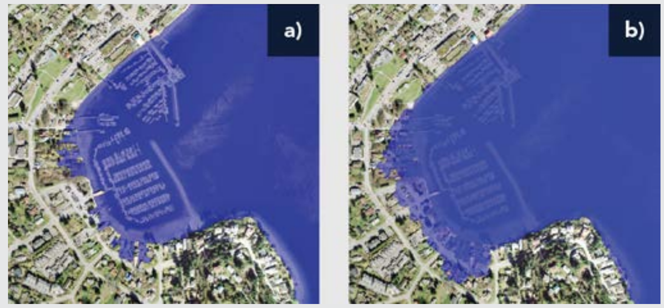

FIGURE 16: Projected future water levels in Gibsons Harbour under conditions of **a)** 1 m of sea-level rise, and **b)** 1 m of sea-level rise (dark blue) and a 1.1 m storm surge (light blue). The town's main sewer line is submerged in both models, whereas three blocks of high-value properties, a gas line and marina facilities are exposed to storm-surge impacts (N. Vadeboncoeur, unpublished data, *base image from* Google, 2015).

As part of their 2013 strategic planning process, the town decided to undertake, over the next several years, a systematic assessment of the shoreline. Data collected will build on the modelling provided by the town's research partners and assist analyses of adaptation options (e.g., where armouring might be required, where slopes are unstable and where natural plantings might assist in reducing risk). A comprehensive review of the Official Community Plan (OCP), which guides future development of the town, is underway, and has provided an opportunity for a broader integration of specific climate adaptation policies into community planning. This allows adaptation measures to be considered along with life-cycle and cost-benefit analyses of infrastructure that form part of the OCP review.

CASE STUDY 7

QUALICUM BEACH: A LAND-USE APPROACH TO ADAPTATION

(Luke Sales, Director of Planning, Town of Qualicum Beach)

The waterfront plays an important role in the economy and social identity of the Town of Qualicum Beach, located on the eastern shore of Vancouver Island. Maintaining the character of the town waterfront is a top priority. Historically, the town has taken a reactive approach to foreshore management of storm impacts, including ecosystem degradation, beach loss, waterfront flooding and damage to the sea wall (Figure 17). However, Qualicum Beach is now in the planning phase of a comprehensive Waterfront Master Plan that will include planning for adaptation to sea-level rise. The work will be undertaken in two phases,

FIGURE 17: Qualicum Beach waterfront walkway during a strong winter storm in 2009. *Photo courtesy of S. Tanner.*

the first aimed at understanding the technical and scientific dimensions of change, and the second focused on planning to manage the change.

The first phase, completed in late 2014, involved an assessment of local meteorological, oceanographic and geomorphological conditions, and the dynamic processes that control the nature of the town's waterfront. This analysis highlighted the specific impacts that waves, storms and sediment-transport rates have on the shoreline, and that different areas of the waterfront behave differently. For example, there are some areas where sediment travels aggressively, eroding quickly in places and accumulating in others. In contrast, the central waterfront (where parks and many services are concentrated) has very little erosion. The results of the first analysis will inform the second phase of the project, which will help refine planning approaches to provide for a sustainable waterfront that is resilient to climate change impacts. For example, the town is now considering 'soft' approaches, such as gradually building up their central waterfront over time as a potential adaptation measure.

The second phase of the project will focus on public consultation and a detailed examination of opportunities for shoreline restoration, land use, ecological protection, tourism, pedestrian and cycling infrastructure, parking, design standards, public access and other community priorities. Cross-disciplinary approaches to coastal planning will draw upon experts in the fields of geomorphology, urban design and coastal biology to develop a comprehensive plan for community sustainability.

The project goals include:

- improving the town residents' understanding of local foreshore ecology and natural processes;
- identifying strategies for managing a changing foreshore interface and minimizing cumulative impacts on the coastal environment;
- developing a comprehensive waterfront master plan that identifies strategies and actions required to adapt to sea-level rise while maintaining amenities; and
- developing guidelines for shoreline works that can be followed by private property owners as part of an integrated approach to shoreline management.

While the project presents an opportunity for the community to improve the waterfront for future generations, the process will likely be emotional and some community members perceive it as threatening to the owners of waterfront homes and businesses. During the second phase, the town will initiate a dialogue about these concerns and evaluate feedback on the range of options from the community.

CASE STUDY 8

CITY OF VANCOUVER: PREPARING A HIGH-DENSITY CITY FOR SEA-LEVEL RISE

(Tamsin Mills, (former) Senior Sustainability Planner, City of Vancouver)

The City of Vancouver has, for more than 20 years, been committed to addressing climate change (City of Vancouver, 1990). Vancouver faces considerable risks from climate change, and was recently identified as the 11th city most at risk to sea-level rise in the world, based on the total value of exposed assets (Hallegatte et al., 2013). With many high-density areas and other uses adjacent to the ocean (Figure 18), options to respond to the effects of climate change are limited. Adaptation measures are likely to involve a combination of protection measures coupled with urban-planning instruments, based on a sophisticated

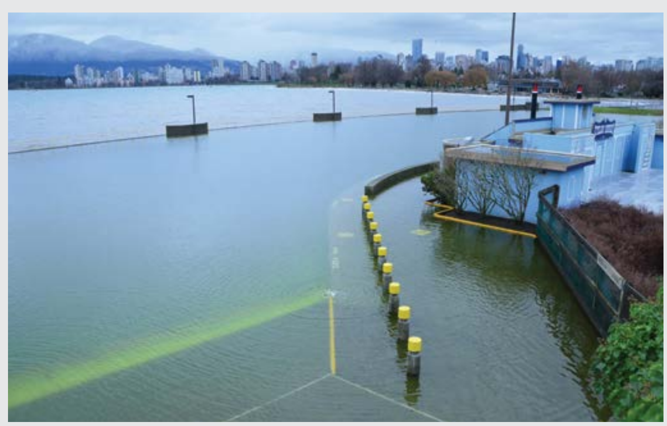

FIGURE 18: King tide of December 17, 2012 with little accompanying wave action caused localized inundation in the City of Vancouver, including flooding of the Kitsilano Pool. *Photo courtesy of the City of Vancouver.*

understanding of the spatial distribution of potential floods.

In 2007, largely in response to findings of the IPCC Fourth Assessment Report, Vancouver City Council passed a motion to initiate an adaptation-planning process. First steps included a risk analysis to identify priority areas for adaptation, leading to a more comprehensive climate action plan that was adopted unanimously by Council in July 2012. The primary actions identified in the action plan are now being addressed and the city is, at the time of writing, acquiring the data required for implementation of the plan. For example, LiDAR imagery was collected in early 2013 to assist with mapping of the vegetation canopy and coastal flooding. The coastal-flooding maps have since been integrated into a model showing the area, depth and flow rate of overland flooding.

In 2013, Vancouver became the first city in British Columbia to adopt formal consideration of 1 m of sea-level rise in development and planning requirements. The city is currently weighing a number of other development-planning options. Because of its location in the centre of coastal Metro Vancouver, adaptation in Vancouver is a particularly collaborative process. For example, the city is working with the Port of Metro Vancouver, the Fraser Basin Council (a nongovernment organization) and the neighbouring City of Burnaby to develop a strategy for managing sea-level rise in shared floodplains that would include improved coastal armouring.

CASE STUDY 9

CITY OF WEST VANCOUVER: AN EXAMPLE OF ACCOMMODATION OF WAVE IMPACTS

(David Youngson, Director of Planning, City of West Vancouver)

The growth of West Vancouver, a community of more than 43 000 people, has resulted in urbanization of the watershed and waterfront, producing a hardening of the shoreline and channelization of watercourses. The resulting disruption to sedimentation processes has increased sediment transport and reduced rates of deposition. For example, it is not uncommon for hundreds of cubic metres of sediment to be eroded from local shorelines during a single rain event. Such erosion results in deeper nearshore waters, exposing West Vancouver's infrastructure, near-shore habitat and beaches to increased wave energy (Figure 19). The city is working to achieve a stable shoreline that takes into account projected sea-level rise, protects uplands and promotes marine life.

In 2005, the West Vancouver Engineering Advisory Committee developed a Long-Term Shoreline Planning Framework. Later that year, the West Vancouver Shoreline Preservation Society was created. These organizations together acted as a catalyst for channelling more than

FIGURE 19: Wave damage to the West Vancouver seawall during a storm. *Photo courtesy of the West Vancouver Shoreline Preservation Society.*

30 years of research on the shoreline into a process for restoring the district's beaches. The result, the 2012 Shoreline Protection Plan (SPP), is a living document designed to respond to the ecological and social needs for the shoreline, to direct available resources and to take advantage of opportunities for the greatest benefit of the foreshore.

The first SPP action was the creation of nine municipally funded, shoreline-protection pilot projects, located between the Capilano Groyne and Navvy Jack Point. These projects varied in scale, cost and focus, but shared the key goal of improving shoreline protection. Each project involved an array of coastal-engineering and habitat-enhancement strategies to restore sites to a more natural state and to provide self-sustaining, soft-armouring measures for the shoreline. For example, a pilot project involving the addition of subtidal boulders (located just below the low-tide mark) has reduced erosion and sediment transport while improving habitat (Figure 20).

Benefits of the work undertaken to date include:

- naturalization of the shoreline through removal of more than 200 m of concrete sea walls;
- increased biodiversity of riparian, intertidal and subtidal zones;
- improved creek access for salmon;
- re-establishment of functioning surf smelt habitat;

FIGURE 20: Submerged boulders provide habitat for plants and echinoderms while enhancing spawning grounds for smelt. *Photo courtesy of the West Vancouver Shoreline Preservation Society.*

- increased public access through the installation of bridges and nearshore pathways; and
- improved shoreline stability and high beach habitat through the accumulation of large woody debris and organic material.

Five privately sponsored initiatives have subsequently built upon the pilot projects and demonstrate the potential for sustainable management of the entire 30 km of West Vancouver's privately and publicly owned waterfront. The private initiatives have resulted in more than $3 million of shoreline restoration work being undertaken between Dundarave and Horseshoe Bay. This has helped to retain sediment (decreasing water depth and wave power) and to reduce the impact of waves on the shoreline.

4.2.3 LESSONS LEARNED

A common theme among these case studies is that collaborative efforts with other organizations or with private partners enabled local governments to move forward on adaptation planning and implementation. In all cases, external partners helped support adaptation and, in the case of the Capital Region District, they also helped support member local governments in planning for change. In several studies, data highlighting the timeline for projected impacts have allowed adaptation to be considered along with existing cost-benefit analyses, such as for infrastructure maintenance schedules, and permitted adaptation to be 'mainstreamed' into existing policy processes, such as official community plans.

The adaptation measures adopted by each municipality varied based on its specific needs and the projected effects of climate change on their communities. As demonstrated in the West Vancouver Case Study, municipalities need not rely solely on dikes for coastal protection. Sub–sea-surface structures located within tidal areas can help mitigate erosion by reducing wave energy reaching the shore and by enriching habitat. In some cases, coastal protection on its own may be insufficient for addressing storm impacts accentuated by sea-level rise and, as in the case of Vancouver, changes to urban planning and development regulations, such as elevated Flood Construction Levels, may be needed.

Adaptation measures intended to build community resilience to climate change can have positive effects on local assets and local society, as well as on local ecosystems. Adaptation can assist with maintaining beaches, protecting existing habitat and creating new habitat. However, implementation of some adaptation measures, such as restrictive zoning and coastal setbacks, can present challenges for both communities and individuals. Because the effects of coastal adaptation to climate change can be far-reaching, public consultation is an important part of adaptation planning and ensuring that changes are implemented in a timely, controlled manner that is respectful of the needs of stakeholders. When adaptation measures are applied in response to local disasters (e.g., a major storm event), the often sudden alterations to local land use can be difficult for affected members of a community to accept.

Communities along the coast have access to a variety of sources of information on the effects of climate change on coastal areas, and a range of potential partners with whom they can work to develop effective adaptation responses (Box 3). To date, responses are aimed overwhelmingly at reducing the increased risk of coastal flooding due to sea-level rise and storm surges. As municipal awareness of the need for climate adaptation continues to build, partnerships between local governments and external partners can assist in identifying and managing other climate risks to coastal communities.

4.3 TRANSPORTATION INFRASTRUCTURE

As Canada's 'Gateway to the Pacific', British Columbia features several facilities of national importance, such as Vancouver International Airport (YVR) and major marine transshipment ports (e.g., Port Metro Vancouver, Kitimat Port and Prince Rupert Port). Coastal areas are also home to regionally important economic and social links, including ferry services to small communities, a major road link to small communities along the north coast (Highway 16) and an array of smaller land- and water-based airports. This section reviews potential risks this infrastructure may face as a result of climate change.

BOX 3

ADDITIONAL RESOURCES FOR COMMUNITIES

Adapting to Climate Change: An Introduction for Canadian Municipalities:
https://www.nrcan.gc.ca/environment/resources/publications/impacts-adaptation/reports/municipalities/10079

Agricultural Adaptation in Delta:
http://www.delta.ca/environment-sustainability/climate-action/adapting-to-change

BC Agriculture and Food Climate Action Initiative:
http://www.bcagclimateaction.ca/

BC Real Estate Association (BCREA) Flood Protection:
www.bcrea.bc.ca/government-relations/flood-protection

BC Sea-level Rise Adaptation Primer:
http://www.civicinfo.bc.ca/Library/Reports_and_Briefs/Sea_Level_Rise_Adaptation--Climate%20Action%20Secretariat%20--2013.pdf

Collaborative for Advanced Landscape Planning (CALP):
http://calp.forestry.ubc.ca/

ICLEI Canada Adaptation Framework:
http://www.icleicanada.org/programs/adaptation/barc

Joint Program Committee for Integrated Flood Hazard Management:
www.fraserbasin.bc.ca/water_flood_projects.html

Pacific Institute for Climate Solutions (PICS):
http://pics.uvic.ca/

Pacific Climate Impacts Consortium Plan2Adapt Tool:
http://www.pacificclimate.org/analysis-tools/plan2adapt

Stewardship Centre of BC Green Shores Program (Sea-level Rise Accommodation):
www.stewardshipcentrebc.ca/greenshores

4.3.1 AIRPORTS

Of the 78 airports in British Columbia that have International Aviation Transportation Association codes, five are exposed to increasing risk of flooding as a result of sea-level rise and storm surges because of their low elevations (<5 m above sea level). These are Vancouver International Airport, three regional airports (Boundary Bay, Pitt Meadows and Masset) and one recreational airstrip (Courtenay). Vancouver International plays a major role in the regional economy (Case Study 10), while the other airports contribute substantially to their local economies. Throughout British Columbia, water-based airports provide an important link for many rural coastal communities and complement other transportation modes in major cities such as Vancouver and Victoria.

CASE STUDY 10

VANCOUVER AIRPORT AUTHORITY

Vancouver International Airport is the largest air transportation hub on Canada's West Coast and the second busiest airport in Canada, moving approximately 17 million passengers each year through nearly 300 000 aircraft movements. Airport operations support approximately 24 000 jobs in Metro Vancouver, generate $5.3 billion in total gross domestic product and contribute $11.7 billion in total economic output. The airport itself is located on Sea Island, which is on the western boundary of Metro Vancouver between the cities of Vancouver and Richmond. Elevations of parts of the airport are near current sea level and part of the Fraser River floodplain (Figure 21). As a result, the airport is exposed to hazards associated with sea-level rise, storm surge and heavy-precipitation events. Most of the built environment, such as taxiways, runways, roads and buildings, is located above current flood levels, but much of the undeveloped land, such as the grass infields between taxiways and runways, is low lying and subject to flooding during major rainstorm events.

The Vancouver Airport Authority manages flood-control dikes on Sea Island and is working to gradually increase the height of these dikes. Both the Authority and the City of Richmond have authority over sections of the Sea Island dike system and, through a strong working relationship, keep one another abreast of their dike maintenance plans so that the flood risk for Sea Island can be collaboratively managed. There is an existing program to increase the height of the original dikes (constructed 1930–1940), now under the control of the Airport Authority, to a crest elevation of 4 m to better handle future ocean conditions. The Airport Authority recognizes that a 4 m dike elevation will provide insufficient protection for the year 2100 and is undertaking a systematic retrofitting initiative to both help spread costs over time and be able to respond to changing sea-level projections. Based on current sea-level rise projections to the year 2100, the potential flood level for the Vancouver Airport is 4.9 m and the estimated required

FIGURE 21: Vancouver International Airport from the air. *Photo courtesy of the Vancouver Airport Authority.*

crest level is 7.9 m (Delcan, 2012), indicating that major upgrades to the Sea Island dike system will be needed. It is also noted that, while it will be relatively easy to make these changes for much of the Sea Island dike system, there are some locations where current land-use will make dike upgrades difficult.

In addition to maintaining a dike network, the Airport Authority also maintains a storm-water management system that drains accumulated water into the Fraser River by gravity at low tide, with pumps available to assist with drainage during the remainder of the tidal cycle. As sea level rises, the potential for gravity drainage will decrease, necessitating additional costs for pumping infrastructure and maintenance.

4.3.2 PORTS AND NEAR-PORT INFRASTRUCTURE

British Columbia supports major goods-shipping terminals and is home to a growing energy-export industry. Its approximately 135 public and private ports provide a strategically important trade link to the international market, facilitating roughly 95% of international trade in the province. The port system has helped to diversify BC's and Canada's export markets in response to global economic changes. For example, the proportion of BC's exports going to the United States declined from approximately 70% in 2001 to 44% in 2012 (BC Stats, 2013c).

Current major infrastructure installations include, for example, the Trans-Mountain Pipeline, Westridge Marine and Burnaby terminals, and the coal-export terminals on Roberts Bank (Port Metro Vancouver) and at Prince Rupert (Ridley Terminals). Several liquefied natural gas export terminals are under consideration for the Prince Rupert and Kitimat areas. Currently, existing and planned energy-related infrastructure along the BC coast is valued in excess of $100 billion.

The two main ports are the Port of Metro Vancouver and the Port of Kitimat. Each faces challenges as a result of climate change. Although sea-level rise alone is unlikely to present a direct challenge to infrastructure in British Columbia's two major ports by the year 2100, associated impacts, such as changing sediment-transport rates around port infrastructure, could factor into operational planning (e.g., Hill et al., 2013). The Port of Metro Vancouver (Case Study 11) is already working with bordering communities to identify vulnerabilities and plan for adaptation (e.g., a review of dike vulnerability along the border of the City of Vancouver). However, the many jurisdictions with which the port must interact (e.g., 17 sea-dike authorities responsible for maintenance and upgrading of protective works) complicate the potential for, and timing of, adaptation.

CASE STUDY 11
PORT OF METRO VANCOUVER

The Port of Metro Vancouver is a central part of the BC economy and delivers considerable additional benefits at the national scale (Tables 4 and 5). It links more than 160 countries through its 28 major marine terminals, moving 130 million tonnes of cargo each year. It is the busiest port in Canada, fourth busiest in North America and the most diversified on the continent, with services accommodating a range of needs from bulk and breakbulk[2] to cruise ships. The port lands include more than 600 km of ocean and river shoreline that borders with 16 municipalities and one treaty First Nation, and intersects with a further seven traditional territories.

The Port of Metro Vancouver considers sea-level rise on a project-by-project basis and is satisfied, based on current sea-level rise estimates, that its terminals are sufficiently elevated to avoid inundation. However, there has been no comprehensive characterization to date of the exposure of port facilities to sea-level rise. Land-based port infrastructure may be vulnerable if dikes of the municipalities bordering port facilities are not updated to an adequate standard. While there has been significant progress on adaptation in the City of Vancouver and Corporation of Delta (Section 4.2.2), a comprehensive assessment of risk is not possible until all 17 neighbouring dike authorities have released more detailed plans for adaptation. This is because of both the need for a co-ordinated flood-protection strategy and the effect that hard-armouring flood-prevention measures can have on sediment-transportation processes.

2 Breakbulk cargo is commodity cargo that must be loaded individually into a ship's cargo hold. The goods can be packaged in bags, cases, crates, drums of barrels, or kept together by baling and placed onto pallets. Typical breakbulk commodities include paper, lumber, steel and machinery (Port Metro Vancouver, 2013).

TABLE 4: Economic benefits of Port Metro Vancouver (Intervistas Consulting Inc., 2009).

Jurisdiction	Contribution to GDP (billion $, estimated)	Total economic output (billion $, estimated)	Total wages (billion $, estimated)	Number of jobs
British Columbia (direct impact)	4.1	9.8	2.2	47 700
British Columbia (indirect and induced effects)	3.8	7.3	2.6	58 400
Canada (excluding BC)	2.6	4.9	1.3	23 400
Canada (total)	10.5	22	6.1	129 500

TABLE 5: Tax revenue from Port Metro Vancouver (Intervistas Consulting Inc., 2009).

Jurisdiction	Annual tax revenue (million $, estimated)
Federal	648
Provincial	417
Municipal	157
Total	1 222

Climate change may have an impact on operations at other smaller ports throughout the province. Increased frequency or magnitude of storms (*see* Chapter 2) could impact shipping, but there is insufficient information to draw conclusions about the individual or collective vulnerability of small ports to climate change.

4.3.3 HIGHWAYS

Although most coastal highways in British Columbia are located at elevations above projected increases in sea level and storm-surge flooding, available elevation and LiDAR data suggest that some sections of provincial highways could be vulnerable (Figure 22; BC Ministry of Transportation and Infrastructure and Nodelcorp Consulting Inc., 2011). The impacts of storm waves could present major challenges for some road sections, but assessing these vulnerabilities will require site-specific assessments. Flooding of highways by storm surges and storm waves can result in a sudden and temporary loss of what is often the only high-volume, rapid connection between coastal communities (Case Study 12). Some highways located near sea level have been protected by a series of dikes (e.g., in the Corporation of Delta; Section 4.2.2).

FIGURE 22: Areas of provincial coastal highways identified as being at risk from sea-level rise (*modified* from D. Nyland).

CASE STUDY 12

SUNSHINE COAST HIGHWAY IN DAVIS BAY

A section of the Sunshine Coast Highway in Davis Bay currently experiences periodic closures due to storm-surge flooding (Figure 23; Vadeboncoeur, 2014). For residents west of Davis Bay (approximately 20 000 people), closure of this highway blocks access to the Langdale Ferry Terminal, the only vehicle access point to Vancouver. For residents to the east (approximately 10 000 people) access to the regional hospital is blocked.

FIGURE 23: Storm surge on the Sunshine Coast Highway (Highway 101) at Davis Bay, February 6, 2006. *Photo courtesy of B. Oakford.*

Sea-level rise will amplify the impact of storms and could result in substantial erosion and structural damage to both the road and the power and gas lines that follow it. A 1 m storm surge that occurs in association with a 1 m rise in sea level would raise water levels nearly 1 m above the existing roadway, resulting in significant flooding in the surrounding area (Figure 24). To respond to this increasing risk of flooding, the Sunshine Coast Regional District, in collaboration with the province, is considering the eventual relocation of this stretch of highway through a new connection to a renovated existing road located at a higher elevation.

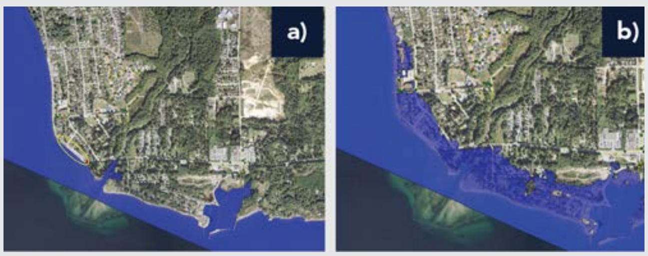

FIGURE 24: Sea-surface height (in purple) during the February 2006 storm surge on the Sunshine Coast Highway (Highway 101) at Davis Bay **a)** and during a 1 m storm surge with a 1 m of sea-level rise **b)**. (N. Vadeboncoeur, unpublished data, *base image from* Google, 2015).

4.3.4 BC FERRIES

Passenger ferry services operated by BC Ferries transport more than 20 million people each year to 49 terminals on 40 routes. Many ferry terminals are located in sheltered bays, while some have moderate exposure to wind and waves. However, the major terminal at Tsawwassen, which connects the lower mainland with southern Vancouver Island and the Gulf Islands (i.e., Victoria, Nanaimo), is situated in a location highly exposed to the Strait of Georgia.

Sea-level rise and increased exposure to storms present challenges to terminal infrastructure, including docks and access roads. Weather-related sailing delays and cancellations are relatively uncommon in British Columbia, affecting roughly 0.5% of all trips (BC Ferries, 2013). Although climate change increases the risk of such delays, it is unlikely that this will have a noticeable impact on the average British Columbian because weather accounts for only 6% of all delays or cancellations (BC Ferries, 2013). Increased storminess may present a challenge for remote communities that depend on ferry service for food and supplies if relatively infrequent (e.g., weekly) service is interrupted.

5 ADAPTATION PLANNING

Reactive approaches have traditionally dominated responses to changing environmental conditions in British Columbia (Walker and Sydneysmith, 2008). This is beginning to change. Several local governments have begun planning for the proactive management of sea-level rise (Section 4.2.2). Although adaptation is a shared responsibility between all orders of government, industry, nongovernment organizations and civil society (e.g., Bizikova et al., 2008), local governments have a particularly strong role to play with respect to adapting to sea-level rise along Canada's Pacific coast. Legislation enacted in 2004 placed the construction and maintenance of sea dikes and the designation of flood plains under municipal jurisdiction. As a result, there are now nearly 100 dike authorities in British Columbia, and each municipality is largely responsible for their own adaptation to ocean hazards.

Updating risk-management policies of local governments in British Columbia is one step that could help enhance climate resilience (Swanson and Bhadwal, 2009). However, as has been observed across Canada, this approach can be limited by the capacity of local governments to initiate adaptive actions and by their ability to actually implement proposed actions to enhance resilience (e.g., Burch, 2010).

Considerable work to advance adaptation in British Columbia has provided municipal decision makers with information resources on the potential impacts of a changing climate (e.g., Burch and Robinson, 2007; Harford, 2008; Burch et al., 2010; Ausenco Sandwell, 2011b, c; Delcan, 2012; Forseth, 2012; Arlington Group et al., 2013; Hill et al., 2013). However, municipal climate change adaptation is still relatively new, and several complicating issues that have commonly been raised by local governments have yet to be addressed completely. These include the need for cross-scale institutional collaboration on adaptation (i.e., the province, local governments and First Nations), the availability of information on local impacts, and the legal implications of taking action. The following sections summarize these concerns.

5.1 EVOLVING POLICIES ON COASTAL FLOODING AND SEA-LEVEL RISE

Existing flood policies in British Columbia were designed primarily to deal with flooding associated with spring snowmelt in rivers and ocean-storm surges. These policies assume that the timing and magnitude of riverine flooding, and the height of future storm-surge flooding, would remain in line with the historical record. However, these assumptions of climate stability are no longer appropriate and policies are therefore under review. The nature of future changes in both riverine and coastal flooding will vary, sometimes significantly, across coastal British Columbia. For example, in rainfall-dominated regimes, streamflows are expected to decrease on the south coast but increase in the north (Section 2.3). Storm-surge flooding will also increase in magnitude as a result of sea-level rise, with recent analyses calculating the elevation change needed to maintain the present frequency of flooding (Zhai et al., 2014). Sea-level rise leads to larger, more powerful waves reaching shorelines, potentially overtopping dikes and increasing erosion (as in the case of the Corporation of Delta; Shaw et al., 2006).

Local governments in British Columbia have autonomy over land-use planning within their jurisdictions, including the ability to manage land use and approve development in flood-prone areas, designate floodplains and set building requirements (Table 6). The *Local Government Act* grants this authority and allows local governments to use a variety of policy tools, such as Official Community Plans, bylaws, development permits, building permits and zoning restrictions, to plan for adaptation (e.g., Richardson and Otero, 2012). Potential actions for integrated flood-hazard management in British Columbia (Table 6) are outlined below.

5.1.1 LAND USE

Local governments control land-use and construction permitting in flood-prone areas via zoning bylaws. Local governments can, and often do, impose special requirements for construction (such as minimum Flood Construction Levels). The recently updated British Columbia guidelines for development in flood-risk areas clearly identifies the need for Flood Construction Levels in line with the increased risk presented by sea-level rise (Ausenco Sandwell, 2011b). Many municipalities throughout the province (e.g., the City of Vancouver) are revising their requirements for new buildings. However, existing buildings remain at risk of inundation. Solutions to flood risk that include both zoning and permitting are currently being considered throughout the coastal region (Section 5.1.2).

5.1.2 FLOOD PROTECTION

Provincial guidance on management of coastal-flood hazard is currently outlined in *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use*, which includes three components: 1) *Sea Dike Guidelines* (Ausenco Sandwell, 2011c); 2) *Guidelines for Management of Coastal Flood Hazard Land Use* (Ausenco Sandwell, 2011b); and 3) *Draft Policy Discussion Paper* (Ausenco Sandwell, 2011a).

- The *Sea Dike Guidelines* provide direction for the design of protective dikes for low-lying lands exposed to coastal-flood hazards. They recommend that the heights of dikes, sea walls, and flood construction levels of buildings be revised to accommodate a sea-level rise of 0.5 m by the year 2050, 1.0 m by 2100 and 2.0 m by the year 2200 (Ausenco Sandwell, 2011c).
- The *Guidelines for Management of Coastal Flood Hazard Land Use* support the development and implementation of local-government land-use management plans and subdivision-approval processes and planning in areas exposed to coastal-flooding hazards, and provide a list of land-use management tools (Ausenco Sandwell, 2011b).
- The *Draft Policy Discussion Paper* is an attempt to bridge the gap between science and the practical application of measures to address climate change in coastal BC (Ausenco Sandwell, 2011a).

TABLE 6: Overview of responsibilities and policies of relevance to flooding in British Columbia.

Jurisdiction	Land use	Flood protection	Flood response and recovery
Federal	▪ National parks ▪ Indian reservations ▪ Department of National Defence sites	▪ Infrastructure funding	▪ Disaster financial assistance ▪ Emergency management*
Provincial	▪ Crown lands ▪ Subdivision approvals outside municipalities ▪ Construction-setback guidelines ▪ Flood Construction Levels guidelines	▪ Approval of municipal flood-protection works ▪ Technical guidance for municipalities ▪ Infrastructure funding	▪ Disaster financial assistance ▪ Emergency management
Local	▪ Municipal land-use planning/ zoning ▪ Internal subdivision approvals ▪ Construction-setback implementation ▪ Flood Construction Level implementation	▪ Construction/ management of protective works ▪ Infrastructure funding	▪ Emergency management

* This in not a normal part of federal responsibility, but this level of government has provided support via the armed forces in extreme cases.

This work was undertaken as a first step toward updating the 2004 guidelines published under the *Environmental Management Act*. Since the release of these reports, the BC Ministry of Environment has been consulting with stakeholders and the Union of British Columbia Municipalities on implementation. It is important to note that, while the maximum likely increase in sea level by 2100 presented in this report is less than the 1 m estimate referenced in the provincial climate change adaptation guidelines, the guidelines provide a margin of safety that allows for possible additional sea-level rise resulting from factors with significant uncertainty, such as contributions from the Antarctic Ice Sheet.

Although upgrading dike infrastructure will likely be required for the protection of many residences, commercial/industrial buildings and public infrastructure (e.g., Delcan, 2012), soft-armouring approaches may be more effective and less costly in some cases than hard armouring. Some communities have already begun to implement these alternative approaches with success (e.g., North Vancouver, Section 4.2.2).

5.1.3 DISASTER RECOVERY

Recovery from a disaster can, in some situations, provide an opportunity for implementation of adaptation measures as part of the rebuilding process. The Disaster Financial Assistance Program of Emergency Management BC can fund 80% of eligible (uninsured) damages incurred due to a disaster, up to a maximum of $300 000 for homeowners, residents, small-business owners, farm owners and charitable organizations. Additional disaster assistance for local governments may be available on a case-by-case basis from both the federal and provincial levels. Given the present level of flood exposure in the province, it is likely that private-property owners, together with all levels of government, will incur increasing costs as a result of flood events.

Infrastructure funding is an important facilitator of adaptation to sea-level rise. Federal and provincial governments have, in the past, partnered to fund infrastructure projects that provide flood protection to communities across BC. The Provincial Flood Protection Program and the Disaster Mitigation Category of the Federal Building Canada Plan are good examples of this. In British Columbia, the Provincial Flood Protection Program funds infrastructure projects based on applications received from local governments, and funding of some projects has, in the past, been shared equally between federal, provincial and local governments. Communities in British Columbia can also access infrastructure funding through the Federal Gas Tax Fund, BC utilities and nonprofit organizations, including the Community Energy Association, BC Hydro and the BC Stewardship Council.

5.2 COMMUNITY PERSPECTIVES

Recent studies, and conversations with local-government officials from across coastal British Columbia, have revealed several concerns regarding the development and implementation of climate change adaptation measures (e.g., Burch, 2010; Burch et al., 2010; Vadeboncoeur and Carlson, work in progress). The concerns expressed include a perceived absence of specific information on local climate impacts, a lack of capacity to develop and implement adaptation strategies, and potentially negative political and legal consequences of both action and inaction. These are outlined below.

5.2.1 LOCAL DATA NEEDS

Sea-level rise has not yet been integrated into many existing floodplain maps or planning activities. This is because of both data availability and the capacity of local governments for data analysis. For example, approximately 25% of coastal communities in BC have no access to LiDAR data for detailed flood mapping and just over half (54%) of communities with access to digital geospatial data (LiDAR and/or Orthophoto) have not used the data in planning (Vadeboncoeur, 2015). Most of the population of coastal BC (75%) lives in an area where LiDAR data are available, but this is divided asymmetrically between Metro Vancouver and the Capital Regional District (98.8% coverage, by population) and the rest of the coast (39.1% coverage, by population; Vadeboncoeur, 2015). Despite provincial guidelines that recommend adapting to 1 m of sea-level rise by the year 2100 and 2 m by 2200, some local governments have delayed adaptation planning until more detailed information is available on the projected local extent of sea-level rise in their communities. New data on regional sea-level rise (Section 2.3 and *see* Chapter 2; James et al., 2014) provide communities with updated estimates of long-term local changes to sea level and can be used to help predict changes in potential flooding. Coastal regions lacking detailed topographic information, such as LiDAR data, may benefit from new surveys.

Local governments have also expressed concerns over the potential impacts of heavy precipitation events. These include the need for improved local data on intense precipitation events, as well as factors affecting slope stability and the potential for landslides. Municipalities also have concerns over the potential for potable-water shortages.

Publicly available data and tools on potential climate changes and associated impacts in British Columbia include an online database that provides floodplain maps, a water-balance model (www.bc.waterbalance.ca) and two online planning tools to help communities understand climate changes: Plan2Adapt (www.plan2adapt.ca) and the BC Climate Action Toolkit (www.toolkit.bc.ca). Communities can use these resources to customize outputs for their geographic region, thereby providing a good characterization of the potential level of risk a community can expect to face as a result of changing climate.

5.2.2 UNINTENTIONAL CONSEQUENCES OF ADAPTATION

Local governments have also expressed concern over how designating floodplains may impact the property values of their constituents. Properties lying within designated floodplains are generally less valuable than equivalent ones outside floodplains, particularly after storms that have caused damage (Bin and Polasky, 2004; Bin and Landry, 2013). However, the reduction in value has been observed to disappear within the 5–6 years following a storm (Bin and Landry, 2013), suggesting that the desirability of waterfront lots may continue to increase property values even when subjected to periodic storm damage (so long as damages are followed by a period of relative calm). To date, the real-estate market in British Columbia does not appear to attach a flood-risk premium to at-risk areas, suggesting that buyers are either uninformed about, or more likely insensitive to, flood risks.

Legal liability is a concern for local governments. Liability issues could arise in the form of negligence or nuisance claims if, for example, it can be proven that reasonable care toward its residents has not been exercised. This topic is explored in Case Study 13.

CASE STUDY 13:

ADAPTATION AND LEGAL LIABILITY: CONCERNS FOR LOCAL GOVERNMENTS

The legal framework in which coastal municipalities operate may condition or determine some adaptation responses because legal liabilities, both demonstrated and perceived, can be relevant to planning. As elsewhere in Canada, local governments in BC derive their powers and related duties from provincial legislation. They may also be affected by federal and provincial government requirements that can direct planning decisions at the local level (e.g., building codes). In some cases, this exercise of federal or provincial jurisdiction may align with or support local government policies and objectives; in other cases, it may pose barriers (Vadeboncoeur and Carlson, work in progress). As a result, adjacent municipalities within a region might have quite different approaches to the same set of issues.

The risk of legal liability, while far from being a dominant driver for adaptive responses to sea-level rise by local governments, does seem to be a factor to consider, given the potential financial impact. This is because local governments are subject to common law precedents developed through decisions of the Court, unless protected by statutory immunity or other provisions. There are examples of municipalities in Canada that have been targeted in class-action lawsuits to recover property damage caused by extreme climate events.

Local governments may be subject to liability for extreme events, such as flooding, through both negligence and nuisance claims. Such claims may be based on local government decisions and actions related to design, building, operation and inspection of infrastructure in cases where infrastructure fails or is in some way hazardous or damaging to people or property. Given currently available information regarding sea-level rise, coastal flooding may be seen as a factor that a local government should take into account in operational decisions and actions, where relevant.

Local governments in British Columbia enjoy statutory immunity under the *Local Government Act* where sewer systems, water or drainage facilities, dikes or roads break down or malfunction, and interfere with private-property use. However, BC courts have found that this immunity does not apply where property damages arise from a design that is inadequate for the purpose it is meant to fulfill. Infrastructure built today may be affected by sea-level rise in the future and could present a liability if that rise is not factored into design. In order to minimize liability and avoid the high capital cost of avoidable upgrades or relocations, local governments require good technical information about infrastructure vulnerability. This information will also be relevant for the siting of new infrastructure to minimize risks related to inundation and storm damage.

Risks of legal liability associated with possible infrastructure failure may be an additional factor in catalyzing action on the part of local governments to prepare for rising sea levels.

6 CONCLUSIONS

Current and anticipated impacts of climate change on coastal British Columbia are a result of both direct impacts from changing atmospheric conditions and the indirect, climate-driven alterations to coastal ecosystems. These changes present risks and challenges to local governments and First Nations, and represent a risk to the broader British Columbia economy. Key conclusions emerging from this chapter are summarized here.

CLIMATE CHANGE IS ALREADY IMPACTING THE COAST

Climate records indicate that there has been a gradual warming trend in coastal British Columbia since 1900, particularly in winter. Higher precipitation has been observed in winter and fall, while decreased summer rainfall may influence periods of seasonal drought. Increased winter temperatures have led to a decline in precipitation that falls as snow, resulting in increased runoff and less water storage as snow and ice at high elevations, exacerbating summer water shortages in some years for some areas.

Geological effects will amplify or offset the impact of sea-level rise on coastal communities. In some regions, crustal uplift will cause relative sea levels to be less than the global average, whereas subsidence in others will result in accelerated sea-level rise. Increased storminess will exacerbate the problems presented by sea-level rise because deeper water allows waves to gain more power, exposing coastal settlements to greater risk of storm damage and flooding.

CLIMATE CHANGE WILL INCREASE EXISTING STRESSES ON BRITISH COLUMBIA'S FISHERIES

Although the fishing industry has changed significantly during the past two decades, having decreased in size and developed a substantial commercial-capture component, it remains an important part of the social and cultural identity of many British Columbians.

The distribution of the availability of some endemic fish species will likely change as the range of marine species shifts northward. It is possible that the southern range of healthy salmon stocks will decline while their northern range expands. If this occurs, the species available for wild capture, sport and First Nations fishers will change, particularly in the southern part of the province. Farmed salmon would not likely be affected by these distributional changes, but commercial capture operations could still be impacted by climate change via increased risk of storms (that can damage net pens) and warmer waters (that can increase risk of disease).

Shellfish are affected by increased ocean acidity. Acidification, combined with increased water temperature, affects shellfish by limiting their ability to reproduce and decreasing their (vertical) habitable range.

The commercial-capture fishery, its regulators and the market have responded to the major declines in salmon and herring by increasing use of other commercial fish. This suggests that the British Columbia fishery can cope with changing availability of target species. Information on First Nations fisheries is scarce, and the pivotal cultural importance of salmon (and activities associated with its catch, processing and distribution) suggests that there is limited ability to adapt to sudden fluctuations, or a steady decline, in salmon runs. Adaptation has been supported in some First Nations communities, but concrete proactive actions remain rare.

STRATEGICALLY IMPORTANT INFRASTRUCTURE IN BRITISH COLUMBIA FACE NEAR- AND LONG-TERM CHALLENGES FROM CLIMATE VARIABILITY AND CHANGE

Climate change presents a suite of risks to critical infrastructure, such as Port Metro Vancouver and Vancouver International Airport, and regionally important infrastructure, such as highways, and electricity and gas lines. The anticipated expansion of primary-resource development within the province, and the associated infrastructure needs, including export terminals along the north coast, will increase exposure to climate impacts. Although related research remains limited, these industries have demonstrated understanding of the risks that climate change presents to their operations and are either taking steps to address these (e.g., Vancouver International Airport) or are comfortable with their preparations to date and possess the data required for an updated risk assessment when it is deemed appropriate (e.g., Port Metro Vancouver).

THERE ARE REGIONAL DIFFERENCES IN VULNERABILITY

Vulnerability to climate change reflects the social, cultural and geographic diversity of coastal British Columbia. For example, salmon fishers in the southern part of the province will experience the impacts of increased stress on fished stocks earlier than northern fishers. Communities exposed to long stretches of open water will experience more risk from storms than those in more sheltered areas. First Nations peoples and other communities where primary incomes are based on salmonid fisheries will experience effects related to a decline in commercial catch similar to other groups, but they would also be affected culturally and socially if their subsistence catch were to also decline.

There are also differences between rural and urban communities. The former often rely more heavily on natural resources, while the latter have more diversified economies and have greater capacity to respond to risks. As such, rural adaptation often requires an additional emphasis on managing the socio-economic impacts of changes to resource- and place-based economics.

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APPENDIX A

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

Projected relative sea-level changes to 2100 are provided here for 19 locations shown on the accompanying map (Figure A1) for the West Coast region (*after* James et al., 2014–2015; Section 2.4 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.

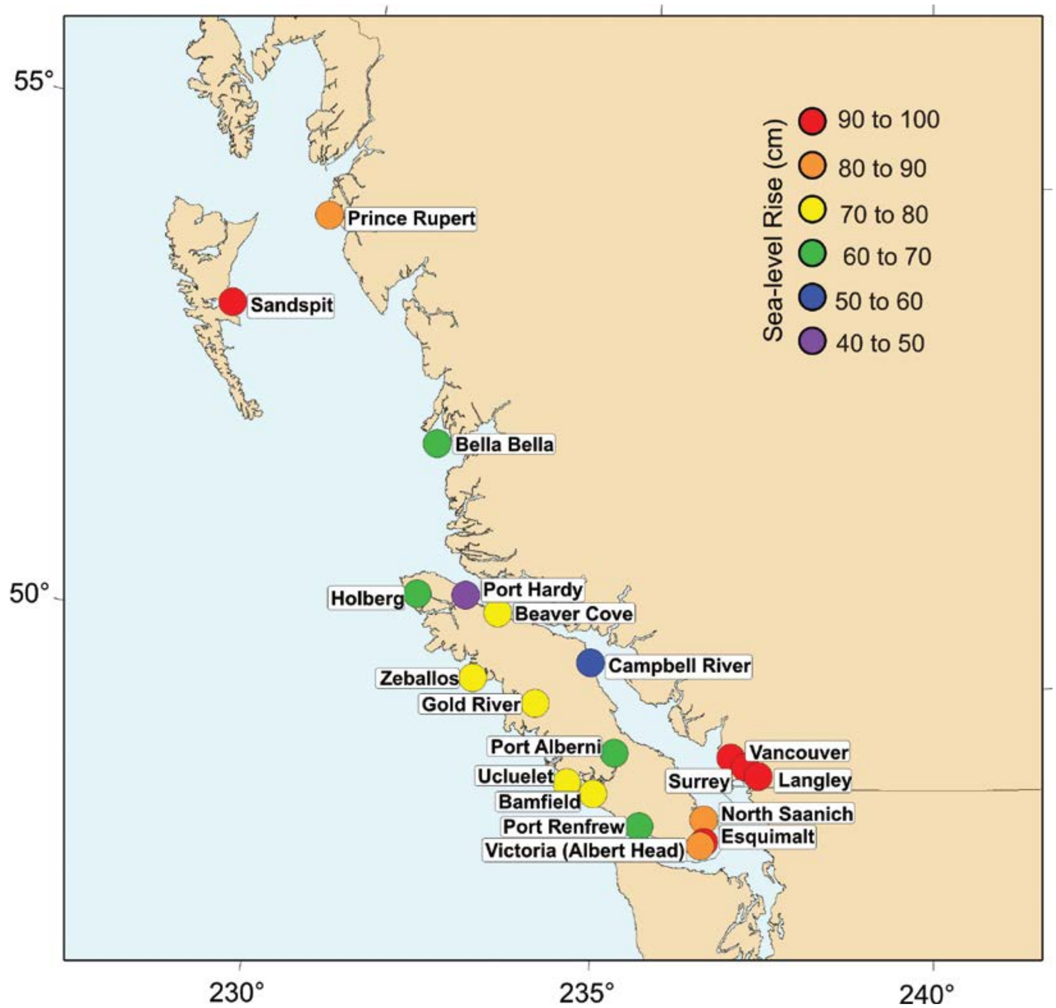

FIGURE A1: Locations for which sea-level projections are provided through the 21st century (Figure A2). Dots are colour coded to indicate the projected sea-level change at 2100 for the 95th percentile of the high-emissions scenario RCP8.5 (*after* James et al., 2014-2015)

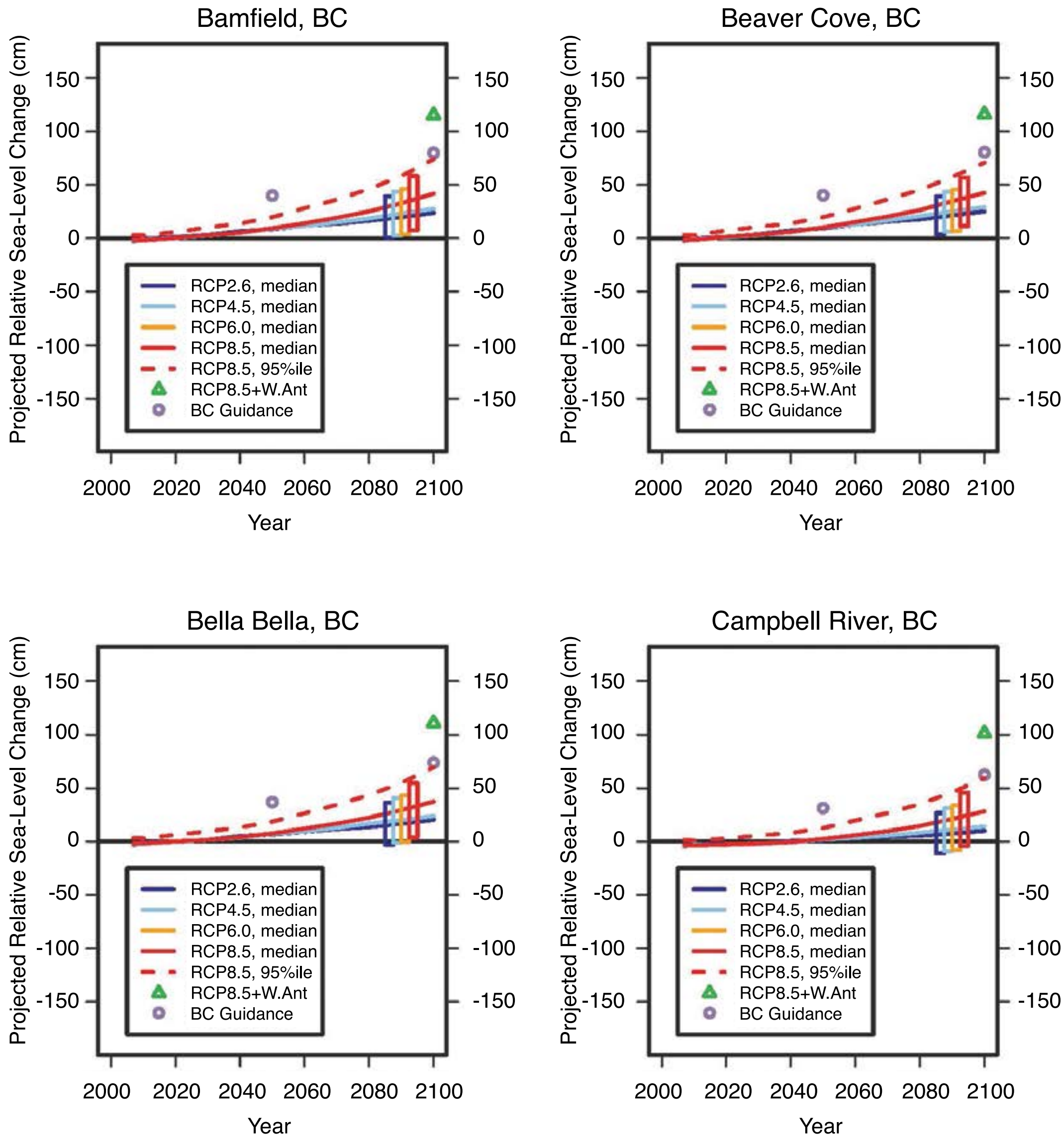

FIGURE A2: Projected relative sea-level change through the 21st century for selected locations in the West Coast region (*after* James et al., 2014–2015). RCP2.6 is a low-emissions scenario, RCP4.5 is an intermediate-emissions scenario and RCP8.5 is a high-emissions scenario. The projected value at 2100 is also given for the high-emissions plus Antarctic ice-sheet reduction scenario, an augmented scenario, in which West Antarctica 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 dashed red line gives the 95th percentile value for the high emissions scenario. The allowance for sea-level rise (BC Guidance) specified by the government of British Columbia is also given (Ausenco Sandwell, 2011b).

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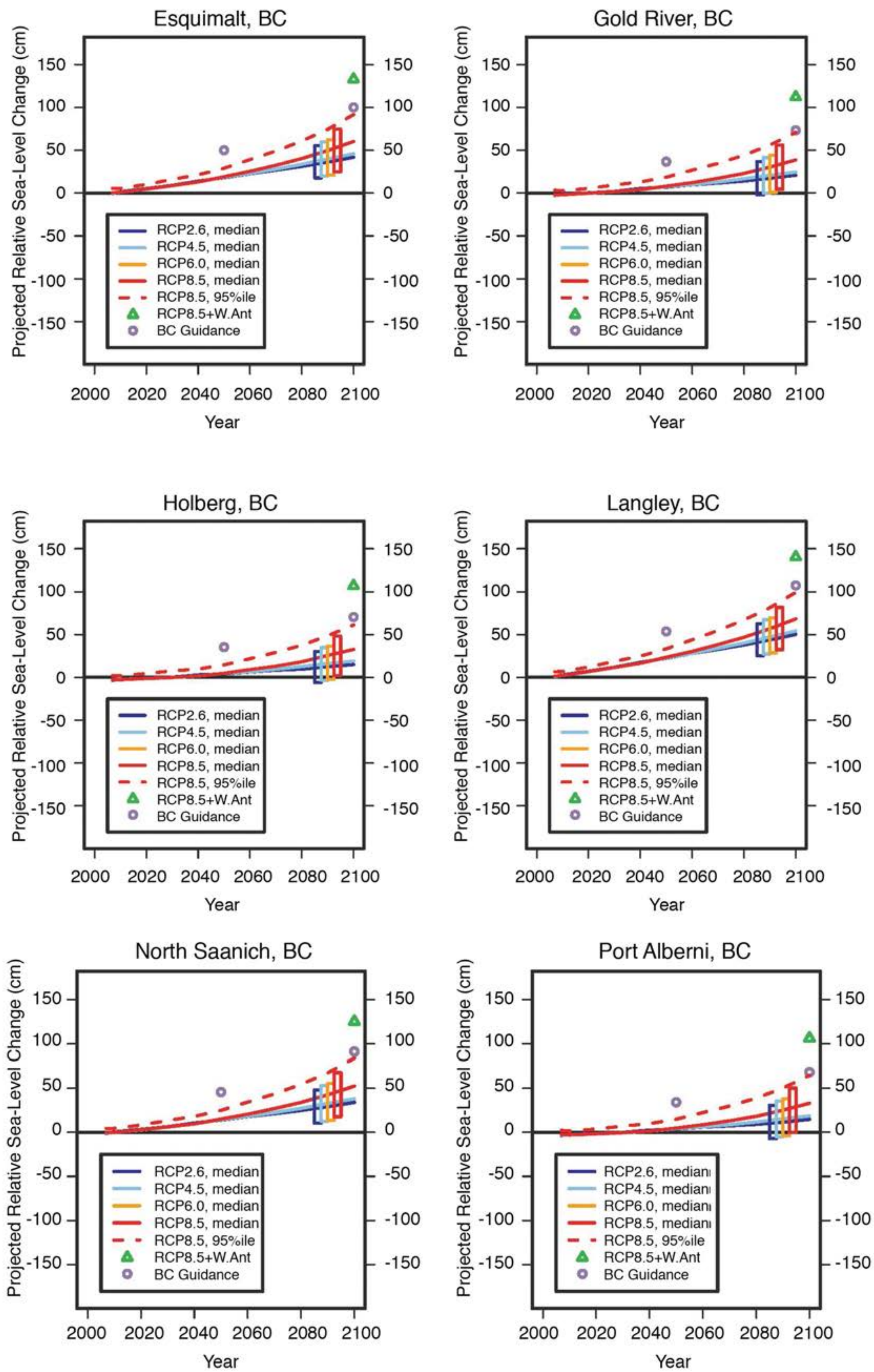

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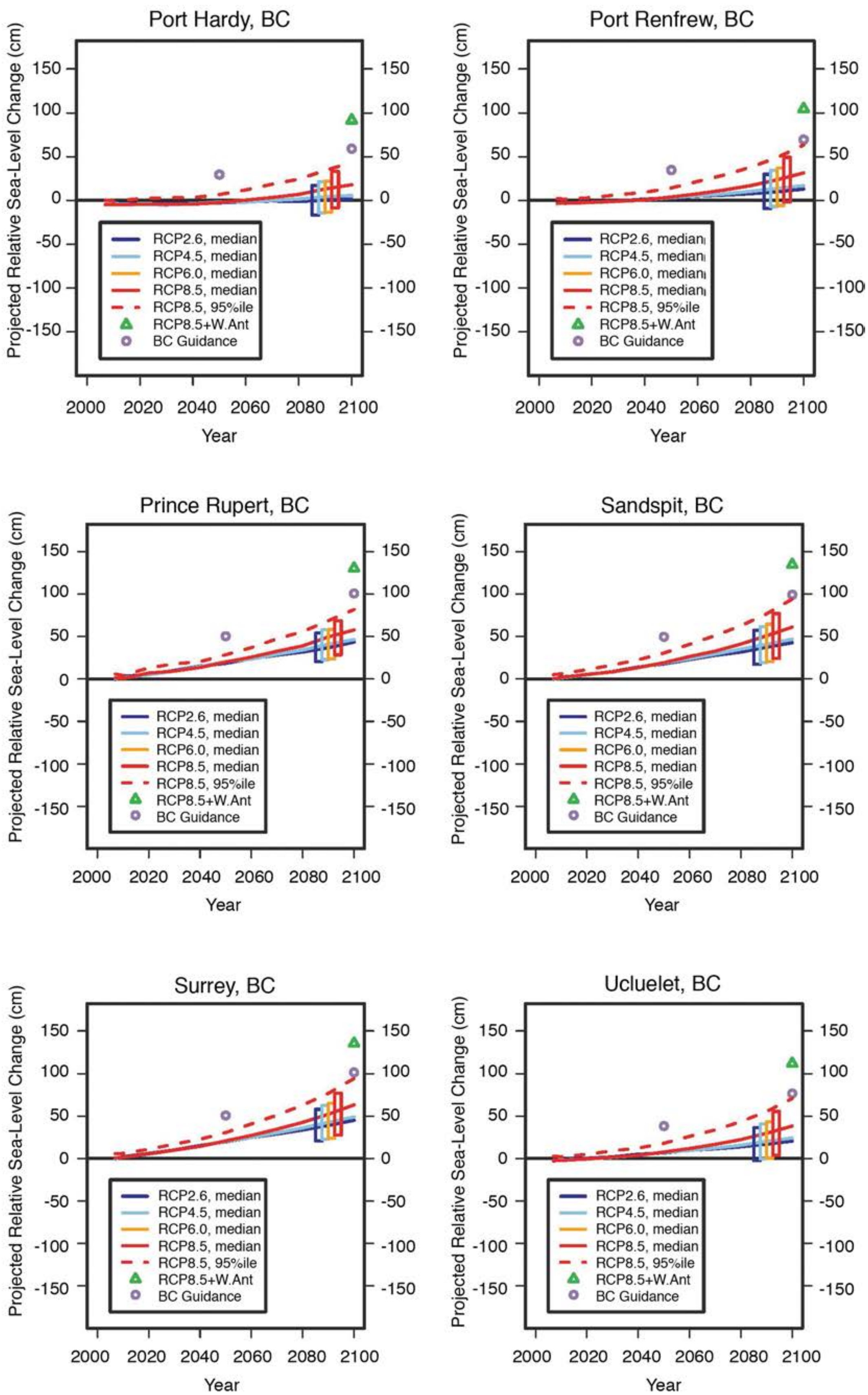

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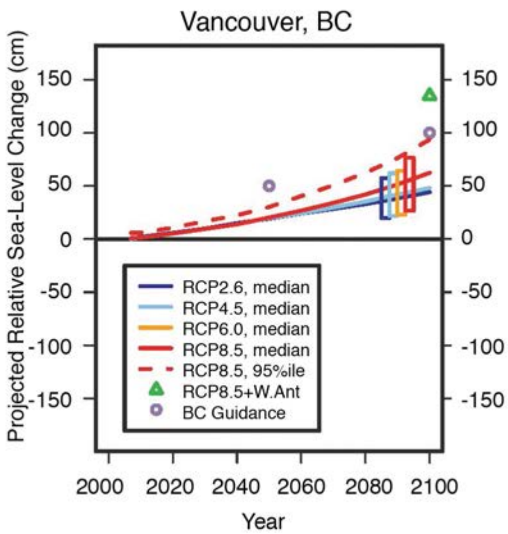
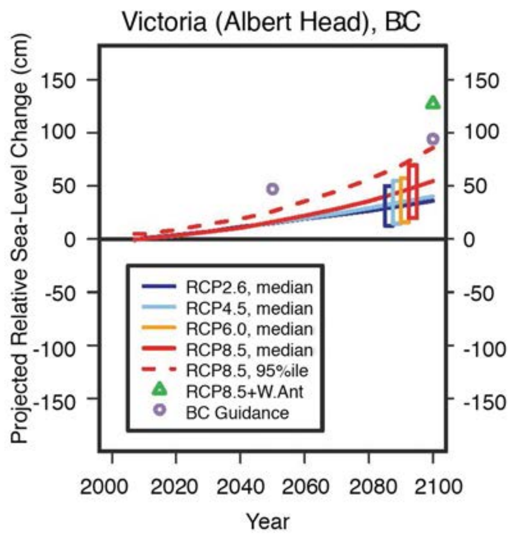
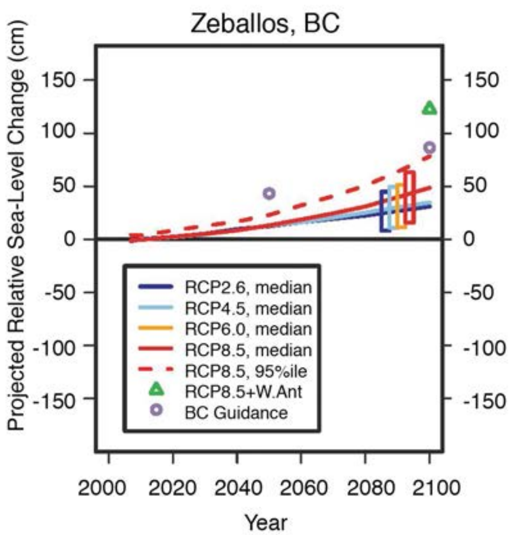

Vancouver, BC
Projected Relative Sea-Level Change (cm)
150
100
50
0
-50
-100
-150
2000 2020 2040 2060 2080 2100
Year
RCP2.6, median
RCP4.5, median
RCP6.0, median
RCP8.5, median
RCP8.5, 95%ile
RCP8.5+W.Ant
BC Guidance


Victoria (Albert Head), BC
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
BC Guidance


Zeballos, BC
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
BC Guidance

CHAPTER 7: FREQUENTLY ASKED QUESTIONS

Editors:
Fiona J. Warren and Donald S. Lemmen (*Natural Resources Canada*)

Recommended Citation:
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TABLE OF CONTENTS

EDITORS' NOTE

This chapter presents a series of frequently asked questions (FAQs) relevant to understanding climate change impacts and adaptation in Canada's coastal regions. It is clear from the regional chapters that climate is changing, with coastal regions experiencing changes in air and water temperatures, precipitation patterns, storms, sea level and sea-ice cover. The impacts of these changes on ecosystems, communities and sectors will differ within and between regions due to a number of factors, such as the nature of the coastline, the presence of natural and built protection (e.g., beaches, marshes, seawalls, dikes and breakwaters) and the capacity to adapt.

These FAQs are intended to provide concise answers to questions decision makers are asking to better understand the implications of climate change for Canada's coastal regions. They are not comprehensive, nor do they provide detailed explanations. Instead, they focus on highlighting relevant examples and encouraging readers to consult the full chapters of *Canada's Marine Coasts in a Changing Climate*, as well as the resources listed in FAQ 12, for more information.

FAQ 1: WHAT IS A COASTAL ASSESSMENT, AND WHY AND HOW WAS THIS REPORT PRODUCED?

Author: Fiona J. Warren *(Natural Resources Canada)*

Science assessments are syntheses of existing information, developed to present the state of knowledge on specific issues. This coastal assessment, *Canada's Marine Coasts in a Changing Climate*, focuses on climate change impacts and adaptation in Canada's marine coastal regions. Considering both the natural and built environments, the report aims to provide answers to questions such as "How is the climate changing in coastal regions?"; "How are these changes affecting the physical coastline, communities, ecosystems and economic sectors?"; and "How are Canadians adapting to these changes to reduce risks or take advantage of potential opportunities?"

Assessment reports aim to be relevant to policy issues (i.e., to address issues of concern to decision makers) but not be policy prescriptive. Therefore, this assessment does not provide policy recommendations or prescribe specific actions, but rather serves as a knowledge foundation to inform decisions. Previous science assessments that complement this report include the Canadian publications *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (2014) and *From Impacts to Adaptation: Canada in a Changing Climate* (2008; Figure 1), as well as international reports such as those of the Intergovernmental Panel on Climate Change (IPCC).

In this report, *Canada's Marine Coasts in a Changing Climate*, the main chapters present regional (East, North and West) perspectives. In these chapters, the authors introduce the regions and then discuss observed and projected changes in climate, as well as climate risks, opportunities and adaptation approaches. Supporting chapters—'Dynamic Coasts in a Changing Climate' (Chapter 2) and 'The Coastal Challenge' (Chapter 3)—provide the context for the regional discussions by presenting national-scale overviews on issues such as the diversity of marine coasts, sea-level change and approaches to adaptation. In all cases, the chapter content reflects the availability and accessibility of information, while the expert judgement of the author teams brings added value to the summary of existing knowledge.

The main goal of the report is to provide an up-to-date, reliable source of information that informs decision-making, planning and policy development by:

- describing the current state of knowledge relevant to understanding how climate change presently impacts, and will continue to impact, the natural and built environment in Canada's marine coastal regions; and
- consolidating information relevant to adaptation decision making in coastal areas, including experience with practical adaptation measures.

Developing the coastal assessment involved contributions from a team of editors, 12 lead authors and 44 contributing authors. The work was overseen by a 14-person Advisory Committee that included multidisciplinary experts and practitioners from the federal, provincial and territorial governments, academia and the private sector. This

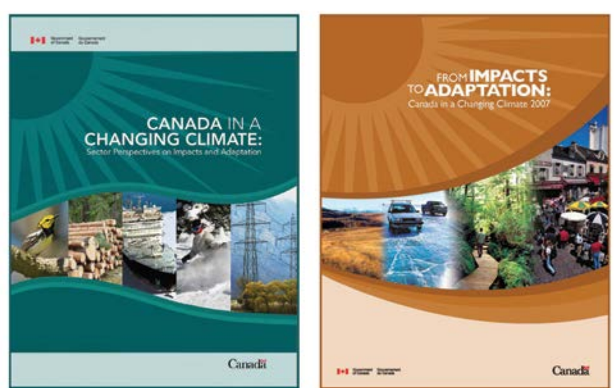

FIGURE 1: Recent Canadian science assessments on climate change impacts and adaptation.

committee was engaged throughout the assessment process, including the initial planning to help ensure that the report addressed the right questions and was organized in a manner would meet the information needs of decision makers. During the writing process, the authors gathered, assessed and synthesized information from academic journals, reports, presentations and local/practitioner knowledge to produce draft chapters. Edited drafts were reviewed by experts in the field (74 in total for report). The more than 2 500 comments received through this review process were then used by the chapter authors to develop their final drafts.

FAQ 2: WHAT IS ADAPTATION TO CLIMATE CHANGE AND HOW DOES IT RELATE TO CLIMATE CHANGE MITIGATION?

Author: Fiona J. Warren (*Natural Resources Canada*)

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "the process of adjustment to actual or expected climate and its effects" (IPCC, 2012). It involves making changes in our activities and decisions to reduce the harm from negative impacts of climate change and take advantage of any positive impacts. As such, adaptation is a broad concept that encompasses a wide range of possible actions. It can be as simple as installing shut-off valves in homes to reduce the risk of sewer backup causing basement flooding during heavy rainfall events, or as complex as planning and implementing a shoreline-protection strategy to reduce the risks of flooding due to sea-level rise. Regardless of the scale, adaptation is undertaken to help ensure that our lives, our communities and our economy are better prepared for climate change, both now and in the future.

Although adaptation can be undertaken spontaneously in response to specific events such as extreme weather, this report, *Canada's Marine Coasts in a Changing Climate*, focuses on planned adaptation, which includes modifying operations, introducing new technologies, changing planning guidelines and approaches, and revising investment practices, regulations and legislation. These changes often require careful planning and collaboration that are guided by both scientific research and a strong understanding of the systems involved. They are also affected by local capacity and resource availability. Many of the adaptation approaches discussed in the report involve dealing with sea-level rise and include actions to reduce the risks of flooding. However, adaptation in coastal regions also involves managing other impacts, such as warmer temperatures, shifting precipitation patterns, reduced sea ice and changes in inland hydrology (e.g., river flows), as well as addressing the risks of extreme weather events such as hurricanes and other major storms.

> Without careful planning, the risk of *maladaptation* increases. Maladaptation refers to actions that serve to increase, rather than reduce, vulnerability.

Adaptation is a necessary complement to reducing greenhouse gas emissions (mitigation) in responding to climate change. Mitigation actions decrease the amount of greenhouse gases entering the atmosphere in two ways. The first is by reducing emissions of carbon dioxide, methane, nitrous oxide and other greenhouse gases, and the second is by enhancing greenhouse gas sinks, such as forests and wetlands. Mitigation reduces both the magnitude and the rate of climate change. For example, scenarios considered by the IPCC in its latest assessment report suggest that, for the period 2081–2100, average global surface temperature could increase by less than 2°C above pre-industrial levels with very aggressive mitigation measures but by more than 4.5°C above pre-industrial levels with only very limited mitigation effort. For the same scenarios, the likely range of global sea-level rise is 26–82 cm for the period 2081–2100. Therefore, the extent and amount of adaptation needed depends on the success of mitigation efforts. Without efforts to reduce greenhouse gas emissions, some natural and managed systems would be overwhelmed and unable to adapt successfully. Strong and successful mitigation measures will provide more time to plan and implement adaptation, as changes will occur more gradually and be less extreme.

There can be co-benefits, or synergies, between these two responses to climate change, where actions taken to adapt also serve to reduce greenhouse gas emissions, or mitigation actions also reduce vulnerability to climate change (Figure 2). For example, green roofs, where vegetation is planted and maintained on the roofs of buildings, have both adaptive benefits (e.g., moderated storm-water runoff, reduced urban-heat-island effect and improved air quality) and mitigative value (e.g., reduced energy consumption, reduced greenhouse gas emissions and increased carbon dioxide absorption). However, there is also the potential for conflict between adaptation and mitigation, where adaptation choices can increase greenhouse gas emissions. Use of air conditioners to deal with higher temperatures, for example, is associated with increased energy use and related emissions. These examples highlight the need for co-ordinated policy responses.

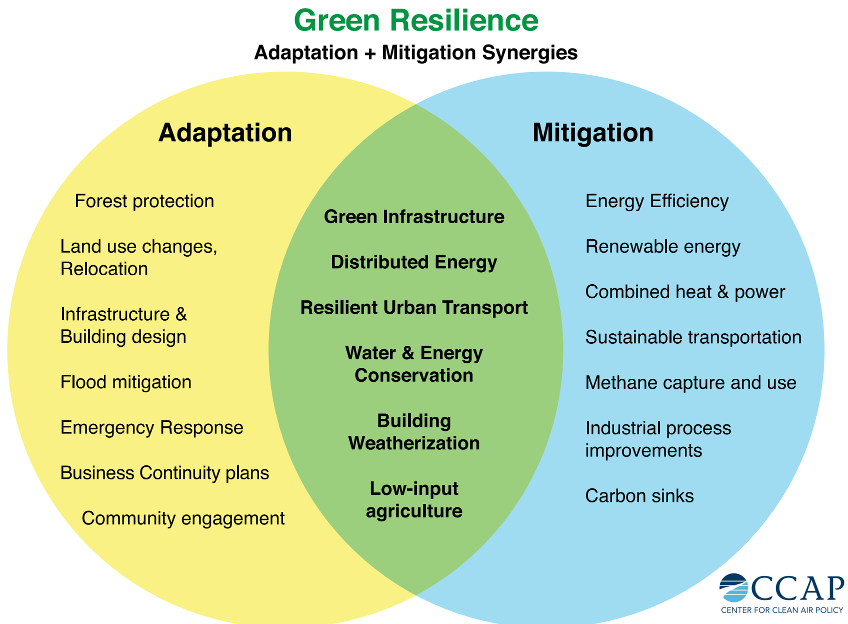

FIGURE 2: Examples of adaptation, mitigation and overlap between the two approaches. *Image courtesy of Center for Clean Air Policy, 2016.*

REFERENCE

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FAQ 3: WHAT IS THE DIFFERENCE BETWEEN CLIMATE CHANGE AND CHANGING WEATHER?

Author: Kevin Anderson *(Environment Canada)*

Weather refers to the state of the atmosphere at a given time. For instance, at some time on a given day in Halifax, it may be 20°C and sunny with winds blowing from the east. But those conditions probably won't be the same 12 hours later or 6 months down the road. The weather changes constantly—during the course of a day and from season to season. This is a normal consequence of the continually changing state of the atmosphere and ocean.

Climate can be thought of as the 'average weather'. More rigorously, it can be defined as the statistical description of weather, including the mean and variability, over a period of time ranging from seasons to decades to thousands of years. When two distinct areas experience different average weather conditions over the long-term, we say that they have different climates. For example, most of Australia does not usually get snow and its summers can be very hot. Those conditions are quite different from the weather we generally experience in Canada, so we say that Canada has a different climate than Australia. Even within Canada, we can say that Toronto has a different climate than Vancouver (because of the generally drier summer and much wetter and milder winter in Vancouver) even though, at a particular time, these two cities may experience similar weather.

The Earth's climate varies from season to season and from year to year. For example, some winters are colder and have more snow than others, while some summers are warmer and drier than others. This is called natural climate variability and it happens on a global, regional and local scale. On top of this natural climate variability, however, the overall climate system of the Earth has been changing due to increased levels of greenhouse gases that are emitted into the atmosphere.

The increase in global average temperature (known as 'global warming'; Figure 3) is only one indicator of how much the Earth's climate is changing. There are also many other changes associated with this warming climate, such as changing precipitation patterns, widespread melting of snow and ice, thawing of permafrost and increasing frequency of some severe weather around the world (IPCC, 2013). To understand how climate is changing, scientists look at the total change over a given time period (e.g., over time scales ranging from decades to centuries and beyond), as well as how each climate-system indicator (e.g., temperature, rain, snow) changes on a seasonal or yearly basis within that longer time period.

As climate changes, so does the general weather. This means that we may experience different average weather conditions than what we were used to in the past. For example, what we think of today as a very cold winter day in different parts of Canada is generally not as cold and/or as frequent as it used to be 50 years ago. This is due to the increase in winter temperature.

REFERENCE

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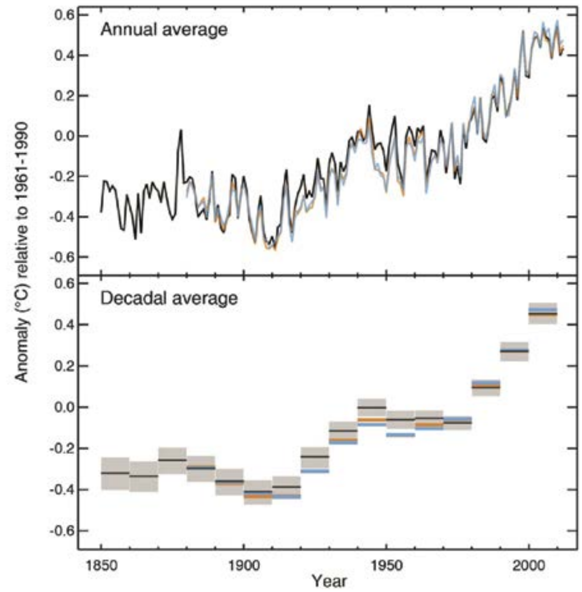

FIGURE 3: Observed, globally averaged, combined land and ocean-surface temperature anomalies, 1850–2012 (IPCC, 2013).

FAQ 4: CAN RECENT EXTREME EVENTS OBSERVED IN COASTAL REGIONS BE ATTRIBUTED TO CLIMATE CHANGE?

Author: Kevin Anderson *(Environment Canada)*

A changing climate can be expected to lead to changes in climate and weather extremes. For example, the Intergovernmental Panel on Climate Change (IPCC, 2013) noted that the number of warm days and nights, and the frequency of heat waves in certain parts of the world (large parts of Europe, Asia and Australia) have increased since about 1950 and that the number of heavy precipitation events over land has increased in more regions than it has decreased. However, it is challenging to associate a single extreme event with a specific cause (such as increasing greenhouse gases) because a wide range of extreme events could occur even in an unchanged climate, and because extreme events are usually caused by a combination of factors. As of the publication of this report, observed extreme events in Canadian coastal regions have not been attributed to a particular cause. Despite this, it may be possible to make an attribution statement about a specific weather event by analyzing how a particular cause may have changed the probability of the event's occurrence or its magnitude.

Attribution of extreme events to causes is an active area of research in the scientific community around the world. On the global scale, many events have been studied with the rigour required to determine whether or not there was a human influence (Herring et al., 2014). Studies show clear evidence for human influence on some events and little evidence for human influence on others. For example, human influence may have at least doubled the odds of the 2003 European heat wave (Stott et al., 2004); and, while natural climate variability is capable of producing the magnitude of the 2010 Russian heat wave, the odds of that heatwave occurring were significantly increased due to human influence (Otto et al., 2012).

Studies on Canadian extreme weather events have been focused on the broad scale. For example, changes in certain extremes have been confidently observed in many parts of Canada: the number of hot days and nights has increased, while cold extremes (e.g., the number of cold days and nights) have decreased (Wang et al., 2013). With respect to coastal extremes in Canada, research shows that extreme North Atlantic surface-wave heights have increased in the high latitudes (e.g., Newfoundland coast and north) but decreased in the mid-latitudes (Wang et al., 2009). This trend contains a detectable response to anthropogenic (e.g., greenhouse gases) and natural (e.g., volcanic eruption) influences combined. These changes are consistent with expected changes due to increases in atmospheric greenhouse gases.

Looking toward the future, climate change is projected to affect both the intensity and the frequency of many types of extreme events. State-of-the-art climate models project an increase in hot extremes, a decrease in cold extremes and an intensification of the global hydrological cycle that will lead to more concentrated episodes of rain/snow and longer dry periods in between, all of them associated with rising global temperatures due to the continued increase of greenhouse gases in the atmosphere. This is the basis for expecting changes in extreme events such as heat waves, heavy precipitation and drought.

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FAQ 5: HOW IS THE CLIMATE GOING TO CHANGE IN CANADA'S COASTAL REGIONS AND HOW ARE THESE PROJECTIONS DETERMINED?

Author: Thomas James *(Natural Resources Canada)*

Understanding the risks that climate change presents to Canadian coasts requires, among other things, information regarding likely changes in climate parameters. This information can be obtained from complex computer models that simulate the Earth's climate system, building on observations of past climate variability. Output from these models is commonly discussed in terms of changes in temperature, precipitation patterns, sea-ice extent and global sea level. However, managing coastal risks also requires knowledge of other climate parameters, such as wind, waves, fog and local sea-level change (*see* Chapter 2). In general, confidence in projected climate changes is greatest for temperature, somewhat less for precipitation changes and sea level, and generally low for factors such as wind, waves and fog.

Air temperatures in Canada are projected to rise through the 21st century, with the largest increases in the winter (December to February) and in the North Coast region. Averaged across Canada and over the time period 2081–2100, winter temperatures are projected to rise from as little as 1.5–3.4° C for the low-emissions scenario (RCP2.6) to a high of 7.2–10.8° C for the high-emissions scenario (RCP8.5), relative to 1986–2005[1] (Box 1; IPCC, 2013; Environment Canada, 2015). Projected temperature increases are generally smaller for the coastlines of the East and West Coast regions than for noncoastal regions (Figure 4a, b).

Precipitation in Canada is projected to increase in most regions and seasons, with the notable exception of parts of southern Canada in summer, where little change or a decrease is projected. The largest projected percentage increases in precipitation are in the North Coast region in the winter. Here, median precipitation is projected to increase by 10–30% for the low-emissions scenario and by more than 50% in most of the region for the high-emissions scenario in 2081–2100, relative to 1986–2005 (Figure 4c, d). Larger absolute changes in precipitation (expressed in actual amounts rather than percentages) are anticipated in the East and West Coast regions, in comparison to the North Coast region.

Regional projections of ocean temperatures are less certain, but average temperatures are expected to increase in the upper kilometre of the ocean for all scenarios at all latitudes by the end of the century (Collins et al., 2013). A projected decrease in the maximum area of sea ice (Figure 4e, f; *see* Chapters 2, 4, 5) is linked to higher atmospheric and ocean-water temperatures. The time of freeze-up (onset of sea ice) is also projected to be delayed. The Arctic Ocean is projected to be essentially ice free at the time of minimum sea-ice extent (September) by mid-century (IPCC, 2013).

1 Ranges are derived from the 25th and 75th percentiles.

BOX 1
CLIMATE MODELS AND SCENARIOS

Climate projections are generated from computer models of climate that are based on the fundamental physical and chemical laws governing the transfer and motion of heat (energy) and mass into, within and among the components of the climate system and evaluated against observations. While early models (General Circulation Models or GCMs) focused on the atmosphere, the global ocean also plays a key role in climate (e.g., as a repository of heat and some atmospheric constituents). Therefore, ocean circulation models were developed and coupled to GCMs to better simulate the climate system (Atmosphere-Ocean General Circulation Models or AOGCM). A modern Global Climate Model (also having the acronym GCM) is composed of an AOGCM and also considers interactions of the atmosphere with the Earth's solid surface, including soil, vegetation and the cryosphere (glaciers and ice sheets, permafrost, sea and freshwater ice, and snow). Chemical transport models may also be coupled to a global climate model to better track, for example, the path of anthropogenic carbon in the atmosphere and oceans, or the projected recovery of the ozone hole. Earth System Model (ESM) is a general term to describe computer models that add biochemical and geochemical processes to the coupled physical climate system and therefore allow, for example, projections of ocean acidification as part of the response of the climate system to increasing greenhouse gases.

The GCMs and ESMs use scenarios* of future atmospheric greenhouse gas concentrations to project changes in the climate system. The projections** summarized in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change were based on four Representative Concentration Pathway (RCP) scenarios (*see* Chapter 2). This is in contrast to the Fourth Assessment Report, which was based on the Special Report on Emissions Scenarios (SRES) scenarios. The projections in the Fifth Assessment Report and in this report are derived from an international comparison and synthesis of climate-model projections called the Coupled Model Intercomparison Project, Phase 5 (CMIP5). The Canadian modelling contribution to CMIP5 was provided by the second generation of the Canadian Earth System Model, CanESM2, developed by the Canadian Centre for Climate Modelling and Analysis of Environment Canada.

Environment Canada provides a web-based service, 'Canadian Climate Data and Scenarios', to give maps, plots and tables of projected temperature and precipitation changes for Canada (Environment Canada, 2015). Values include median projected values and 25th and 75th percentiles, giving an indication of the uncertainty in projections. Information is available for different time ranges, and summary statistics are available for the provinces and territories. The service can be accessed at http://ccds-dscc.ec.gc.ca/?page=main. The Fifth Assessment Report projections are available under the CMIP5 menu. A guidebook for adaptation practitioners on how to use climate projections (Charron, 2014) is available at http://www.ouranos.ca/media/publication/352_GuideCharron_ENG.pdf.

* A scenario is a "plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions." (IPCC, 2014).

** A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models (IPCC, 2014).

Associated with the projected increases in temperature, fewer cold-weather extreme events and more hot-weather extreme events are expected, although these will vary regionally. Naturally occurring climate variability and dynamics play an important role in determining extreme events. The El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are important contributors to extreme events in the West Coast region (*see* Chapters 2, 6). Projected increases in extreme ENSO events (Cai et al., 2014) may contribute to increased extreme water-level events in the West Coast region (Barnard et al., 2015). There is an expectation of increasing storminess in the future on a global scale. However, storminess at any specific location may or may not increase, depending on the position relative to storm source regions and tracks. Region-specific projections of storminess and associated storm surges have low confidence (*see* Chapter 2; IPCC, 2013).

Globally, wind speed and wave height have increased in recent decades (Young et al., 2011). In much of the Arctic, including the Beaufort Sea, wave heights are projected to increase in the future due to the combined effects of winds and reduced sea-ice concentrations (*see* Chapter 2; Khon et al., 2014). Increased wave heights in the winter are also expected in parts of the East Coast region, associated with reduced sea-ice concentrations in coming decades. Larger waves tend to have greater erosive power.

There is high confidence that projected increases in mean relative sea level (FAQ 6) and reductions in sea ice will lead to increases in the frequency and magnitude of extreme water levels (IPCC, 2013). This is expected for parts of the East Coast region and the Beaufort coastline. The West Coast region is also susceptible to increased extreme water-level events arising from projected increases in sea level.

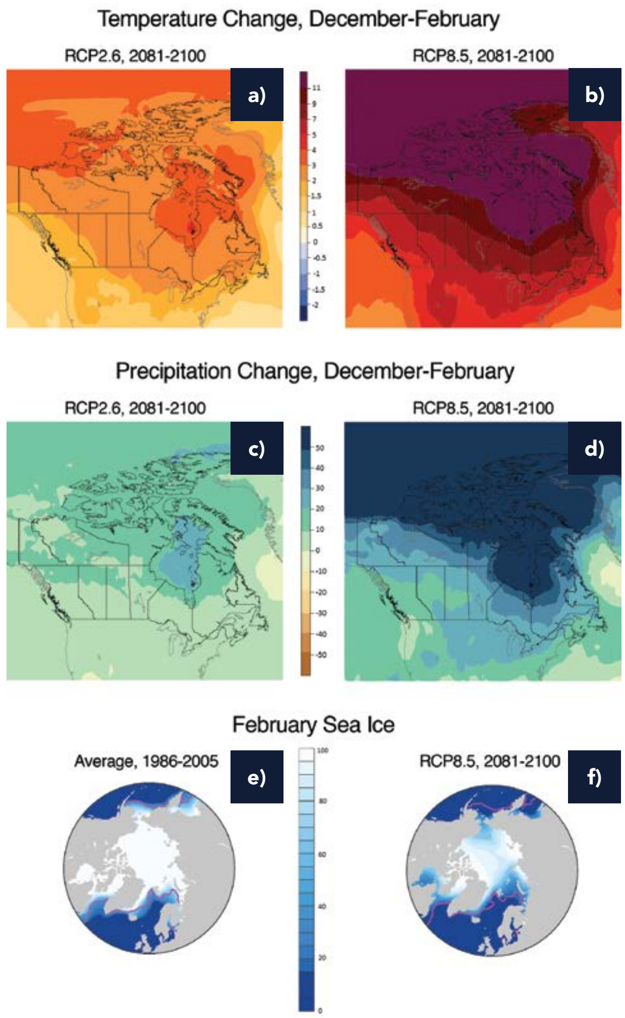

FIGURE 4: Projected median temperature changes during the winter months for the **a)** low-emissions; and **b)** high-emissions scenarios for 2081-2100, relative to 1986-2005 (IPCC, 2013; Environment Canada, 2015). Projected median precipitation changes during the winter months for the **c)** low-emissions and **d)** high-emissions scenarios for 2081-2100, relative to 1986-2005 (IPCC, 2013; Environment Canada, 2015). Observed **e)**; average for 1986–2005) and projected **f)**; high-emissions scenario for 2081–2100) February Arctic sea-ice extent (*extracted from* Collins et al., 2013, Figure 12.29). The red line is the observed 15% concentration contour for 1986–2005.

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FAQ 6: HOW WILL SEA LEVEL CHANGE IN CANADA AND HOW ARE THE PROJECTED CHANGES DETERMINED?

Author: Thomas James *(Natural Resources Canada)*

Globally, mean sea level is projected to rise by tens of centimetres, and possibly by more than a metre, by 2100 (Figure 5a; *see* Chapter 2; IPCC, 2013). The main causes of global sea-level rise are warming of the upper layer of the oceans (steric effect), and meltwater and iceberg-discharge contributions from glaciers, ice caps and grounded ice sheets. Antarctica has the potential to contribute additional tens of centimetres to sea-level rise by 2100. The magnitude and timing of this potential contribution is unknown and its occurrence unlikely (IPCC, 2013), but it may need to be considered in cases where the tolerance to risk of sea-level rise is low (*see* Chapter 3). Sea-level rise has the potential to contribute to increased coastal erosion and to increase extreme water-level events that cause coastal flooding.

Projected relative sea-level change varies regionally due a number of factors (*see* Chapter 2; Milne et al., 2009). Of these factors, vertical land motion (uplift and subsidence) has a dominant effect in Canada. Relative sea-level change is the change in water level experienced on the solid land surface. It is the combined result of changes to global (absolute) sea level and vertical land motion. Land uplift reduces projected relative sea-level rise at a location, whereas land subsidence increases projected relative sea-level rise. In cases where land-uplift rates are large, relative sea level may be projected to fall, even though global sea level is projected to rise.

The highest projected relative sea-level rise is for parts of the East Coast region (*see* Chapters 2, 4). Sea level is projected to rise elsewhere in the East Coast region, through all of the West Coast region and on the Beaufort Sea coastline of the North Coast region (Figure 5b–d; *see* Chapters 2, 4, 5, 6). In contrast, sea level is projected to fall in Hudson Bay and most of the Canadian Arctic Archipelago of the North Coast region (Figure 5b–d; *see* Chapters 2, 5), where the land is rising rapidly. For the most part, these broad-scale patterns of projected relative sea-level change reflect vertical land motion.

Throughout most of Canada, glacial isostatic adjustment (GIA, also known as postglacial rebound) is the dominant source of vertical land motion (*see* Chapter 2). Large ice sheets covered most of the Canadian land mass during the last ice age and depressed the surface of the Earth, which was accommodated by slow viscous yielding at great depths in the Earth's interior. During and following deglaciation, the depressed land surface began to rise toward its former elevation. In regions at the margins of and outside the former ice sheets, the land rose due to flow in the interior of the Earth during glaciation, and these regions are presently sinking. The Earth's interior responds on a time scale of thousands of years, and the GIA-induced vertical land motion is still occurring today, thousands of years after deglaciation.

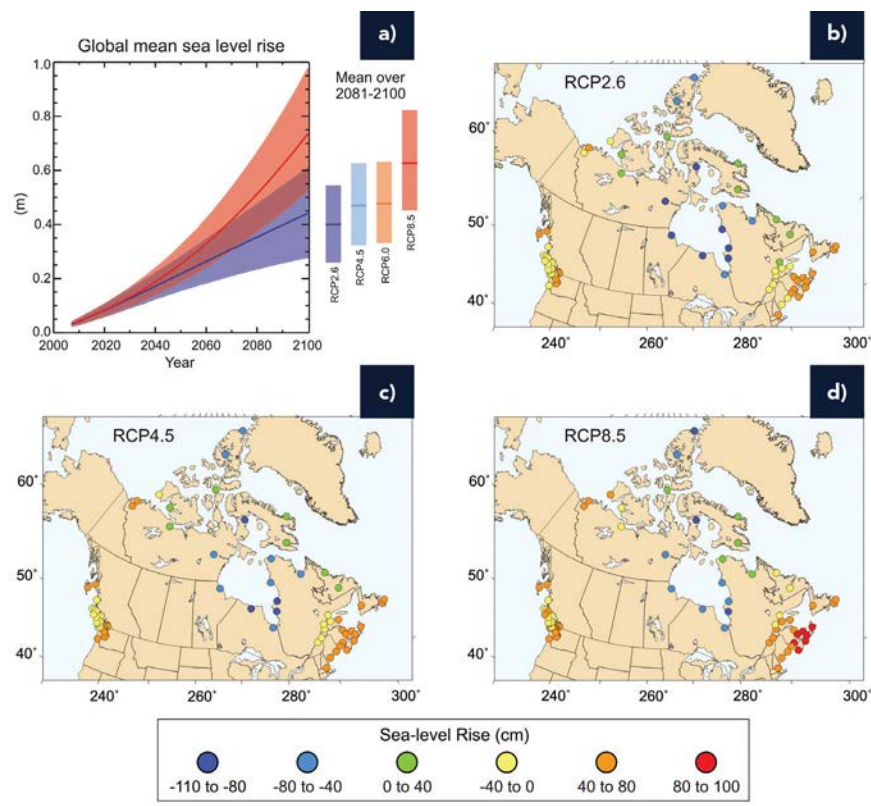

FIGURE 5: a) Projected global sea-level rise through the 21st century for the low-emissions (RCP2.6) and high-emissions (RCP8.5) scenarios (IPCC, 2013, Figure SPM.9). The mean projected global sea-level rise over 2081–2100 (rectangles in panel **a)** includes the projections for intermediate-emissions scenarios RCP4.5 and RCP6.0. Projected relative sea-level rise at 2100 (median values plotted here) are given for localities in Canada and the adjacent mainland United States for the **b)** low-emissions scenario, **c)** intermediate-emissions scenario (RCP4.5), and **d)** high-emissions scenario. Projections are relative to 1986–2005 and are based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Church et al., 2013a, b), modified to incorporate vertical crustal motion measured at Global Positioning System sites (James et al., 2014, 2015). The median projections and their associated 5–95% confidence intervals encompass the likely range of sea-level change, defined as having a probability of 66–100% (IPCC, 2013).

The land is rising in Hudson Bay and much of the Canadian Arctic Archipelago due to GIA. Parts of the East Coast region and the Beaufort Sea coastline of the North Coast region are sinking. Elsewhere, the land is rising but at slower rates. On the deltas of the Fraser and Mackenzie rivers, sediment consolidation is generating local subsidence, which contributes to relative sea-level rise. In the West Coast region, active tectonics arising from the interaction of the Pacific and Juan Fuca plates with the North America plate also contribute to vertical land motion.

Projected reductions in the mass of grounded ice from melting and iceberg discharge add to global mean sea level but reduce projected relative sea-level rise in the West and North Coast regions. The effect is substantial in the northeastern part of the North Coast region, which hosts the glaciers and ice caps of the Canadian Arctic Archipelago and is located near the Greenland Ice Sheet. All of these ice masses are projected to undergo major reductions in mass throughout the century. This will cause the land to rise and contribute to reductions in local sea-level rise. As well, the reduced gravitational attraction of the shrinking ice masses causes the surface of the ocean to fall. At nearly all locations, projected relative sea-level changes are greater for IPCC (2013) scenarios with larger emissions and higher rates of projected global sea-level change. An exception occurs at Alert, Nunavut, where the larger amounts of ice-mass reduction projected by the larger emissions scenarios cause greater crustal uplift and higher rates of projected sea-level fall.

The projections of mean sea level described here are the basis for considering future changes to extreme water events and their associated consequences of flooding and coastal erosion (*see* Chapters 2–6). In the short term (years to a few decades), natural climate variability and dynamics cause fluctuations in sea level that are expected to dominate extreme water events. In particular, in the West Coast region, the El Niño/Southern Oscillation and the Pacific Decadal Oscillation drive cycles of sea-level change of several tens of centimetres over periods of several years (Thomson et al., 2008). Over the longer term, the slow background rise in mean sea level projected for many locations in Canada will cause extreme water-level events to occur more frequently. The effect may be pronounced for locations such as Halifax and Tuktoyaktuk that have high rates of projected relative sea-level rise. Here, extreme water-level events having a present return time of several decades are projected to recur every few years or even more frequently by the end of the century (*see* Chapter 2; Forbes et al., 2009; Lamoureux et al., 2015).

In summary, projected relative sea-level change in Canada varies substantially due to differences in vertical land motion and other factors. In some locations in the East Coast region, projected relative sea-level change exceeds projected global values, but projected relative sea-level change in most localities is less than the global value (James et al., 2014 [Figure 9], 2015). Across large portions of the North Coast region, relative sea level is projected to continue to fall due to land uplift.

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FAQ 7: HOW WILL CLIMATE CHANGE AND SEA-LEVEL RISE AFFECT COASTAL ECOSYSTEMS?

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Coastal environments in Canada encompass a complex array of linked terrestrial, aquatic and marine ecosystems. Throughout much of the country, limited information on trends in health of coastal ecosystems, especially in environments distant from human populations, constrains effective planning for change. Since the arrival of European settlers, land-cover and -use patterns along Canada's southern coasts have changed from largely forested to predominantly agricultural and urbanized. These changes in diversity and ecosystem services can greatly affect the capacity of coastal ecosystems to respond and adapt to any changes.

Climate change in Canada already contributes to change in coastal ecosystems, causing loss of habitats, species migration, shifts in productivity, changes in ecosystem functions and services, and rising sensitivity to nutrients and pollutants. Warming in the environment jeopardizes survival of some wild species unless they can migrate farther north. In some areas of the coast, anticipated changes in the physical environment, driven by sea-level rise or other climate-related phenomena, may occur at a pace that exceeds the capacity of species and ecosystems to adapt. Alternatively in some areas, changes in climate may improve conditions for some species and create opportunities for new or enhanced ecosystem services. Ensuring the sustainability of ecosystems and ecosystem services requires an understanding of the cumulative effects of climate change and increasingly severe weather, along with the relationships among forests, rivers, marine waters and people.

Scientists struggle to predict which species and communities in coastal ecosystems will be most at risk, as well as where and when tipping points (points where rapid catastrophic change is initiated) will be reached. However, a growing body of Canadian and international literature addresses the negative and, in some cases, positive effects of changes in air and water temperature, shifting precipitation patterns, rising sea level and severe weather events on the fauna and flora in coastal areas. The key findings about these effects in Canada include:

- Changes in the productivity of terrestrial ecosystems (e.g., forests and wetlands) will impact the survivability of native species and may improve conditions for invading species. Extended periods of heat and drought will enhance conditions for wildfires. Changes in vegetation, coupled with increases or decreases in seasonal precipitation loads in watersheds, will change the timing of peak riverine flows, and flooding or droughts will affect aquatic ecosystems, altering species and habitats. Increased rates of erosion in streams resulting from higher peak flows, changes in the loading and deposition of sediments, and altered nutrient loads from overland runoff will affect the productivity of nearshore waters, as well as the physical and biological health and functioning of salt marshes.
- In nearshore marine waters, higher sea temperatures will affect predator-prey relationships in the food web by disproportionately favouring some species (e.g., predators or prey) and by changing the timing of food availability. Warmer waters may increase competition for food and habitat among some species, as southern species extend their range farther north and new species are introduced. Strong evidence already indicates a northward shift in snow crab, for instance, pushing them farther from populated coastal communities. Higher water temperatures also increase the frequency and magnitude of disease outbreaks for both aquaculture and wild fish and shellfish populations. Warmer water temperatures associated with lower water flows in rivers may challenge the survival and/or reproduction of cold-water fish species, such as trout and salmon.
- Acidification of sea water from rising concentrations of carbon dioxide adds significant concern. In some areas of all three coasts, waters already considered corrosive to some forms of calcium threaten the integrity of shells and skeletons. Higher acidity reduces the growth and survival of shellfish species such as clams and oysters and will likely reduce catches in important sea fisheries (e.g., oysters, mussels, sea urchins). Ocean acidification may also affect the performance of pink salmon in both fresh-water and nearshore marine waters. Ocean acidity will continue to increase during the 21st century, and it is worth noting that some of the geoengineering solutions that have been proposed to limit increases in temperature will not reduce ocean acidification.
- Rising concentrations of nutrients in coastal waters resulting from agricultural run-off and urbanization (as well as more intense precipitation events) will increasingly stimulate phytoplankton blooms that eventually sink and decompose, depleting the water of oxygen. Such eutrophication can lead to hypoxia (depleted oxygen) in coastal waters, creating dead zones where fish and invertebrates struggle to survive. Progressively worsening hypoxia in the deep waters of the Gulf of St. Lawrence, especially in some regions, drives away many fish, mollusc and crustacean species, including Atlantic cod.

- Rising sea levels in parts of the country and higher storm surges will increase rates of erosion and change patterns of sediment deposition. Warmer sea-surface temperatures will also reduce nearshore ice cover, increasing exposure to winter storm surges and larger waves, accelerating erosion on some shores and changing local topography, water depths and current patterns. Increased exposure and more severe storm events may also promote resuspension of contaminated sediments in shallow coastal waters and harbours.
- Rising sea level and more frequent storms may erode or flood vulnerable salt marshes, dune formations and eelgrass beds, pushing them inland or eliminating them partly or completely. Salt marshes, eelgrass beds, beaches and other ecosystems will be threatened where shoreline topography or engineered structures such as dikes prevent landward migration. For example, Roberts Bank, BC, an ecologically critical area, supports more than 300 species of birds and more than 80 species of fish and shellfish. Dikes built in the early 20th century to stabilize the coastline now prevent intertidal vegetated areas, including coastal marshes, from migrating in response to sea-level rise, thus eliminating critical marsh habitat (Figure 6). Changes in seasonal precipitation will also affect the health of salt marshes, altering nutrient influx and increasing the occurrence of floods and droughts.
- In Canada's North, terrestrial ecosystems will struggle with changes in seasonality, loss of snow and ice, and thawing permafrost. Shorelines will become more unstable, altered by increased erosion, changes in depositional patterns and flooding, all of which will affect local ecosystems and the well-being of human communities dependent on traditional hunting and fishing. Declines in sea ice will reduce birthing habitat, and impair hunting activities for species such as polar bears, seals and walrus. Greater access to Arctic waters will also increase the potential for human activities such as shipping and oil-and-gas production, and the likelihood for pollution, contamination and species introductions associated with these activities. Noting the fragility of these Arctic coastal ecosystems and the distances from emergency-response services, pollution may become widespread and irreversible, with severe consequences for productivity and biodiversity.

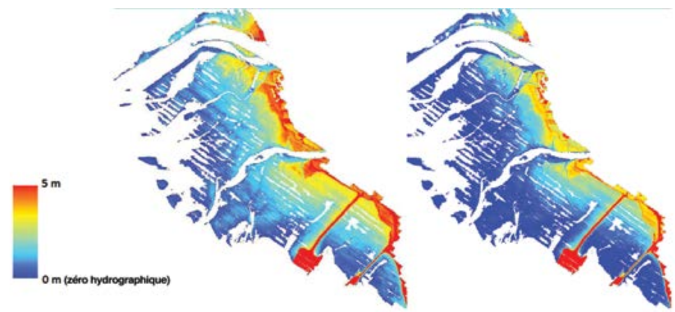

FIGURE 6: Effect of a 0.88 m sea-level rise on Roberts Bank. Cyan and blue tones denote areas below mean water level, with higher vegetated areas depicted in yellow and orange tones (Hill et al., 2013). The result is a significant decrease in the extent of the upper vegetated zones, which include highly brackish marshes. The Port Metro Vancouver and Tsawwassen Ferry terminals, the two linear structures shown in orange, extend onto the Bank.

The current state of scientific knowledge cannot predict with confidence the effects that climate change will bring to Canada's coastal environments because of limited knowledge of how quickly organisms can adapt or exactly how different environmental variables will interact with ocean life. Although some positive change may occur for species that thrive in warmer waters or different species mixes, many changes will have negative impacts relative to oceans past and present. A sea change in oceans is one certainty associated with climate change.

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FAQ 8: HOW WILL SECTORS IN COASTAL REGIONS BE IMPACTED BY CLIMATE CHANGE?

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Industries and businesses in coastal regions are facing a range of challenges and opportunities associated with climate change. In addition to rising temperatures and shifts in precipitation patterns, they are dealing with sea-level change, coastal erosion, flooding and, in northern regions, significant reductions in sea-ice cover and permafrost degradation. These impacts can have major economic consequences: studies estimate that, by 2020, annual economic damages from sea-level rise and storm surges in Canada could be $2.6–5.4 billion, and could reach $48.1 billion by 2080 (Stanton et al., 2010). Examples of impacts on specific sectors are highlighted in this FAQ, focusing on four (fisheries, tourism, energy and transportation) that depend on the coastal environment for their operations. Further details can be found in the regional chapters (*see* Chapters 4–6), as well as in Chapter 3 ('The Coastal Challenge') of this report.

FISHERIES

Canada's marine fisheries are an important component of the economy and culture in coastal regions. The impacts of climate change will be felt primarily through effects on individual species (e.g., health, populations and distribution) and on fishing infrastructure (e.g., ports, wharves, piers), with the degree of impacts, and their importance, differing by region, subregion and type of fishery (e.g., commercial, aquaculture, traditional and recreational).

Most fish species are sensitive to changes in their environment. For example, a study of fish stocks off the coast of eastern North America found that 26 (out of 36) fish species shifted northward in response to increased water temperatures between 1968 and 2007 (Nye et al., 2009). Such shifts have both negative and positive implications for the timing of fishing seasons and the species available for fishing. In the North, for example, there are potential opportunities for new commercial fisheries as a result of a northward shift in the distribution of cod and other species (*see* Chapter 5).

Climate change is also associated with increased ocean acidity and decreased levels of oxygen (hypoxia). Commercially valuable shellfish on the east and west coasts are vulnerable to acidification during many stages of their development. Hypoxia can result in reduced stocks of both finfishes and crustaceans through impacts on fish mortality, development and growth. The shellfish industry is also vulnerable to increases in exotic-species invasions associated with warming waters, and closures from biological contamination. For example, shellfish closures along the coast of Nova Scotia have increased steadily since the 1940s and, in 2000, 60% (277 harvesting sites) of the shellfish areas were closed (CBCL Limited, 2009).

Fisheries are also impacted by the effects of extreme weather events, sea-level rise and erosion on coastal infrastructure. Climate change–related damage to ports, wharves and piers is a key concern identified by Fisheries and Oceans Canada.

TOURISM

Tourism in coastal areas depends heavily on the natural environment and the services it offers (e.g., beach visits, fishing, boating and hiking). Although research on the relationship between climate change and tourism in Canada is limited, it suggests that there will be both positive and negative impacts.

Benefits in the East Coast and West Coast regions tend to be related to longer seasons for tourist visits and summer recreational activities (e.g., golfing and fishing). However, sea-level rise and the impact of extreme weather present risks to tourism infrastructure (e.g., wharves and coastal properties), cultural resources (e.g., Haida Gwaii and L'Anse-aux-Meadows) and beaches (e.g., Prince Edward Island National Park). Warmer waters may also make the beaches less attractive if there are associated increases in algal blooms and decreases in water quality.

In the North, greater opportunities for cruise-ship tourism due to reduced sea ice are expected (*see* 'Transportation' section), with trends indicating that this has already begun (*see* Chapter 5). In the southern Hudson Bay region, however, cruise-ship and other tourism activities may decrease as species that attract visitors, such as polar bears, shift northward (*see* Chapter 5).

ENERGY

In the North, reduced sea ice and a longer navigable season may present opportunities for the oil-and-gas industry with respect to exploration and development. Potential offshore reserves in the western Arctic have been estimated at up to 150 trillion cubic feet of natural gas and more than 15 billion barrels of oil (Government of the Northwest Territories, 2015). Oil companies have indicated interest in developing new offshore oil platforms, such as in the Beaufort Sea (*see* Chapter 5).

In British Columbia, existing and planned energy-related infrastructure along the Pacific coast has been valued in excess of $100 billion (*see* Chapter 6), and recent interest in energy development and shipping has led to growth in some communities on BC's north coast. In these communities, climate change impacts of concern relate to sea-level rise and increased storminess, which can affect coastal export terminals and create hazardous conditions for shipping.

Increased damage to energy-transmission infrastructure is an issue for all regions. In the North, for example, there are concerns regarding the impact of potential increases in freezing-rain events and stronger storms on electrical wires (*see* Chapter 5). Changes in streamflow patterns can affect hydroelectricity production, either positively or negatively (Lemmen et al., 2014).

TRANSPORTATION

Throughout Canada (including in the coastal regions), most transportation infrastructure, including roads, rails, bridges, ports and airports, has not been built to withstand future climate extremes and coastal erosion. For the transportation sector, potential impacts include disruptions to ferry and airport services, road closures and costly damage to infrastructure (Figure 7). There are also potential opportunities for the sector, mostly for shipping, associated with reduced sea ice and deeper water in harbours.

FIGURE 7: Damage to the highway and bridge near Port Rexton, NL due to Hurricane Igor. *Photo courtesy of Fire and Emergency Services, Newfoundland and Labrador.*

Reliable transportation networks are required for trade, economic competitiveness and resilient and safe communities. In the East Coast region, large volumes of goods travel by rail and road between the provinces of New Brunswick and Nova Scotia through the low-lying Chignecto Isthmus. If this route were to be blocked, it would stall $50 million in trade per day (*see* Chapter 4). Flooding of rail lines located on floodplains in British Columbia can result in a temporary loss of access to ports (*see* Chapter 6), and rural coastal communities can become cut off when highways are flooded. Five airports in British Columbia are exposed to increased risk of flooding as a result of sea-level rise and storm surges due to their low elevations (<5 m above sea level; *see* Chapter 6).

Ferry services are an important component of the transportation system in both the East and West Coast regions. Disruptions to ferry services can isolate communities and reduce access to services. Ferry services can be disrupted due to extreme-weather delays and cancellations, as well as damage from storms (to the wharves or roads that access the ferry terminals). Such disruptions are a concern for many small communities on Vancouver Island and several areas in the East Coast region.

With reduced sea ice, increased marine traffic in the North is expected and northern ports may become more viable (*see* Chapter 5). This presents opportunities for cruise-boat tourism (with potential employment and income-generating benefits), cargo shipping (e.g., for resource activities, community supply and moving resources south) and development of natural-resource industries, such as mining. The northern sea routes also provide a shorter trip between Europe and Asia, with significant potential cost savings for the shipping industry. However, there are associated risks (e.g., from ice damage and other marine hazards) and the North Coast region has limited sea charts and search-and-rescue capacity.

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FAQ 9: WHAT IS BEING DONE TO ADAPT TO CLIMATE CHANGE IN CANADA'S COASTAL REGIONS?

Author: Fiona J. Warren *(Natural Resources Canada)*

As is evident throughout the regional chapters of this report, adaptation is currently occurring in all of Canada's coastal regions. Types of adaptation include plans and strategies, institutional changes (such as updating policies, legislation and regulations) and on-the-ground implementation of measures to reduce vulnerability (e.g., beach nourishment and wetland restoration). This FAQ highlights some of the activities being carried out in each coastal region of Canada to reduce current and future vulnerability to climate change. It provides an overview and examples; further information on the specific adaptation measures can be found in the regional chapters of the report (*see* Chapters 4–6), while discussion of adaptation in general is presented in Chapter 3 ('The Coastal Challenge').

EAST COAST REGION (CHAPTER 4)

An inventory of vulnerability assessments conducted since the late 1990s in the East Coast region counted 226 individual studies, most of which focused on coastal erosion, flooding and ecosystem restoration (*see* Chapter 4). This demonstrates the considerable work being done to map and understand vulnerabilities to climate change, and to raise awareness of the risks presented by sea-level rise and storm damage.

Hard-protection measures, such as rip-rap, seawalls and groynes, are among the most common approaches to reduce risks from coastal erosion in the region. Although the use of such hard-protection measures has been increasing, they can serve to actually increase rather than reduce vulnerability, especially for adjacent lands, if they are not designed and placed properly or adequately maintained. Risks include accelerated erosion, loss of beaches and coastal squeeze of habitats and ecosystems. Soft-protection measures (such as the use of clean sand from dredging to replenish beaches) offer alternatives to hard approaches.

Accommodation approaches have been used by some municipalities to reduce risks from flooding and other hazards. For example, the Municipal Planning Strategy and Land Use By-Law for the downtown Halifax waterfront area requires any ground-floor elevation development to be a minimum 2.5 m above the ordinary high water mark. Avoidance and retreat strategies have also been used in the region to reduce vulnerability to sea-level rise. In Prince Edward Island National Park, for instance, the decision was made to abandon some campgrounds and relocate the main coastal road landward to deal with coastal erosion.

NORTH COAST REGION (CHAPTER 5)

The North has been warming much faster than the rest of Canada, with widespread and severe impacts already being observed. As a result, there has been considerable attention on climate change adaptation in the region, with many adaptation plans and initiatives in place. All levels of government are active on adaptation. For example, Indigenous and Northern Affairs Canada has a program to reduce vulnerability of community infrastructure to climate change; the Nunavut and Yukon territorial governments both have formal adaptation strategies in place; and several communities have developed adaptation plans that focus on increasing the resiliency of the built environment.

Much of the adaptation work in the region has focused on dealing with changes in permafrost and sea ice. For example, new standards that factor in climate change have been developed to inform building on permafrost. A study in three coastal settlements in the Northwest Territories concluded that 'informed adaptation' could reduce the cost of impacts from permafrost degradation by one-third relative to the cost when no action is taken (*see* Chapter 5). To adapt to changing patterns of sea ice, new technologies are being used to share information on sea-ice thickness and other surface features to reduce safety risks (associated with travel on sea ice, for example). For instance, SmartICE (Sea-Ice Monitoring And Real-Time Information for Coastal Environments) is a sea-ice information gathering and dissemination system being piloted with communities in Nunatsiavut and Nunavut.

Access to information is a barrier to adaptation that is being addressed through many initiatives, including an online portal developed under the Arctic Council. This adaptation information portal was developed to facilitate knowledge exchange on climate change adaptation in the circumpolar north and serve as an information hub for those making decisions on the issues (e.g., communities, researchers, public and private sectors). Access to the portal is through the Arctic Adaptation Exchange website (http://www.arcticadaptationexchange.com).

WEST COAST REGION (CHAPTER 6)

In the West Coast region, the risks associated with sea-level rise and coastal flooding have received considerable attention by the provincial and local governments. Several local governments have begun planning for sea-level rise. Examples of recent adaptation projects include a cost assessment of upgrading Metro Vancouver's dike system; a risk assessment of sea-level rise in the Victoria Capital Regional District; and the placement of boulders below the low-tide level off the West Vancouver shore to reduce impacts from storm surges. Important economic hubs (e.g., Vancouver International Airport and the Port of Metro Vancouver) are also working with neighbouring municipalities on adaptation.

At the provincial level, British Columbia has updated guidelines for development in flood-risk areas, and municipalities are beginning to incorporate sea-level rise into Flood Construction Levels. In 2013, Vancouver became the first city in British Columbia to adopt formal consideration of 1 m of sea-level rise in development and planning requirements, and the city is currently evaluating a number of other development-planning options. Guidelines are available to support engineered approaches to adaptation (e.g., coastal protection structures, such as dikes), and work on promising nontraditional protection approaches, such as wave attenuation, is underway in the region.

FAQ 10: WHO IS RESPONSIBLE FOR ADAPTATION IN COASTAL REGIONS?

Author: Patricia Manuel *(Dalhousie University)*

Adaptation to climate change in coastal regions is a shared responsibility that involves actions by all levels of government, community organizations, the private sector, academia and individuals. This FAQ illustrates the roles and responsibilities of the different groups in preparing coastal areas for climate change broadly, rather than addressing specific climate impacts.

In coastal regions, governments use a range of tools and mechanisms to protect public health and safety, guide and regulate the use of land and coastal waters, and protect environmental quality. Governments also build knowledge about climate change and the impacts on coastal environments by conducting and supporting research, and providing information and advice. Governments can set good examples through their own responses to climate change: they can demonstrate best practices of where and how to build, develop or operate in coastal locations to minimize impacts on coastal systems and to protect public investment.

The federal government, through a wide range of departments, has multiple roles at the national scale, including building and transferring knowledge; providing frameworks for co-ordinated action; implementing and supporting adaptation, including actions by Indigenous communities; and regulating the use of, and access to, coastal waters and the seabed, including the intertidal zone (the area between high and low tide). The federal government also sets the national rules, regulations and requirements that protect public health and safety, and establishes codes and standards for design and construction of infrastructure. Conditions at the coast are challenging, can be extreme (e.g., storm surges, hurricanes, ice jamming and rafting) and are changing (e.g., accelerating erosion, loss of sea ice and thawing permafrost). Revising codes and standards as necessary is part of adapting to coastal environmental change.

Provincial and territorial governments also build knowledge about climate change and adaptation specific to the coastal systems, coastal uses and development patterns in their jurisdiction. Provincial governments regulate land, air and fresh-water environmental quality, and have a role in setting infrastructure design and siting codes and standards. With the federal government, they share responsibility for regulation of the intertidal coastal environment and for emergency preparedness (along with municipal governments). They also manage and regulate land and resource development, set policies and make laws about where and how to develop land, and can protect land and special environments from development (e.g., coastal wetlands and beaches). Through land-use policy and regulation, in particular, they can establish the type and intensity of land use in coastal regions across their jurisdiction and can move development back from the coast in order to protect people and investment from coastal hazards, and coastal environments from development impacts. Both strategies—protecting people and protecting environments—are key objectives of adaptation.

Local governments (the governments of cities, towns, villages, amalgamated regions and rural districts) are often best positioned to influence coastal land use and put adaptation measures in place. Provincial governments typically delegate land-use planning and regulation to local governments through enabling legislation. Local governments can take the broader provincial policies and frameworks, where they exist, and refine them for the local context; or they can create their own planning and development rules (maintaining at least the minimum provincial requirements). In this way, local governments can control the details of land use and development in coastal regions in their jurisdiction through planning and regulation, and through site-specific planning and design. Local governments, however, have varying levels of capacity (e.g., human and financial resources) to address the issue, and not all local governments choose to practice land-use planning and land-development control. Where there are no local-level planning and controls, provincial policies and regulations still apply.

Private industry and business owners and operators, and private land owners are responsible for adhering to the requirements, standards, laws and regulations that control development and activity in the coastal regions. They must also ensure the resilience of their buildings and structures through proper design and maintenance, and they should have the appropriate safeguards in place (e.g., insurance, flood protection, emergency plans) to deal with extreme weather events. It is important to understand that the rules that protect the private sector (and their investment) from coastal hazards also serve to protect the environment from their coastal-use activities. Where the rules are not yet developed, or have not been updated to reflect changing environmental conditions, paying attention to what is happening at the coast and being informed about the best approaches for development will help private operators and property owners to make sustainable decisions over the long term.

Community, nongovernmental and professional organizations, and educational institutions also have roles in adapting in coastal regions. Community and nongovernmental organizations represent the special interests of citizens. In the context of adaptation for coastal regions, these organizations help build awareness about climate change and its impacts, and advocate for adaptation through, for example, coastal environmental protection and improved land-planning and land-development practices. Professional associations establish codes of practice and provide guidance to their members on operating in the coastal region. For example, engineering, architecture and planning are professions with roles for developing and/or promoting standards for best practices of building, design and development in coastal regions. The real-estate and insurance professions complement this effort by encouraging people (through disclosure of information and through insurance availability and rates) to make good choices about where to buy coastal property and where to build when they do buy coastal land. Educational institutions—universities and colleges, in particular—have specific capacity to build knowledge about climate change and the coast, and to transfer that knowledge broadly to ensure the highest standard for adaptation in coastal regions and help educate and inform the public about coasts and climate change.

In coastal regions, the complexity of the environment, the diversity of interests and the wide range of regulations and controls mean that a co-ordinated, multistakeholder approach to adaptation is required. A common understanding of the challenges, and common goals, supported by strong information, frameworks, standards and rules, will help ensure that the different groups can work together effectively toward adapting to climate change in coastal regions.

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FAQ 11: HOW DO THE COSTS OF CLIMATE CHANGE IMPACTS COMPARE TO THE COSTS OF ADAPTATION?

Authors: Jimena Eyzaguirre *(ESSA Technologies Ltd.)* and Gerett Rusnak *(Natural Resources Canada)*

Knowledge of the social, economic and environmental costs of climate change impacts and of adaptation measures in coastal marine areas of Canada is limited. A few studies, at different scales, have been undertaken in recent years. These studies provide a partial picture, generally capturing only a narrow range of the full costs. They rarely differentiate the added cost that future climate change presents to coastal systems already subject to risks in today's climate. Nevertheless, these studies together suggest that adaptation measures can generate benefits exceeding their costs by reducing damages from climate-related coastal impacts. However, for some locations and for some measures, adaptation costs can outweigh the benefits. The studies also indicate that the relative costs and benefits of different types of adaptation measures—such as nature-based and engineered protection, flood-proofing or relocation—can vary considerably between locations.

A national-scale analysis by the National Round Table on the Environment and the Economy (NRTEE) estimated the cost of flooding damages to homes from sea-level rise and storm surge along Canada's coastlines (NRTEE, 2011), under a variety of future climate and economic- and population-growth scenarios, at $4–17 billion per year (in 2008 dollars, undiscounted) by the middle of the century. This represents 0.2–0.3% of projected annual GDP levels, and climate change is responsible for 20–49% of these damages. The same study found that more than 90% of coastal-flooding damage nationally would occur in British Columbia, where the concentration of people and assets vulnerable to sea-level rise and storm surge is greater than in other parts of Canada. A recent national study, which incorporated a wider range of costs but employed the lower bound of future economic- and population-growth scenarios from the NRTEE study,[2] estimated the combined cost of sea-level rise and storm surge in coastal provinces and territories of Canada during the period 2009–2054 at a cumulative total of $53.7–108.7 billion (expressed in terms of present-value GDP, given in 2008 dollars, discounted at 4%), depending on the extent of future climate change (Withey et al., 2015).[3] At the local level, a few community-scale studies have been conducted to estimate the property or land values at risk from sea-level rise, storm surges and/or erosion made worse by climate change. Estimated costs vary widely between cases but can be in the millions or even billions of dollars for some communities (McCulloch et al., 2002; BGC Engineering Inc., 2009; Hallegatte et al., 2013; AECOM, 2015). Aside from differences in scope, assumptions and methods, variations relate to the extent of vulnerability to climate change (e.g., number and value of assets and services exposed to climate-related hazards).

COMPARING RESULTS BETWEEN STUDIES

Comparing results of studies estimating the costs of climate change is difficult due to variations in scope, assumptions and methods. Variations in scope include differences in the type and number of climate-related hazards examined (e.g., coastal flooding, coastal erosion, storm surges), as well as differences in the extent to which cost estimates reflect the relevant, direct physical impacts (e.g., damage to private property and public infrastructure, habitat loss) and indirect impacts (e.g., disruption of transportation and business, lost economic productivity, changes in wages and prices, mental health effects). Different assumptions about the future (rate and magnitude of changes in climate conditions, and rates of population and economic growth) and about the extent of adaptation action already underway also contribute to variations in estimates. Methods vary considerably, ranging from basic direct-costing techniques to economy-wide modelling.

Studies that compare the costs of coastal impacts related to climate change with and without adaptation suggest that planned adaptation can reduce costs substantially. Analysis presented by NRTEE (2011) found that banning new homes in areas projected to be at risk of flooding by 2100, and relocating homes from at-risk areas after flooding occurs, result in a 96–97% reduction in aggregate cumulative damages. Another study found that for land that is highly sensitive to sea-level rise, investing in shoreline protection in the amount necessary to mitigate against any impacts from current and future climate-induced sea-level rise and storm surge is economically beneficial for almost all coastal provinces (Withey et al., 2015).

At a local level, cost-benefit analyses (CBAs) of adaptation options to reduce erosion and flooding in coastal communities are starting to be undertaken. One such analysis, for the Municipality of Sept–Îles (*see* Chapter 4; Tecsult Inc., 2008; Ecoressources, 2013), determined that the preferred adaptation strategy from a cost-benefit perspective would yield net benefits to the community with a net present value estimated at more than $850 000 (2008 dollars) during the 25-year period assessed. This adaptation strategy included a combination of proactive relocation and replenishment of sand on shorelines to slow erosion (a form of 'beach nourishment'). By adopting this strategy, the municipality could avoid losses of $15.8 million (2008 dollars) in net-present-value terms that would have occurred in the base case (do nothing until relocation is required).

Studies evaluating adaptation options also shed light on strategies that may be most beneficial or least costly for small communities and localized sites. 'Holding the line' with hard-engineering structures makes the least economic sense in some local-level CBA studies, especially when social and ecological values are considered. The CBA for the Municipality of Sept–Îles, for example, showed that the most economically beneficial adaptation strategy involves beach nourishment in six of thirteen coastal sites assessed, and proactive relocation in another six of these sites. In contrast, the two options that focused on hard-engineering solutions (e.g., barriers and breakwaters along shorelines) were shown to be more costly than the base case for all sites assessed.

Early results from a CBA for the touristic waterfront of the historic village of Percé, QC show that all adaptation options assessed would avoid climate change costs and offer an overall benefit in consideration of economic, social and environmental benefits and costs.[4] The most beneficial option is beach replenishment with large pebbles, whereas hard engineering structures are less beneficial.

A British Columbia study profiling three local-level coastal sites assessed 'soft armouring' (e.g., beach nourishment and the addition of nearshore rock features) to 'hard armouring' (e.g., seawall elevation and sea-dike construction) alternatives

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2 Withey et al. (2015) employed estimates of the direct-damage costs to homes, agricultural land and forest land in Canada's coastal areas from sea-level rise and storm surge found in Stanton et al. (2010) to model the indirect costs of these damages due to changes in prices and wages associated with the loss of land and capital, across the economies of six coastal provinces (the Atlantic provinces, Quebec and British Columbia) and the three territories using economy-wide models ('computable general equilibrium' models). The study excluded impacts on nonmarket values (such as ecosystem values and recreational activities); the cost of damage to public infrastructure (e.g., ports, roads and railways) and commercial property (e.g., factories, stores and marinas); and losses due to business interruption.

3 The lower end of this range corresponds to the Intergovernmental Panel on Climate Change's (IPCC) 'Rapid Stabilization' climate scenario, and the higher end of the range corresponds to the IPCC's 'Business as Usual' climate scenario (IPCC, 2000).

4 This work is part of a pair of regional economic studies led by Ouranos and the University of Prince Edward Island, through which CBA case studies are being conducted in eleven coastal locations in Quebec and the Atlantic Provinces. Further information is available at Ouranos (2014).

with respect to ecological, economic and adaptation-effectiveness criteria (Lamont et al., 2014). The study found that, for soft- and hard-armouring options offering the same level of flood protection in a scenario of climate change–related sea-level rise, soft armouring provided 30–70% greater cost savings than the hard-armouring alternatives.

The presence of high-value properties, major infrastructure, amenities and/or large populations in areas exposed to coastal impacts can strengthen the case for hard-protection options (*see* Chapter 6; McCulloch et al., 2002; Withey et al., 2015). The estimated adaptation cost of upgrading the 250 km of diked shorelines and low-lying areas of Metro Vancouver to protect current populations and high-value assets from a 1 m rise in sea level and a once in 500 years flooding event is $9.47 billion (2012 dollars; Delcan Corporation, 2012). For comparison, an estimated $33 billion of assets are currently exposed to a once in 100 years flood in Vancouver (Hallegatte et al., 2013). Research to estimate the potential costs avoided or reduced through enhanced flood protection in British Columbia's Lower Mainland is underway, but previous analysis suggests the avoided costs could be substantial. For example, the City of Chilliwack's 2009 flood-risk assessment found that damage and loss from a single dike-breach event could exceed $1 billion (BGC Engineering Inc., 2009).

Although basic cost-benefit analysis can be a useful tool to help inform adaptation decision making, it is important to recognize that the best adaptation option may not be the one that appears so from a simple comparison of costs and benefits. There may be added value in adaptation options that are more flexible and reversible, given uncertainties related to the magnitude and timing of damages and the effectiveness of adaptation options. Economic analysis that incorporates the value of flexibility can help inform strategies to manage coastal risks adaptively in light of uncertainty (Gersonius et al., 2012).[5] Moreover, the distribution of costs and benefits of adaptation among groups in society can be uneven (e.g., all tax payers may contribute to shoreline protection but only a small group of property owners may benefit). By disaggregating results geographically and/or by social groups, economic analysis can help decision makers address questions about the fairness of adaptation options (e.g., Boyd et al., 2012).

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5 This includes economic analysis in a risk-management framework that provides guidance on balancing adaptation timeframe and cost considerations, and approaches such as 'real options' that can test alternative investment paths over time (Gersonius et al., 2012; Lin et al., 2014).

FAQ 12: WHERE CAN I FIND ADDITIONAL RESOURCES ON ADAPTING TO CLIMATE CHANGE IN COASTAL REGIONS?

Author: Mary-Ann Wilson *(Natural Resources Canada)*

There are many resources and tools available to aid in the planning process for adaptation to climate change. These can help with all stages of the adaptation process, including getting up to speed on the issue, learning how climate will change in your region, assessing climate sensitivities, building capacity to adapt, implementing adaptation and sharing your successes (and lessons learned) with others. This FAQ highlights some key resources to help Canadian stakeholders get started on adaptation.

INVENTORIES OF INFORMATION

NATIONAL

Adaptation Library (http://www.icleicanada.org/resources/item/164-adaptationlibrary):
This inventory of resources was developed by ICLEI Canada and provides a database of reports and tools to help you assess vulnerability to climate change and move forward on implementing adaptation options. Many of the resources are community focused.

Natural Resources Canada: Impacts and Adaptation (www.nrcan.gc.ca/environment/impacts-adaptation/10761):
This website provides links to adaptation resources that have been developed by, or with support from, the Climate Change Impacts and Adaptation Division (CCIAD) at Natural Resources Canada. Some of these resources include assessment reports, case studies, project reports, tools and guides.

REGIONAL

Atlantic Climate Adaptation Solutions Association (ACASA; www.atlanticadaptation.ca):
This site provides access to tools and resources that can help decision makers address coastal erosion, coastal and inland flooding, infrastructure design and groundwater management.

Coastal and Ocean Information Network Atlantic (COINAtlantic; http://coinatlantic.ca/):
This website is a hub for coastal and ocean information in Atlantic Canada. Through the site, you can access data, information and applications (including geospatial tools) relevant to Atlantic Canada.

Ouranos (http://adaptation.ouranos.ca/en/):
This site provides a searchable database you can use to access resources and information on climate change adaptation in Quebec.

Fraser Basin Council (http://www.retooling.ca/):
On this website, you can find links to project profiles, reports, guides, case studies, presentations and tools relevant to work on climate change adaptation in British Columbia.

Adaptation to Climate Change in British Columbia (http://www2.gov.bc.ca/gov/content/environment/climate-change/policy-legislation-programs/adaptation):
This provincial website provides links to summary reports on climate change impacts, indicators and the province's adaptation strategy.

Pan-Territorial Adaptation Partnership (http://www.northernadaptation.ca/):
This partnership is a collaboration between the Governments of Nunavut, the Northwest Territories and Yukon. Their website provides links to resources for addressing climate change in the North and updates on relevant activities.

Nunavut Climate Change Centre (http://climatechangenunavut.ca/):
This website is designed to help Nunavummiut learn about Arctic climate change, and how they can engage and adapt. It includes an overview of climate change in the Canadian Arctic and access to the latest research and information on traditional and local knowledge of climate change.

UNDERSTANDING AND USING CLIMATE SCENARIOS

A Guidebook on Climate Scenarios (http://www.ouranos.ca/media/publication/352_GuideCharron_ENG.pdf):
This guidebook is a tool for decision makers to familiarize themselves with future climate information. It is aimed at everyone involved in climate change adaptation, from those in the early stages of climate change awareness to those implementing adaptation measures.

Canadian Climate Data and Scenarios (http://ccds-dscc.ec.gc.ca/?page=main):
This Environment Canada website provides maps, plots and tables of projected temperature and precipitation changes for Canada. Information is available for different time ranges, and summary statistics are available for the provinces and territories.

Pacific Climate Impacts Consortium (PCIC; https://pacificclimate.org/):
Located at the University of Victoria, this regional climate service centre provides practical information on the physical impacts of climate variability and change in the Pacific and Yukon regions of Canada.

ADAPTING TO SEA-LEVEL RISE

Sea Level Rise Adaptation Primer (http://www2.gov.bc.ca/assets/gov/environment/climate-change/policy-legislation-and-responses/adaptation/sea-level-rise/slr-primer.pdf):
This resource for local governments and land-management authorities provides information on a range of tools that can be used as part of a sea-level–rise adaptation strategy.

ONLINE COMMUNITIES

Climate Change Adaptation Community of Practice (CCACoP; https://ccadaptation.ca/en/landing):
This interactive online community serves as a place where researchers, experts, policy makers and practitioners from across Canada can come together to ask questions, generate ideas, share knowledge and communicate with others working in the field of climate change adaptation.