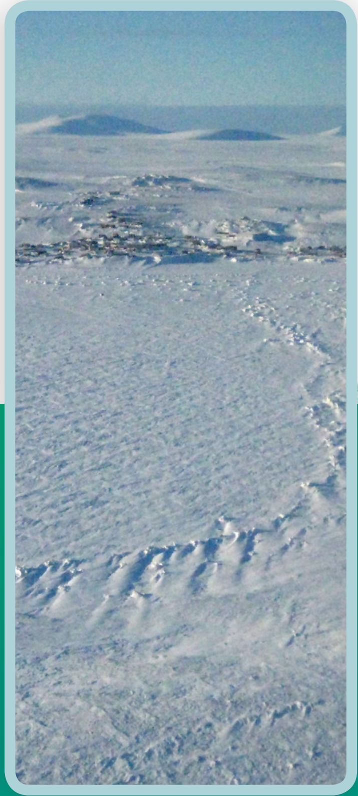
State of the Arctic Coast 2010

Scientific Review and Outlook



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Executive Summary

The coast is a key interface in the Arctic environment. It is a locus of human activity, a rich band of biodiversity, critical habitat, and high productivity, and among the most dynamic components of the circumpolar landscape. The Arctic coastal interface is a sensitive and important zone of interaction between land and sea, a region that provides essential ecosystem services and supports indigenous human lifestyles; a zone of expanding infrastructure investment and growing security concerns; and an area in which climate warming is expected to trigger landscape instability, rapid responses to change, and increased hazard exposure. A high proportion of Arctic residents live on the coast and many derive their livelihood from marine resources.

This report addresses a recognized need for a more detailed assessment of the impacts of environmental and social change in the Arctic coastal zone. The Arctic Climate Impact Assessment (ACIA, 2005) provided an overall synthesis of observed and anticipated impacts on social and ecological systems in the Arctic, but did not attempt a focused treatment of the coastal zone. Five years on, the circumpolar Arctic coast is arguably one of the most critical zones in terms of the rapidity and the severity of environmental change and the implications for human communities dependent on coastal resources.

Rapid environmental, social, economic, political and institutional changes are defining characteristics of the past decade in the Arctic basin. In the physical environment, the prospect of a seasonally ice-free Arctic Ocean appears more likely and imminent, as previous records for annual minimum sea ice extent have been broken successively in recent years and the trajectory of ice loss is more rapid than the most extreme model projections in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a). The past decade has also been the warmest on record for global surface air temperature and some Arctic regions have grown warmer at an even faster pace than the global mean, validating projections in earlier assessment reports that foresaw earlier and more severe climate change at high latitudes. In the face of unprecedented and jarring changes in the local environment on which traditional livelihoods and cultures depend, Arctic coastal communities are coping with rapid population growth, technological change, economic transformation, confounding social and health challenges and, in much of the Arctic, rapid political and institutional change.

It is evident that the coast is a critical component of the Arctic system requiring explicit attention. As a focus of human activity with attendant hazards, the circumpolar Arctic coast is clearly a priority for monitoring and change detection to support proactive adaptation and sustainable development.

This report is organized in four parts. Chapter 1 provides an introduction. Chapter 2 assesses the state of the Arctic coast under three broad disciplinary themes – physical, ecological, and human systems. Chapter 3 considers the need for and progress toward integrative approaches to monitoring, understanding, and managing change in Arctic coastal systems. Chapter 4 provides a synthesis and identifies data gaps and research priorities over the coming decade.

Key Findings

Physical State of the Circum-Arctic Coast

- The evolution of Arctic coasts over the coming decades will be strongly influenced by changes in the natural environment caused by the effects of climate warming.
- Surface air temperatures have reached record levels over the past decade. Record warm air temperatures in 2010 extended across Greenland and the Canadian Arctic.
- The past decade has seen successive new record minima in Arctic sea-ice extent and 2010 had the third smallest summer minimum extent of the past 30 years. At the same time, the mean ice thickness has been decreasing, driven primarily by export of perennial ice.
- Less extensive sea ice creates more open water, allowing stronger wave generation by winds. This, combined with warmer sea-surface and ground temperatures, has the potential to increase erosion along Arctic coasts. Record warm sea-surface temperatures in 2007 contributed to rapid coastal erosion in Alaska.
- Sea-level rise in the Arctic coastal zone is very responsive to freshening and warming of the coastal ocean (leading to increased sea level at the coast) and is highly susceptible to changing large-scale air pressure patterns.
- Relative sea-level change depends on vertical land motion (uplift or subsidence), the patterns of which are predominantly a legacy of former glaciation. The rate of uplift in some regions exceeds the rate of sea-level rise, leading to falling relative sea level.
- Sea-level rise in much of the Arctic is moderated by gravitational effects (fingerprinting) associated with ice loss from regional glaciers and ice caps and especially from the Greenland Ice Sheet.
- Arctic ice shelves will continue the recent rapid pace of collapse due to climate warming and the decrease in multi-year sea ice.
- Carbon entering the coastal system from terrestrial sources appears to be more labile than in the past. Because this organic matter is a direct source of energy for secondary production and a potentially important indirect source once remineralized, the higher lability may have far-reaching, yet unknown consequences for Arctic coastal marine productivity.
- Despite increasing annual freshwater discharge, some Arctic deltas are being progressively flooded, with most of the Mackenzie Delta front (the second largest Arctic delta) retreating at 1-10 m/year or more.
- Storm-surge inundation of low coastal areas and deltas affects coastal communities and can have profound impacts on delta ecology through salinization of freshwater environments. Early-season surges can disrupt waterfowl breeding and winter surges may flood or break up winter ice roads, a critical form of transportation for many northern activities.
- Decadal-scale mean rates of coastal retreat are typically in the 1-2 m/year range, but vary up to 10-30 m/year in some locations. The highest mean erosion rates are in the Beaufort Sea, the East Siberian Sea, and the Laptev Sea.
- Recent results on erosion of ice-rich bluffs point to the importance of interaction between high sea-surface temperatures, which drive thermal

abrasion and undercutting, and the timing of ice break-up and freeze-up in combination with storm dynamics.
- The distribution and stability of gas hydrates in the Arctic coastal zone is poorly documented, but there is concern that climate change and other effects such as coastal erosion may destabilize some hydrate deposits.
- Rocky shorelines comprise 35% of the Arctic coastline and most are effectively stable on timescales relevant to adaptation planning and management.

Ecological State of the Circum-Arctic Coast

- Arctic coastal habitats are the prime lifeline for Arctic communities and provide a wide range of ecosystem services.
- They support very large populations of fish, mammals and birds that are harvested by Arctic and non-Arctic communities.
- The Arctic coastal zone provides habitat to an estimated 500 million seabirds alone.
- Arctic coastal habitats are highly vulnerable to changing environment conditions, including climate change and growing human activities such as oil and gas exploration and development.
- Arctic river deltas are biological hotspots on the circumpolar Arctic coast. They have high biodiversity and are extremely productive in relation to adjacent landscapes. The high biodiversity remains poorly understood, but may be related to the complex natural patterns of water level fluctuation that occur in these vast lake-rich systems.
- Arctic ice shelf microbial mat cryo-ecosystems are severely threatened by ice shelf collapse, with some of the richest examples already lost.

Social, Economic and Institutional State of the Circum-Arctic Coast

- Social, cultural, health and demographic conditions, economic systems, industrial structure and the relative importance of subsistence activities vary across the spectrum of communities on the circumpolar Arctic coast.
- The Arctic economy as a whole is dominated by four major characteristics: the continuing importance of traditional subsistence activities and local living resources in most regions, the lack of manufacturing industries, the local and regional impacts of large-scale natural resource extraction or exploitation projects, and the major importance of the public sector for service provision and transfer payments from the south.
- Disposable household income (DHI) is largest in the Arctic regions where large-scale resource extraction occurs. These are, however, also the regions where the discrepancy is largest between DHI and gross regional product, demonstrating that actors outside of the region reap a large portion of the benefits from the economic activities there.
- Even though the Arctic has a relatively large proportion of people living in a near-traditional manner, close to nature and utilizing the resources there for food and subsistence, it is also well linked to the global economy, in particular as a large supplier of natural resources. The same processes we see in the advanced industrialized regions, of a knowledge-based economy with a focus

on innovations, are also taking place in the Arctic.

- Although climate change and other processes affecting natural resources and environmental conditions impose large impacts on quality of life and economic activity for communities on the Arctic coast, other factors and processes will often be more important, especially in the short run. Where communities are already stressed, even small changes in the availability or quality of natural resources may be critical.
- Recently established integrated marine regional plans, as for example in the Barents Sea, are milestones in the implementation of ecosystem-based management. Laudable as these efforts are, however, it is clear that more work needs to be done, particularly on societal impacts of industrial activities and on the socio-economic impacts of ecosystem changes in the Arctic coastal zone. In each case, a multifactor perspective is essential.
- The Arctic Human Development Report found that, for people in the Arctic, fate control, cultural integrity and contact with nature are central for well-being and should be included in future statistical data collection efforts. The Arctic Social Indicators project has proposed a suite of indicators for these factors, in addition to aspects considered in the United Nations Human Development Index, and is working toward the implementation of these indicators in the Arctic.
- Statistical data specific to coastal regions are difficult to obtain, at least for circumpolar comparisons. Economic, social and demographic connections between coastal and inland areas hinder a clear delineation of what should be included, or excluded, in a coastal-based study such as this.
- At a time of incipient rapid changes in the Arctic coastal zone resulting from climate change and other factors, there are growing health challenges in Arctic communities. Monitoring of the human health situation across the Arctic is critically important, especially for indigenous people in rural areas and remote communities.

Integrated Approaches to Coastal Change in the Arctic

- Arctic coasts may be usefully viewed as complex social-ecological or social-biophysical systems. A social-ecological system is an ecological system intricately linked with and affected by one or more social systems and vice versa.
- The health of Arctic coastal and marine ecosystems is increasingly under pressure, putting at risk ecosystem goods and services that support coastal communities.
- There are major feedback loops in the Arctic system associated with rapid changes in the regional climate. For this reason, the impacts of climate change in the Arctic may extend to a global scale.
- There are two general approaches to more integrated understanding considered in this report:
    - Indigenous communities in general embrace holistic perspectives on the environment and culture.
    - The traditional scientific approach can be applied within a system science framework, with the application of integrated assessments to analyze the interactions in social-ecological systems, as outlined in the risk-based management approach.

- The holistic perspective of indigenous culture suggests that efforts to understand, manage, and respond to change in Arctic coastal systems may benefit from the integration and complementarity of both approaches. Recognizing the value of traditional ecological knowledge may contribute to enhanced resilience and adaptive capacity in coastal communities.

Monitoring, Detecting and Modelling Coastal Change

- Reduction of negative impacts through adaptation to climate change requires new approaches in monitoring strategies to detect and track changes in the Arctic coastal environment. Understanding and prognosis of change is an essential component of resilience in Arctic coastal communities.
- Biophysical and human monitoring both clearly demonstrate that the Arctic environment is changing rapidly – sustained observation and monitoring is essential to document change and validate projections.
- Field-based monitoring in the Arctic coastal zone is challenged by remoteness, accessibility, communications, and instrument performance in extreme cold, but new survey technologies, instrumentation, and higher resolution of remotely sensed data are revolutionizing monitoring capabilities.
- These new techniques, decreasing costs, and higher resolution are enabling better spatial and temporal coverage of coastal change.
- Models represent key tools for understanding current changes and projecting future changes and associated impacts on Arctic coastal ecosystems and human communities.
- Models provide a means of interpolating between periods or locations of observation, a valuable capacity in times of reduced research and monitoring budgets.

Vulnerability, Adaptation, Adaptive Capacity and Resilience

- Increasingly governments, communities, and industry stakeholders are exploring ways to reduce the negative impacts of climate change and take advantage of new opportunities through adaptation.
- Many Arctic coastal communities are experiencing vulnerabilities to decreased or less reliable sea ice, greater wave energy, rising sea levels, changes in winds and storm patterns, storm-surge flooding or coastal erosion, with impacts on travel (on ice or water), subsistence hunting, cultural resources (e.g. archaeological remains, burial sites) and housing and infrastructure in communities.
- In some places, this has necessitated community relocation, which in some cases increased vulnerability.
- In places, coastal erosion is threatening critical infrastructure or contaminated sites, with potential for spreading of pollutants.
- There has been great progress in recent years in the understanding of exposures and identification of elements of adaptive capacity that may enhance resilience, but other challenges including social, technical, financial, and institutional barriers may be inhibiting successful adaptation.
- There is a wide range of adaptive capacity among coastal communities of the circumpolar Arctic. A community with a greater resource base, including physical resources, financial capacity, knowledge (of all kinds), and social cohesion, is in

a better position to successfully adapt than one that lacks resources and options.
- Arctic indigenous peoples are traditionally resilient. This has allowed them to adapt to a harsh climate and changing environmental conditions over multi-century time-scales.
- With a faster pace of change and numerous compounding challenges, the indigenous peoples of the Arctic are generally less resilient today, although developments in regional governance and cultural initiatives, as well as growing familiarity with climate change, may be improving the situation to some extent.
- Quantitative scientific research concerning past, present, and future environmental changes and impacts is a key component informing policy and decision-making.
- Adaptation strategies perceived as imposed from outside will not be incorporated into the community's reservoir of mechanisms for coping with change, will not form a component of its adaptive capacity, and will thus not contribute to its resilience and ultimate sustainability.

Governance and Adaptation

- National agencies are the main actors in regional governance. In some areas such as northern Canada, regional (or in this case, territorial) agencies may play an equally important part. At national and international scales, almost all international land boundaries are settled, meaning that national jurisdiction at the coast is generally clear.
- There are enormous differences across the circumpolar Arctic in population size and distribution, economy, culture, institutional framework, and other factors.
- There are few Arctic-specific international regimes: the 1973 Polar Bear Treaty is the only legally binding regime.
- The Arctic Council, based on soft law (1996 Declaration), works primarily through assessment programs and projects to develop consensual knowledge and understanding on the status of the Arctic environment and related issues among the eight Arctic countries.
- Integrated coastal area management and integrated ecosystem-based oceans management are desirable strategies for coastal area governance and may embody a number of best practices which have emerged from recent reviews.
- Conclusions from consideration of integrated ecosystem-based management include the following:
    - Management needs to be flexible;
    - Decision-making must be integrated and science-based;
    - National commitment is required for effective management;
    - Area-based approaches and trans-boundary perspectives are necessary;
    - Stakeholder and Arctic resident participation is a key element;
- Adaptive management is critical.
- It has been recommended that future research should focus on increasing support, opportunity, and capacity for local decision-making or effective resident input to decisions on broader institutional policies with local impacts.

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1 Introduction

1.1 Background

Rapid environmental and socio-economic changes are defining characteristics of the past decade in the Arctic circumpolar basin. The probability of a seasonally ice-free Arctic Ocean within decades has increased (Overpeck et al., 2005), as previous records for annual minimum sea ice extent have been broken successively in 2002 and 2007 (Serreze et al., 2007; Comiso et al., 2008; Wang and Overland, 2009) and there have been ongoing losses of thick multi-year ice (Smedsrud et al., 2008). In 2010, the September (annual minimum) ice extent in the Arctic basin was the third smallest ever (Richter-Menge, 2010; Richter-Menge and Overland, 2010). The past decade has also been the warmest on record for global surface air temperature and some Arctic regions have grown warmer at an even faster pace (ACIA, 2005; Barber et al., 2008; Richter-Menge, 2010). "In 2010, there was continued widespread and, in some cases, dramatic … warming [of the] Arctic, where deviations from the average air temperature are amplified by a factor of two or more … relative to lower latitudes" (Richter-Menge and Overland, 2010: 6).

At the same time, Arctic residents are coping with rapid population growth (in some regions), technological change, economic and social transformation, shifting jurisdictions and institutions, and educational and health challenges (e.g. Hamilton and Mitiguy, 2009; Stammler, 2009; Stammler and Peskov, 2008; Suluk and Blakney, 2008; Young and Bjerregaard, 2008; Young and Mäkinen, 2009), while faced with historically unprecedented and sometimes confusing changes in the local environment on which traditional livelihoods and cultures depend (AHDR, 2004; Huntington et al., 2005; Gearheard et al., 2006).

The coast represents an important locus for many of these changes, as numerous northern communities are coastal and dependent on marine resources, while changes in air, ground, and sea-surface temperatures, sea ice, and storm exposure among other factors are driving rapid coastal change. The recognition of these complex adjustments and their implications has led to a rapid increase in research on the exposure, adaptive capacity, and vulnerability of Arctic coastal systems, including northern communities (e.g. Hovelsrud and Smit, 2010), and growing efforts to identify appropriate and effective policy options for adaptation (Ford et al., 2010).

In October 2007, an international workshop on Arctic Coastal Zones at Risk attracted scientists and policy makers from all parts of the circumpolar world. Convened in Tromsø, Norway, it was sponsored by LOICZ (Land-Ocean Interactions in the Coastal Zone), IASC (International Arctic Science Committee), IHDP (International Human Dimensions Programme on Global Environmental Change [a co-sponsor of LOICZ), AMAP (Arctic Monitoring and Assessment Programme [a Working Group of the Arctic Council]), and IPA (International Permafrost Association). This workshop focused on a growing awareness that the Arctic coastal interface is a sensitive and important zone of interaction between land and sea; a region that provides essential ecosystem services, economic resources, and means of subsistence for communities; a zone of expanding infrastructure investment and growing security concerns; and an area in which climate warming is expected to trigger landscape instability, rapid responses to change, and increased hazard exposure (Fig. 1).

Through a number of thematic and cross-cutting working groups, the workshop concluded with a call for an assessment of the state of the Arctic coast (Flöser et al., 2007 [http://coast.gkss.de/events/arctic07/docs/proceedings.pdf]). This report is the outcome of that call and the community response to it.

While acknowledging the enormous and valuable effort that went into the *Arctic Climate Impact Assessment* (ACIA, 2005), we note that there was limited documentation or synthesis of the state of Arctic coastal landscapes and habitats, coastal communities

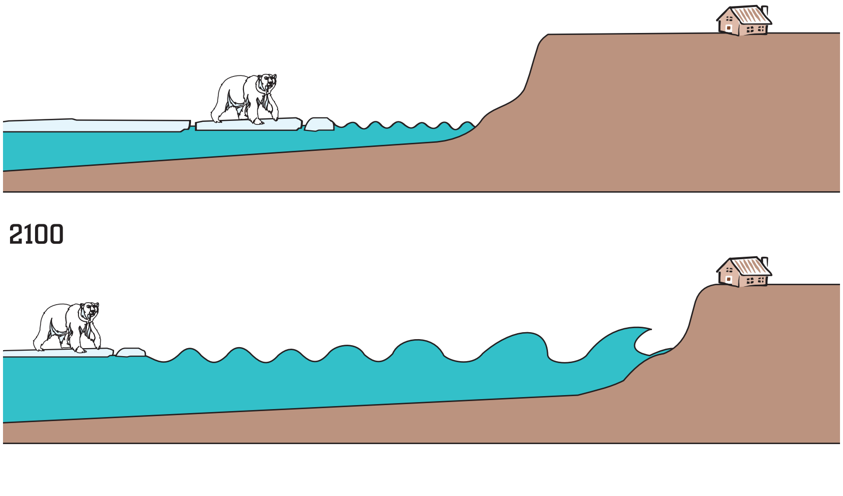

Figure 1. Trends of decreasing sea ice and increased open-water fetch, combined with warming air, sea and ground temperatures, are expected to result in higher wave energy, increased seasonal thaw, and accelerated coastal retreat along large parts of the circum-Arctic coast.

and subsistence activities, coastal management, development and governance. Many instances of rapid change and instability have been reported in the scientific and popular literature, as well as in the ACIA report, but a balanced assessment of vulnerability and risk to *Arctic coastal ecosystems and human resources* remained elusive. This report is intended as a first step in that direction. It provides a general review of the state of physical and ecological systems, human communities, and economic activities on the Arctic coast as of 2010, based on published literature and other sources. It is also intended to provide an assessment of knowledge gaps relevant to Arctic coastal vulnerability and a rudimentary road map to better integration of international research efforts focused on improved management of Arctic coastal systems.

In the interim, a number of initiatives have evolved that bear on this assessment. An international workshop in 1999 initiated the first phase of the Arctic Coastal Dynamics (ACD) Project (Brown and Solomon, 2000), sponsored by the International Arctic Science Committee (IASC) and the International Permafrost Association (IPA). Through a succession of annual workshops (Rachold et al., 2002, 2003, 2005a; Rachold and Cherkashov, 2004), the project undertook a number of initiatives with the overall objective "to improve our understanding of circum-Arctic coastal dynamics as a function of environmental forcing, coastal geology and permafrost, and morphodynamic behaviour" (Rachold et al., 2005b). Initial results were published in a special issue of *Geo-Marine Letters* (v. 25, no. 2-3) in 2005. Among the ACD objectives, one was to develop an Arctic coastal classification and to implement this within a geographic information system (GIS). A paper representing the culmination of this effort was published on-line shortly before the completion of this report (Lantuit et al., 2011) and summarized physical characteristics for the entire circumpolar coast fronting on the Arctic Ocean.

ICARP-II, the Second International Conference on Arctic Research Planning, was convened in Copenhagen in November 2005, in part to direct research activities under the International Polar Year (IPY), and produced a series of Working Group reports outlining critical needs and directions for research in a number of areas (ICARP-II, 2007). Working Group 3 considered coastal issues and provided a partial roadmap for Arctic coastal research needs and objectives over the coming decade. We return to this report and its recommendations in Chapter 4 of the present report.

A number of activities under the International Polar Year (IPY) fostered research on Arctic coastal systems or with relevance to the coastal zone. An outgrowth of the IPY was the recognition that greater coordination, investment, and effort are required to monitor Arctic environmental change. The SAON (Sustaining Arctic Observing Networks) discussions took place over two years (2007-2009) and resulted in recommendations and a report entitled *Observing the Arctic* (SAON, 2009). A Coastal Working Group convened at the Second SAON Workshop in April 2008 defined objectives and identified a number of issues related to coastal monitoring in the Arctic (Couture et al., 2008): "The objective of a coastal observing program is to detect change as it occurs, measure the extent and impacts of past changes, and support prediction of future change as a basis for sound and sustainable policy choices." The Working Group noted the existence of a circum-Arctic network of coastal observatories, ACCO-Net (the Arctic Circumpolar Coastal Observatory Network, a fully endorsed initiative under the IPY), which was established by the Arctic Coastal Dynamics Project (ACD) (Overduin and Couture, 2006; Couture and Overduin, 2008). Limited infrastructure investment has been made in this network, but it provides a framework for future coordinated efforts. The SAON Coastal Working Group proposed a revisioning of ACCO-Net in a modular framework to promote integrated monitoring of environmental change and impacts on the circumpolar Arctic coastal zone, including links to communities (Couture et al., 2008).

1.2 The Circumpolar Arctic Coast

This report adopts no fixed definition of the Arctic coastal zone (Fig. 2). The coast is taken to comprise the land-ocean interface in a broad sense, to include portions of adjacent marine and terrestrial systems substantially influenced by the land-ocean boundary. WG3 of ICARP II adopted the following definition, which is convenient for most purposes of the present report: the Arctic coastal zone comprises "the nearshore marine areas in both benthic and pelagic zones, and the near-shore terrestrial areas that act as drivers to the marine systems or are under a distinct marine influence" (Science Plan 3, in ICARP-II, 2007). However, this report explicitly includes human population centres (Fig. 2) and areas of economic interest adjacent to the Arctic coast and takes a broad and integrated view of coastal systems and dynamics.

Figure.2. The circumpolar Arctic coast, showing various definitions of the Arctic and the main human population centres located within the CAFF Arctic boundary. Most communities are located on rivers, lakes and the coast. In some jurisdictions, almost all are coastal and coastal habitation centres are widely distributed around the Arctic margin. Also shown are the distribution of rock and non-rock (unlithified sedimentary) coasts for those areas mapped by the Arctic Coastal Dynamics (ACD) project (Lantuit et al., 2011).

There are many definitions of the Arctic, based on latitude, climate, ecology, landscapes, marine factors such as sea ice, or institutional, regional, or national boundaries. Some initiatives have aimed to synthesize information on the coastal domain around the Arctic, using various geographic limits specific to the projects involved. A major objective of the Arctic Coastal Dynamics Project was to derive estimates of carbon flux to the Arctic basin (Rachold et al., 2005b). For this reason, most sections of the Arctic coast not fronting directly on the Arctic Ocean (most of the Canadian and Greenland coasts) were excluded. In contrast, the Circumpolar Arctic Vegetation Map (CAVM Team, 2003) included all areas between the Arctic coast and the northern limit of forests. The IPA map of Northern Hemisphere permafrost (Brown et al., 1997) defined the southern limits of continuous, discontinuous, sporadic, and isolated permafrost. The Arctic System Model program (Roberts et al., 2010a, 2010b) defines the Arctic region for integrated modelling purposes as “the geosphere and biosphere north of each of the boreal mean decadal 10°C sea surface isotherm, the surface air 0°C contour that encircles the North Pole, and the southern limit of terrain that drains into the High Arctic” (Roberts et al., 2010a). Thus defined, the Arctic comprises 12% of the Earth’s surface, 9% of the world ocean area, and 22% of the global terrestrial land area (Roberts et al., 2010b).

1.3 Rationale

The pace of cultural, social, economic, and institutional change in the Arctic is extremely rapid. In some areas, many elders and some older middle-aged residents who were born on the land now occupy communities with satellite television and high-speed wireless internet. This pace of technological transformation places great strain on the cultural, linguistic, and social fabric of life in northern communities at a time when they also face rapid environmental change. The exigencies of adaptation to climate change are added to the socio-cultural challenges facing these communities, many of which are coastal.

Virtually all Inuit communities are coastal, a reflection of the cultural dependence on marine mammals. All Greenland communities, all Inuit communities of Nunatsiavut (Labrador) and Nunavik (northern Quebec), all communities but one in Nunavut, all but two Inuvialuit communities in the Northwest Territories, and all Iñupiaq and other marine-based indigenous communities in northern and northwestern Alaska (USA) and in Chukotka (eastern Russian Federation) – almost all are coastal. Even across the Eurasian Arctic, where many indigenous cultures are dependent on reindeer herding and have less connection to the sea, concentrations of coastal settlements can be seen in Sakha, Yamal Nenets, and Nenets, including the large port city of Murmansk in northwest Russia. The majority of the larger communities around the White Sea, on the Kola Peninsula, and in northern Norway are coastal and dependent on the fish stocks in the Barents Sea and White Sea (and more recently, at least in Norway, on offshore hydrocarbon resources), while a similar pattern of fisheries-reliant communities is evident in Iceland and the Faeroes (Fig. 2).

With changing climate, these communities are becoming exposed to unfamiliar environmental patterns and conditions. Natural ecosystems in the coastal zone, as elsewhere, are also facing altered conditions that limit survival or productivity of many species in at least part of their range. These changes are occurring as a result of anomalous warming, which is amplified in high latitudes (ACIA, 2005; IPCC, 2007a; Richter-

Menge, 2010). The response to climate warming is manifest in a succession of other changes, including changes in precipitation, ground temperatures and the heat balance of the ground and permafrost, changes in the extent, thickness, condition, and duration of sea ice, changes in storm intensity, and rising sea levels, among other factors. The stability of Arctic coasts and coastal ecosystems is affected by water levels, sea ice conditions, air, ground, and sea surface temperatures, permafrost and ground ice, storms and wave energy, all of which are exhibiting signs of a response to climate change. There is evidence from some areas for an acceleration in the rate of coastal erosion, related in part to more open water and resulting higher wave energy, in part to rising sea levels, and in part to more rapid thermal abrasion along coasts with high volumes of ground ice. This directly threatens present-day communities and infrastructure as well as cultural and archaeological resources such as cemeteries and former settlement sites, particularly in areas of rising relative sea level (where postglacial uplift is limited or regional subsidence is occurring). Changing ice conditions are threatening indigenous lifestyles and subsistence economics as well, as ice conditions deteriorate, making trips to hunting grounds more hazardous, with more hunting from open water, requiring larger and more expensive vessels and motors. These and other changes are increasing demand on community infrastructure, which itself is threatened by climate impacts including permafrost degradation and increased landscape instability.

Large parts of the Arctic coast are undergoing rapid change. Regions with frozen unlithified sediments at the coast show rapid summer erosion, notably the Beaufort Sea coast in Alaska, Yukon, and the Northwest Territories and large parts of the Siberian coast. The ACD compilation (Lantuit et al., 2011) showed that the Beaufort Sea coast in Canada and the USA had the highest regional mean coastal erosion rates in the Arctic (1.15 and 1.12 m/year in Alaska and Canada, respectively). The next highest rates were in the East Siberian Sea and the Laptev Sea (0.87 and 0.73 m /year, respectively), while the mean rate determined for Svalbard was 0.00 m/year. Locally, within regions, rates can be much higher (e.g. Jones et al., 2008). Rachold et al. (2000) reported retreat of the Laptev Sea coast at rates of ~2.5 m/year, delivering more sediment and carbon to the sea than the Lena River. Most records of coastal change are too short to reveal clear trends or shifts to more rapid erosion. Large annual and decadal variability may relate to variability in frequency and severity of coastal storms and variations in the open-water season (Solomon, 2005; Manson and Solomon, 2007; Overeem et al., 2010).

Increases in sea level are expected to enhance coastal erosion and affect sediment transport in coastal areas. Results from the IPCC Third Assessment Report (IPCC, 2001), re-plotted in an Arctic polar projection for ACIA (2005), demonstrated that seven of nine models used in that report projected higher than global-mean increases in sea level for the Arctic. New approaches to projecting local sea-level trends are discussed in this report and other new material will be available in the forthcoming SWIPA report to be released in mid-2011 (see below).

Extensive coastal lowlands and large deltas on the Arctic coast host ecosystems that are vulnerable to rising sea level. Wetlands may migrate landward and more coastal flooding will occur, with the potential for adverse effects on bird and fish habitats and reproductive success. Rising sea levels, combined with projected decreases in sea-ice extent (leading to longer open-water seasons) imply a higher probability of impacts from storms occurring with open water at the coast. More wave activity in shoulder-season storms with open water may also affect benthic resources. Coastal erosion will have additional negative impacts on community infrastructure and other human activities.

Because of the many distinctive physical, biological, and human conditions found in the Arctic, a full understanding of and predictive capacity for coastal change in northern regions requires an integrated approach to monitoring and analysis and a recognition of complex biophysical and social interactions, despite the small human population and limited biodiversity.

A number of assessments have been undertaken over the past decade to ascertain the environmental conditions of the Arctic. These have typically focused on a variety of ecosystem or environmental compartments or themes. Most notable among these are the following:

- Arctic Human Development Report (AHDR, 2004)
- Arctic Climate Impact Assessment (ACIA, 2005)
- Arctic Oil and Gas 2007 (AMAP, 2007)
- Arctic Marine Shipping Assessment (PAME, 2009a)

The last three of these were sponsored by and affiliated with the Arctic Council (see Section 3.4.2). These have been complemented and succeeded by a broad spectrum of complementary initiatives. Examples, the first two of which are also supported by the Arctic Council, include:

- Vulnerability and Adaptation to Climate Change in the Arctic (VACCA) a project of the Arctic Council Working Group on Sustainable Development (Njåstad et al., 2009);
- Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arctic Council Project on Climate Change and the Arctic Cryosphere (http://www.amap.no/swipa/), which like this report is a follow-up to ACIA (2005);
- Arctic Governance Project (AGP), a new initiative to enable the policy community to frame critical Arctic governance issues and to propose innovative responses for a sustainable future by developing a set of responsible and widely supported policy recommendations for Arctic governance, drawing both on traditional ecological knowledge and scientific knowledge (http://www.arcticgovernance.org/).
- State of the Climate in 2009 (Arndt et al., 2010), with a section on the Arctic climate in 2009 (Richter-Menge, 2010).
- Arctic Report Card: Update for 2010 (Richter-Menge and Overland, 2010), updating Richter-Menge (2010) and synthesizing marine, terrestrial, hydrological, and cryosphere changes through the 2010 summer season (http://www.arctic.noaa.gov/reportcard).

1.4 Objectives and Organization of the Report

Given the background and rationale outlined above, this report has three specific objectives corresponding to the three following chapters:

- Chapter 2: To update and complement the ACIA (2005) report with a focused overview of the Arctic coast, with an emphasis on the state of physical and ecological systems and human communities and activities on the Arctic coast in 2010, based on published literature and other sources.

- Chapter 3: To develop a more integrated approach to the study of Arctic coastal change, including monitoring, detecting, and modelling change, assessing vulnerability and adaptive capacity, and developing policies and governance strategies to support adaptation.

- Chapter 4: To identify knowledge gaps and research priorities, including development of a rudimentary road map for integrated coastal systems research in the circumpolar Arctic, inclusive of northern stakeholders and focused in part on improved management approaches for the Arctic coastal environment.

2 State of the Arctic Coast 2010
– A Thematic Assessment

This chapter provides assessments of the state of the Arctic coast as of 2010 under three thematic headings: the physical state, the ecological state, and the social, economic, and institutional state of the circum-Arctic coastal zone. Following this, Chapter 3 considers more integrated approaches to Arctic coastal change.

2.1 Physical State of the Circum-Arctic Coast

Lead authors: P. Paul Overduin and Steven M. Solomon
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Key Findings

- The evolution of Arctic coasts over the coming decades will be strongly influenced by changes in the natural environment caused by the effects of climate warming.
- Surface air temperatures have reached record levels over the past decade. Record warm air temperatures in 2010 extended across Greenland and the Canadian Arctic.
- The past decade has seen successive new record minima in Arctic sea-ice extent and 2010 had the third smallest summer minimum extent of the past 30 years. At the same time, the mean ice thickness has been decreasing, driven primarily by export of perennial ice.
- Less extensive sea ice creates more open water, allowing stronger wave generation by winds. This, combined with warmer sea-surface and ground temperatures, has the potential to increase erosion along Arctic coasts. Record warm sea-surface temperatures in 2007 contributed to rapid coastal erosion in Alaska.
- Sea-level rise in the Arctic coastal zone is very responsive to freshening and warming of the coastal ocean (leading to increased sea level at the coast) and is highly susceptible to changing large-scale air pressure patterns.
- Relative sea-level change depends on vertical land motion (uplift or subsidence), the patterns of which are predominantly a legacy of former glaciation. The rate of uplift in some regions exceeds the rate of sea-level rise, leading to falling relative sea level.
- Sea-level rise in much of the Arctic is moderated by gravitational effects (fingerprinting) associated with ice loss from regional glaciers and ice caps and especially from the Greenland Ice Sheet.
- Arctic ice shelves will continue the recent rapid pace of collapse due to climate warming and the decrease in multi-year sea ice.
- Carbon entering the coastal system from terrestrial sources appears to be more labile than in the past. Because this organic matter is a direct source of energy for secondary production and a potentially important indirect source once remineralized, the higher lability may have far-reaching, yet unknown consequences for Arctic coastal marine productivity.
- Despite increasing annual freshwater discharge, some Arctic deltas are being progressively flooded, with most of the Mackenzie Delta front (the second largest Arctic delta) retreating at 1-10 m/year or more.
- Storm-surge inundation of low coastal areas and deltas affects coastal communities and can have profound impacts on delta ecology through salinization of freshwater environments. Early-season surges can disrupt waterfowl breeding and winter surges may flood or break up winter ice roads, a critical form of transportation for many northern activities.
- Decadal-scale mean rates of coastal retreat are typically in the 1-2 m/year range, but vary up to 10-30 m/year in some locations. The highest mean erosion rates are in the Beaufort Sea, the East Siberian Sea, and the Laptev Sea.
- Recent results on erosion of ice-rich bluffs point to the importance of interaction between high sea-surface temperatures, which drive thermal

abrasion and undercutting, and the timing of ice break-up and freeze-up in combination with storm dynamics.

- The distribution and stability of gas hydrates in the Arctic coastal zone is poorly documented, but there is concern that climate change and other effects such as coastal erosion may destabilize some hydrate deposits.
- Rocky shorelines comprise 35% of the Arctic coastline and most are effectively stable on timescales relevant to adaptation planning and management.

The coast is a key interface in the Arctic environment. It is a locus of human activity, a rich band of biodiversity, critical habitat, and high productivity, and among the most dynamic components of the circumpolar landscape. The Arctic coastal interface is a sensitive and important zone of interaction between land, sea, and atmosphere, a region that provides essential ecosystem services and supports indigenous human lifestyles; a zone of expanding infrastructure investment and growing security concerns; and an area in which climate warming is expected to trigger landscape instability, rapid responses to change, and increased hazard exposure.

This physical overview begins with a consideration of climate and extreme events, then reviews the Arctic wave climate, sea ice, ice shelves and tidewater glaciers, changing sea levels, freshwater, solute, and suspended particulate fluxes to the Arctic Ocean, Arctic deltas, unlithified coasts (erosional and depositional systems), permafrost and ground ice, gas hydrates, and bedrock coasts.

2.1.1 Climate and weather – present-day patterns and future trends

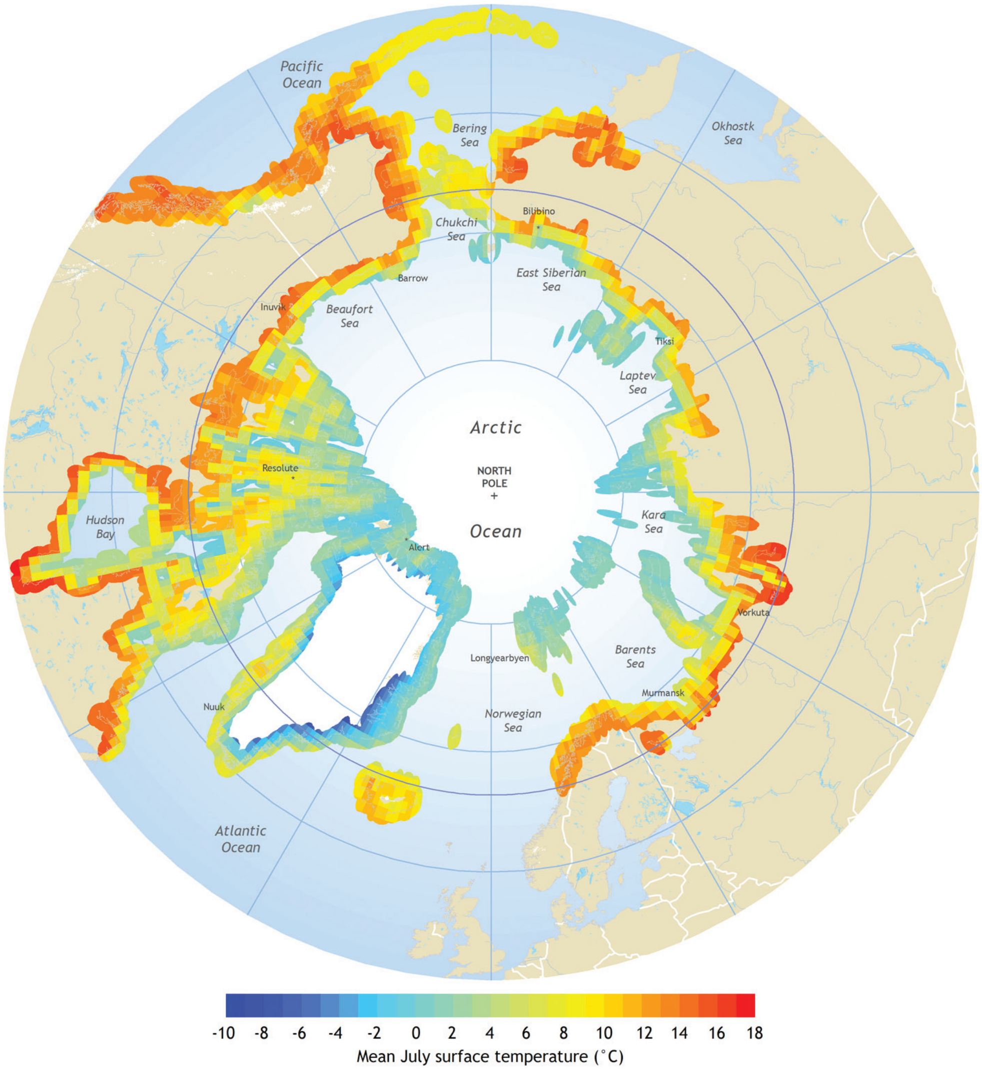
temperature and precipitation

Climate mean July air temperatures in the Arctic coastal zone show considerable geographic variability across a temperature range of almost 28 K (°C) (Fig. 3). In addition, global and Arctic surface air temperatures have reached record levels over the past decade (Arndt et al., 2010). Record warm air temperatures in 2010 extended across Greenland and the Canadian Arctic, as reported in the *Arctic Report Card: Update for 2010* (Richter-Menge and Overland, 2010). The same report noted a "new record minimum in springtime snow cover duration over the Arctic. The warming air temperatures also played a major role in the observed increases in permafrost temperatures around the Arctic rim, … and the increase in the greenness of Arctic vegetation" (Richter-Menge and Overland, 2010: 6).

The primary driver of temperature is solar radiation. Almost all Arctic coastal zones are above the Arctic Circle and so experience periods of both twenty-four hour darkness and twenty-four hour daylight. Extreme seasonality is a prominent feature of high-latitude environments and exerts a major influence on almost every aspect of the circum-Arctic coast.

After the primary solar radiation control, temperatures are influenced by the proximity of coastal regions to the influence of the ocean, which acts to moderate extremes

Figure 3. Mean July air temperatures in the circum-Arctic coastal zone (22-year mean: July 1983 to June 2005).
Source: US National Aeronautics and Space Administration, 2007 (http://swera.unep.net/index.php?id=metainfo&rowid=282&metaid=384).



(Maxwell, 1982). Sea-surface temperatures are strongly influenced by ocean circulation, sea-ice extent, and other factors (Proshutinsky et al., 2010). Coastal locations are cooler in summer than their interior counterparts – often an inversion layer up to several hundred metres in thickness is present, a result of the advection of cool, marine air over the coast (Atkinson, 2000). Depending on prevailing conditions, marine air can penetrate many kilometres inland; during storms, cooling effects can be seen 100 km inland (Atkinson and Hinzman, 2008) of sufficient magnitude and duration to affect ground temperatures at 30+ cm depth. Coastal locations are correspondingly warmer in winter than are their interior counterparts. Sea ice does not completely isolate the ocean from the atmosphere. Exchanges of energy and mass, which warm and add moisture to the low levels of the atmosphere, are able to proceed via open leads and through young ice (Maykut, 1978).

Cloud cover is an important moderating factor in the Arctic. Cloud-free conditions in the summer can lead to persistent, positive surface radiation balances and accompanying rapid loss of ice in the terrestrial and marine environments (Atkinson et al., 2006).

This has important derivative effects, e.g., for thawing of ice-rich materials and the resulting coastal erosion response (Ogorodov, 2003). During winter, cloud cover reduces the loss of radiation emitted from the surface and so mitigates extreme cold conditions.

Many Arctic coastal regions experience an annual range of surface air temperature from approximately -50°C to +20°C, with summer temperatures in excess of 20°C now being experienced in regions unaccustomed to such warm weather. A strong wind chill is often present. Arctic coastal zones often experience periods of fog, especially in the summer, imposing a reduction in air temperature.

Accurate measurement of precipitation on Arctic coasts is challenging (Benning and Yang, 2005). Most falls as snow which, due to conditions of strong wind, is difficult to measure accurately and more difficult still to compare throughout the Arctic due to variations in technique and timing of measurement standards amongst nations (Groisman et al., 1998). Despite this, long-term average monthly precipitation totals have been derived, e.g. by the University of Delaware (Willmott and Rawlins, 1999) and the Climate Research Unit (Hulme, 1992).

Rawlins et al. (2006) describe weak decreasing trends for Eurasian precipitation and snowfall, but indicate that the sparse and variable gauge network over time precludes attachment of estimates of statistical significance. ACIA (2005) also indicates weak trends – positive over Europe/West Asia (~10%/decade), negative over Siberia (~10-15%/decade), positive over Alaska/Canadian Archipelago (~10%/decade), and negative over the northern Mackenzie River region (~10-15%/decade). ACIA (2005) further breaks down these trends by season, showing strong variations in trends, e.g. strong decreases in winter and fall in Siberia.

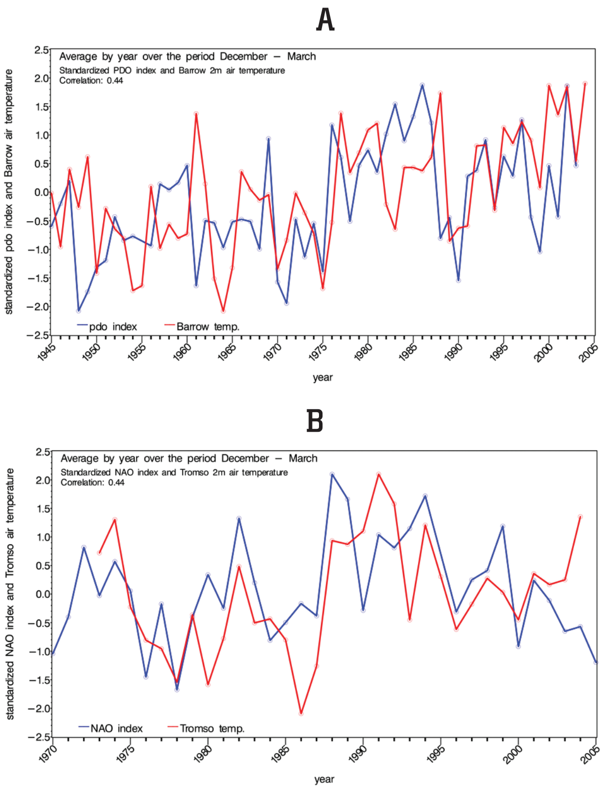
Long-term trends are delineated in the ACIA report, which identified a subset of the IPCC (2007a) general circulation models (GCMs) that represent the Arctic with greater consistent skill. For temperature, these models are uniform in their indication of consistent increasing temperatures throughout the Arctic coastal regions, although magnitudes and regional expression differ. The increase is greatest over the marine areas as the ice cover continues its reduction in thickness and extent. Precipitation, although exhibiting regional differences in trends to date, converges towards increases throughout the Arctic coastal margins.

While temperature and precipitation in many areas have exhibited relatively persistent trends over decades, on shorter time scales the impacts of favoured patterns of the climatic state, as represented for example by the Arctic Oscillation, North Atlantic Oscillation, or Pacific Decadal Oscillation, can cause regional-scale cycling in patterns of temperature or precipitation with periods of several years to a decade or more (e.g. Fig. 4).

Storms

Storms in the coastal zone may be defined as events which bring strong winds because winds drive the damaging sea states and storm surges that are of consequence to the coast. Storms in the coastal zone show a strong mean annual pattern that is spatially variable across the Arctic. Atkinson (2005) reports on storm activity in the Arctic coastal margins (Fig. 5). In the Norwegian/ Barents Sea region, an annual peak in storm activity occurs in fall/winter; this is essentially a mid-latitude pattern and reflects the

Figure 4. **Influence of major regional modes of atmospheric circulation on locally observed 2 m surface air temperature in winter. Monthly temperatures were extracted and averaged over the December-March period to arrive at a single annual value. A single annual datum for the indices was similarly constructed. (A) Temperature from Barrow, Alaska, compared with the Pacific Decadal Oscillation index. (B) Temperature from Tromsø, Norway, compared with the North Atlantic Oscillation index. In both cases the influence on the local-scale temperature regime is apparent. At Barrow the longer-term pre- and post-1975 trend is of note.**



strong influence of the North Atlantic Drift. Moving eastward across the Eurasian north this pattern is gradually superseded by one showing a storm peak in late summer/early fall. This is generally coincident with the open water season, during which more water vapor is available to support storm activity. The Chukchi Sea/Beaufort Sea areas reflect a mix of mid-latitude and open-water influences. Patterns in storm duration and wind-speed are similar, and a combination of speed and duration yields a "storm-potential factor" that is largest in the Chukchi Sea.

Long-term trends towards increasing open water durations and increasing Arctic Ocean marginal sea temperatures will lead to increasing frequency of storm events in the coastal margins of the Arctic. These will be tempered, however, by the superposition of decadal-scale cycling, such as observed long-period variability of storminess in the Beaufort Sea (Hudak and Young, 2002), or other activity changes brought about by circulation changes (e.g. Savalieva et al., 2000). Nevertheless, there is evidence for an increase in Arctic storm activity over recent decades (Zhang et al., 2004).

2.1.2 Waves

Waves are an important aspect of the environmental forcing that determines the state of Arctic coasts. In the Arctic, where a substantial part of the coast is composed of frozen ground, waves play a significant role along with temperature and precipitation. Recent investigations (Ogorodov, 2008) show that in general their role is the more important where ground-ice content is low and less so as ice content increases. In general, in the fetch-limited conditions imposed by the presence of sea ice, wind-induced waves predominate in Arctic seas. Until recently, ocean swell was important at the coast only in the Barents Sea and (to a lesser extent) in the Chukchi Sea, except in areas exposed to the

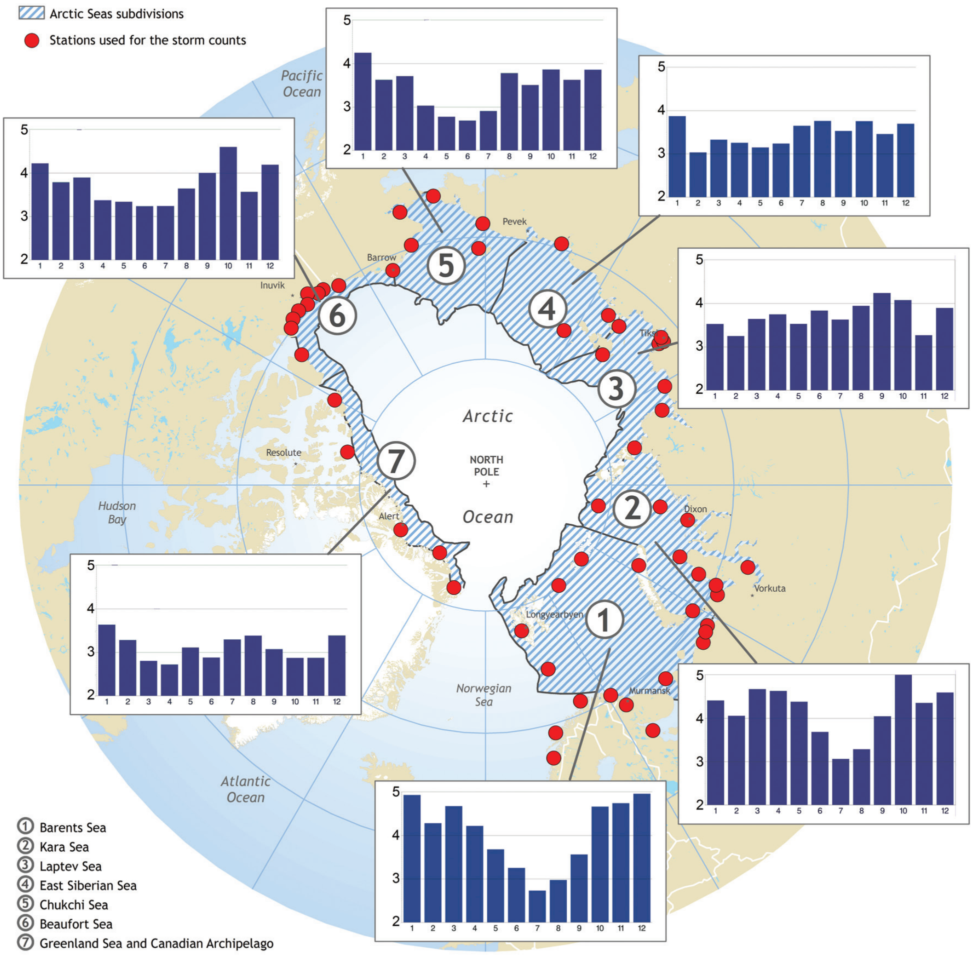


Figure 5. Annual patterns of coastal storm counts (1950-2000) for the circum-Arctic region, summarized for each of seven marginal seas. Histograms are equally scaled from 2 to 5 events and present mean annual storm event counts by month. A 'storm' is classified in this context to be an event in the locally-observed wind speed record that exceeds 10 m/s for at least 6 hours duration.

Source: David Atkinson, University of Victoria

open North Atlantic (Iceland, southern Greenland, Labrador, and southeast Baffin Island). In a number of areas along the Siberian, Alaskan, and western Canadian Arctic coasts, reduced sea ice duration and extent are increasing the potential fetch for wave formation, increasing wave energy levels and enabling the development of swell. Increased wind wave energy is also becoming apparent in inter-island channels of the Canadian Arctic Archipelago and semi-enclosed seas such as Hudson Bay and Foxe Basin (e.g. Manson et al., 2005a; Ford et al., 2009; Laidler et al., 2009; St-Hilaire et al., 2010). Some areas such as the northwest Canadian Arctic Archipelago have negligible open water and some coasts there are almost untouched by waves (Forbes and Taylor, 1994). In others, where tidewater glaciers have shown rapid retreat, newly exposed shorelines have undergone rapid evolution under the influence of ocean waves (Ziaja, 2004; Ziaja et al., 2009).

The evolution of Arctic coasts over the coming decades will be governed by changes in the natural environment caused by the effects of climate warming. Rising temperatures are altering the Arctic coastline by reducing sea ice and larger changes are projected to occur as this trend continues. Less extensive sea ice creates more open water, allowing stronger wave generation by winds. The wave-energy factor acts via the direct mechanical impact of sea waves on the shore, with the potential to increase wave-induced erosion along Arctic coasts (Fig. 6). The effectiveness of waves is determined to an important extent by storm-surge amplitude as well as by storm duration.

To understand how wave development could change in conditions of decreasing ice coverage in the Arctic Ocean, we use the conditions observed during the summer and fall of 2007, when the lowest ice coverage occurred in the history of instrumental observations from satellites (since 1978; http://arctic.atmos.uiuc.edu/cryosphere). In 2007, anomalously widespread ice-free regions in the Arctic seas created unique conditions for the development of wind waves due to the remarkable increase in open-water fetch. In addition, the duration of the ice-free period increased and reached the highest values on record.

Near the shore, waves undergo transformation, including refraction and shoaling. As a result, the observations at coastal meteorological stations are not representative for determination of wave parameters on the open sea. Thus considering the lack (or low representativeness) of long instrumental wave measurements in Arctic seas, estimates of wave parameters are derived primarily on the basis of model computations and forecasts.

Estimates of wave conditions in 2007 have been derived using the spectral-parametric model of the State Oceanographic Institute (Russia) as modified by the Arctic and Antarctic Research Institute (Russia) and approved for the north-European basin of the Arctic Ocean. Wind, the main driving force, is calculated based on the atmospheric pressure fields at sea level. The location of the sea ice margin is available at a daily interval (URL above). The quality of hindcasts using this model for the north-European basin of the Arctic Ocean was determined using observed wave data, with mean absolute error of 0.22 m, mean square error of 0.89 m, and a correlation coefficient of $r^2=0.67$ between observed and hindcast values. Based on the results of model hindcasts for ice-free waters of the Barents and Kara seas, Frolov (2008) derives monthly estimates of significant wave height (H_S) recurrence for an exceedance probability of 13%.

From the analysis of the monthly wave height distribution for 2007 in the Barents and Kara seas, patterns typical for other parts of the Arctic Ocean are clearly traced. Along

Figure 6. Wave action on an Arctic coast, Bylot Island, Nunavut.
Source: R.B. Taylor, Geological Survey of Canada

with the intensity of atmospheric circulation that determines the wind speed, wave heights are a function of fetch, which in turn is determined by sea-ice extent. Data show that in the mostly ice-free Barents Sea, the maximum intensity of atmospheric activity falls in the cold season of the year (October-April) (Fig. 7), during which a local minimum of wave heights corresponds to maximum ice cover in February. In contrast, in the Kara Sea, the highest wave heights are observed in September-October, when this sea is free of ice and wave fetch is maximised, while storm activity is beginning to grow with the approach of winter. Thus with climate warming and an increased duration of ice-free conditions into November and December in the Kara Sea, and comparable patterns in other Arctic seas, a noticeable growth of both wave height and energy can be expected, with potential implications for accelerated erosion of Arctic coasts (see Sections 2.1.8 and 2.1.9).

2.1.3 Sea ice

The presence of a sea-ice cover controls a number of key processes that affect the state of Arctic coasts, in particular the geomorphology and stability of unlithified (non-rock) shores with or without permafrost. We consider the impact of sea ice on coastal waves and the role of sea ice as a geological agent. An ice cover greatly reduces or fully precludes the formation of wind-driven waves and is capable of substantially damping surface waves generated outside the sea-ice zone (Squire, 2007). Hence, the amplitude and period of wind-driven waves and their potential impact on a coastline are typically limited by the position of the ice edge in relation to the coast and the prevailing wind direction (Fig. 1). The prevalence of perennial sea ice in the Arctic Ocean during the summer months in the past has greatly limited the fetch and hence the potential for destructive wave action at the coastline. With progressive reduction in summer

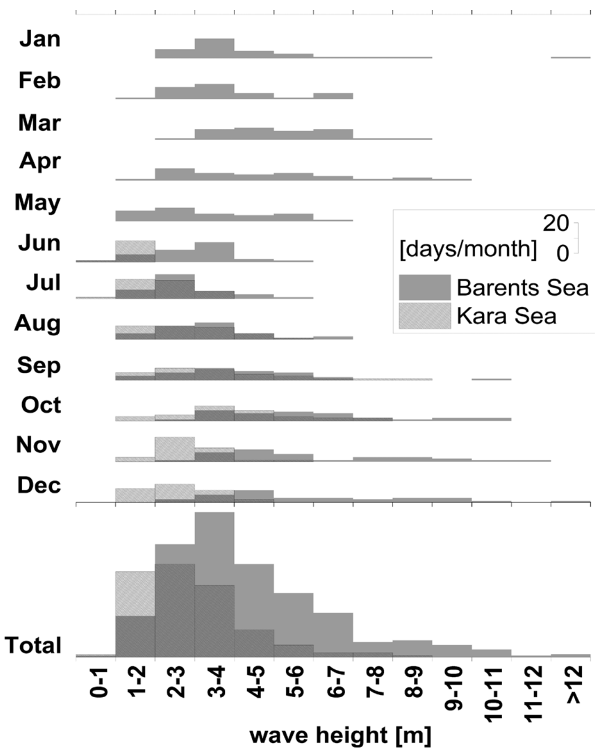


Figure 7. The distribution of wave heights (Hs) in the Barents and Kara Seas by month of the year (2007). Bar height shows the number of days in each month with the wave height indicated on the horizontal axis. Vertical scale is indicated in the legend.

Figure 8. Median maximum (orange) and minimum (light blue) sea ice extents for 1979-2000, annual sea ice minimum for 2007 (dark blue) and projected minimum sea ice extent for 2070-2090 (white).
Data sources: NSIDC, ACIA (2005)

minimum ice extent and multiyear ice, fetch limitation has been reduced over the past decade and, in any case, has been a lesser factor in the Laptev, Kara and Barents Seas, which saw the greatest summer ice retreat.

Previous records for annual minimum sea ice extent have been broken successively over the past decade (Fig. 8), first in 2002 and then again in 2007 (Serreze et al., 2007; Comiso et al., 2008). Climate models point to a rapid reduction of summer minimum ice extent over coming decades (Fig. 8) and recent observations suggest that losses are occurring more rapidly than forecast (Wang and Overland, 2009). In 2010, the September (annual minimum) ice extent in the Arctic basin was the third smallest ever (Richter-Menge, 2010; Richter-Menge and Overland, 2010). In addition, the ice thickness has been decreasing (Rothrock and Zhang, 2005).

There have been ongoing losses in the extent of Arctic multi-year (perennial) ice (Maslanik et al., 2007; Serreze et al., 2007; Stroeve et al., 2008; Kwok et al., 2009; Perovich and Richter-Menge, 2009) (Fig. 9), leading to concern about a possible tipping point associated with ice-albedo feedback, although this appears unlikely in the short term (Eisenman and Wettlaufer, 2009). Export of multi-year ice from the Arctic basin has been a major contributor to the progressive thinning of the sea-ice cover (Smedsrud et al., 2008). Furthermore, recent observations in the Canada Basin revealed that much of what appeared in satellite imagery to be competent multi-year ice was in fact very weak and vulnerable to break-up (Barber et al., 2009).

With autumn freeze-up occurring later in the year (Fig. 10), compounded by changes in storm patterns, the impact of fall storms on shoreline erosion appears to have increased (Atkinson, 2005; Mars and Houseknecht, 2007; Forbes et al., 2008), although the impact

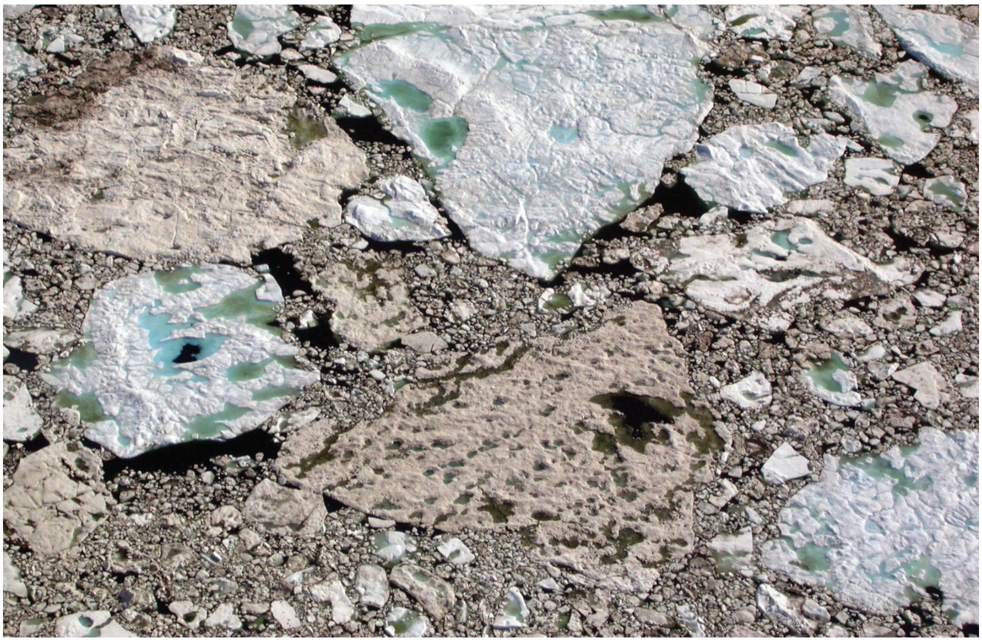


Figure 9. Clean and sediment-laden sea ice formed in the Beaufort Sea and exported to the Chukchi Sea, about 100 km north of Barrow, Alaska, 30 July 2006. Width of view is about 250 ± 50 m.

Source: Hajo Eicken, University of Alaska, Fairbanks

	sea ice (km3)	sediment (Gg)
Beaufort Sea	10	0.5
Chukchi Sea	10	0.1
East Siberian Sea	150	6
Laptev Sea	670	180
Kara Sea	240	17
Barents Sea	35	0.06
Fram Strait	-2850	-125

Table 1. Volume of sea ice and mass of sediment transported from coastal areas to the Arctic Ocean (positive) and exported to the North Atlantic (negative) on an annual basis.

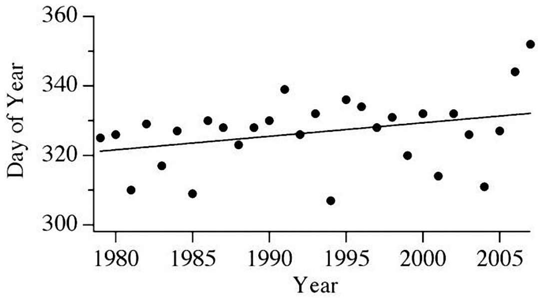
Source: Eicken (2003)

in some areas is moderated by cooler sea-surface temperatures later in the open-water season (Overeem et al., 2010; Wobus et al., 2010).

Despite significant advances in understanding the interaction of ice and waves (Squire, 2007), the limiting ice concentration for wave generation and propagation in Arctic marginal seas is not well understood but potentially important due to the prolonged presence of open drift ice (<10 to 60%) ice cover. Anecdotal evidence and local knowledge indicate that the impact of fall storms can be substantially mitigated by the formation of natural ice berms if the coastal waters are at or close to freezing (C. Hopson, Barrow, pers. comm., 2008; Eicken et al., 2009). The interaction between coastal currents and the ice cover, while highlighted by local and traditional environmental knowledge (Norton, 2002; George et al., 2004) is poorly documented and understood, but potentially important (Reimnitz and Barnes, 1974).

Sea ice also has a direct impact on the state of the coast through its interaction with unlithified sediments, such as in the form of nearshore ice scour and onshore ice-push, ice ride-up, and ice pile-up (Reimnitz and Barnes, 1974; Shapiro and Barnes, 1991; Ogorodov et al., 2005). Ice pile-up has been cited as a mechanism for onshore sediment transport and build-up of barrier crest elevations (Reimnitz et al., 1990) and also represents a coastal hazard when it affects communities or other coastal infrastructure

Figure 10. Date of freeze-up (day of year) for Wales/Bering Strait from passive microwave satellite data (Kapsch and Eicken, unpublished data). The time series shows a delay in onset of freeze-up (statistically significant at the 95% level) parallel to the substantial changes in summer minimum ice extent observed over the same time period.



or overwhelms coastal camps, with documented cases of infrastructure damage from the Labrador, Baltic, Pechora, Chukchi, and Beaufort Seas and from the eastern Canadian Arctic (e.g. Kovacs and Sodhi, 1981; Forbes and Taylor, 1994; Mahoney et al., 2004; Ogorodov, 2005, 2008; Ogorodov et al., 2005). Equally or more important is the entrainment and export of sediments by the ice cover. The latter process contributes significantly to net export of sediments from the coastal and shallow shelf seas (water depths less than 20 to 30 m; Reimnitz et al., 1994; Dethleff, 2005) and figures prominently in the sediment budget of the Arctic Ocean (Larssen et al., 1987; Eicken et al., 2000) (Fig. 9). Anecdotal evidence suggests that the changing Arctic sea-ice regime may result in increased sediment entrainment into and transport by sea ice (Eicken et al., 2005). However, the overall magnitude of this process and in particular its importance for the state of Arctic coasts remains largely unexplored.

2.1.4 Ice shelves and tidewater glaciers

Ice shelves and tidewater glaciers occupy a relatively small proportion of the Arctic coast (in contrast to Antarctica) and their extent is highly sensitive to climate and ice dynamics. Some tidewater glaciers drain parts of the Greenland Ice Sheet and other ice caps and their ice discharge rate is an important factor in the projection of rising sea levels. Arctic ice shelves, on the other hand, have negligible flow rates (though many are rapidly losing mass) and host important and distinctive biological habitats (e.g. Mueller et al., 2003; Mueller and Vincent, 2006).

Arctic ice shelves are thick (>20 m), floating masses of coastal ice that originate from a combination of marine, meteoric and glacial ice. They are found along the northern coastline of Ellesmere Island (Canada), among some Russian Arctic islands (Dowdeswell et al., 1994; Williams and Dowdeswell, 2001) and in northern Greenland (Higgins, 1989). Northern ice shelves can be formed from the termini of coalesced tide-water glaciers (e.g., Matusevich Ice Shelf, Russia) but the better-known and more extensive Canadian ice shelves are formed from the *in situ* accumulation of sea ice and direct precipitation with, less typically, a glacial contribution. The Ellesmere ice shelves formed between 3000 and 5500 years ago (Crary, 1960; England et al., 2008), are between 40 and 100 m thick (Hattersley-Smith et al., 1969; Narod et al., 1988) and therefore contain the oldest and thickest sea ice in the Northern Hemisphere. From explorer's journals, it is estimated that the northern coast of Ellesmere Island was fringed by a continuous 8900 km^2 ice shelf in 1906 (Vincent et al., 2001). Much of this large ice shelf disintegrated in the first half of the 20th Century, producing hundreds of tabular icebergs known as ice islands. Ice shelf changes were less substantial after the 1960s but the rate of break-up events has accelerated in recent years.

Recent break-up events include the fracturing of the Ward Hunt Ice Shelf in 2002 (Mueller et al. 2003) and the complete loss of the Ayles Ice Shelf as well as portions of the Petersen Ice Shelf in 2005 (Copland et al. 2007). Further fracturing and reduction of the Ward Hunt Ice Shelf occurred in 2008 along with the complete loss of the Markham Ice Shelf and more than half of the Serson Ice Shelf (Mueller et al. 2008). By 2008, following a 30% reduction in ice shelf extent over 3 years, the total area of the Canadian ice shelves was reduced to 720 km^2 (8% of the 1906 baseline).

The break-up of thick, 40- to 70-year-old multiyear landfast sea ice along the northern coast of Ellesmere Island between 2005 and 2008 (Mueller et al., 2008) has stymied the regeneration of ice shelves that calved during the early to mid-1900s (Evans and England, 1992), and indicates that the Ellesmere ice shelf loss is now irreversible. The loss of multiyear ice that often fringes ice shelf calving fronts and the presence of open water along the coast have also contributed to the recent decline in the Ellesmere ice shelves (Copland et al., 2007). The northern coast of Ellesmere Island has warmed by approximately 2°C since 1948, with most of this increase occurring in the fall and winter (Copland et al., 2007). Under IPCC scenario A1B the Arctic is projected to warm by an additional 5°C with an increase in precipitation of 18% over the next century (Christensen et al., 2007). An increase in winter precipitation is unlikely to reverse this process, although it might slightly retard the average ice shelf surface mass wasting of 6 cm/year (water equivalent) recorded since the 1950s (Braun et al., 2004). Given indications that these ice shelves are currently at or beyond their thermal limit of viability (Copland et al., 2007), it is very likely that they will continue their collapse in the future with reductions in sea ice exacerbating their decline (Mueller et al., 2008; Copland et al., 2010) (Fig. 11) (see also Section 2.2.1). Since this text was originally prepared, further losses have occurred, including a further 65-70 km^2 from the Ward Hunt Ice Shelf in August 2010 (Sharp and Wolken, 2010).

It is difficult to predict when Arctic ice shelves will disappear completely but the extent of loss over the past century is extraordinary. The influence of under-ice processes is not well understood and recent changes in thickness of these ice shelves have not yet been determined.

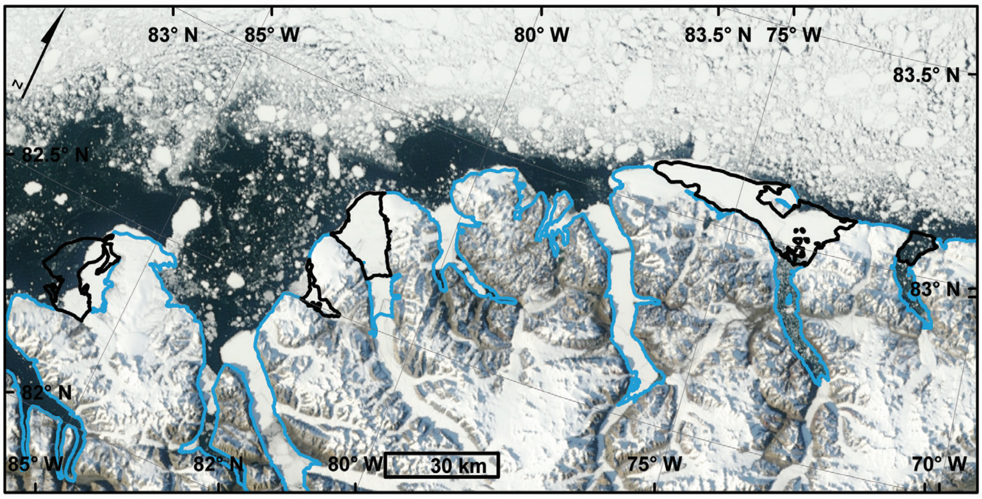


Figure 11. Ellesmere Island ice shelves at the end of August 2008. The 2007 ice shelf extent is outlined in black and coastline in blue. Left to Right: Serson, Petersen, Milne, and Ward Hunt. The unusually wide expanse of open water along the coast likely contributed to the 2008 break-up of three of these ice shelves. 29 August 2008 MODIS image from the Rapid Response System.

Tidewater glaciers are present in many Arctic regions, including Greenland, eastern Nunavut (Canada), Novaya Zemlya, Franz Josef Land, Svalbard, and other small islands (e.g. Sharov, 2005; Burgess et al., 2005; Dahl-Jensen et al., 2009). Many of these show evidence of recent retreat, some changing from tidewater to land-based termini, and this retreat has exposed new coastlines to delta formation, reworking by waves, and other processes (e.g. Ziaja et al., 2009).

Recent results show a continuing decline in the area of the 35 widest outlet glaciers from the Greenland Ice Sheet through 2010 – seven of the 35 advanced over the year 2009-2010, but the mean ice-front retreat over the past 10 years was 1.7 km (Box et al., 2010). The trend for the years 2000-2009 was -104 km^2/year. In August 2010, a large fragment 290 km^2 in area detached from the terminus of the Petermann Glacier emptying to Nares Strait (Box et al., 2010). This was the fourth massive calving event over the past 59 years (Johannessen et al., 2011).

2.1.5 Changing sea levels

Observed trends

Proshutinsky et al. (2004) collected and analyzed relative sea-level monthly data (1954-1989) from the 71 tide gauges in the Barents, Kara, Laptev, East Siberian and Chukchi Seas in order to estimate the rate of sea-level change and major factors responsible for this process in the Arctic Ocean. The data were posted at the Permanent Service for Mean Sea Level (PSMSL) web site (http://www.pol.ac.uk/psmsl/). It was found that the Arctic Ocean sea-level time series showed pronounced decadal variability which

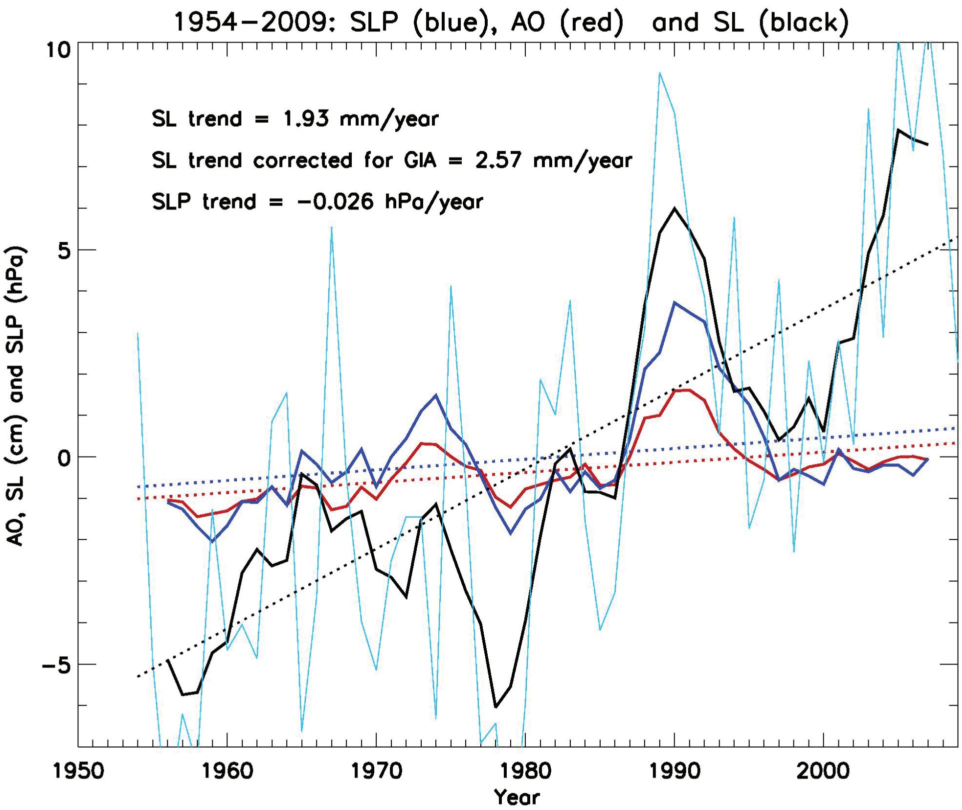


Figure 12. The 5-year running-mean time series of annual mean sea level (1954-2007) at nine tide gauge stations located along the Kara, Laptev, East Siberian, and Chukchi Sea coastlines (black line). The red line is the anomaly of the annual mean Arctic Oscillation Index multiplied by 3. The dark blue line is the sea-level atmospheric pressure at the North Pole (from NCAR–NCEP reanalysis data) multiplied by −1. Light blue line depicts annual sea level variability. Dotted lines depict estimated trends for sea level, Arctic Oscillation, and sea-level pressure.

corresponds to the variability of the North Atlantic Oscillation index. Proshutinsky et al. (2004) employed statistical methods together with numerical models and estimated the contributions of various factors to the observed sea-level change, leading to the following conclusions.

- The contributions to the observed rate of sea-level rise from the steric, inverse barometer, and wind effects were estimated as 0.64 mm/year, 0.56 mm/year, and 0.18 mm/year respectively.
- Subtracting the influence of these factors and estimates of glacial isostatic adjustment (GIA) from the observed regional sea-level trends, Proshutinsky et al. (2004) speculated that the residual term of the sea-level rise water balance (0.48 mm/year), was associated with increased ocean mass in the Arctic Ocean and the global ocean due to melting of ice caps and small glaciers and adjustments of the Greenland and Antarctic ice sheets to observed climate change.

Figure 12 shows sea-level time series from nine coastal stations having representative records for the period of 1954–2007 in the Siberian seas (from the Arctic and Antarctic Research Institute data archives; Proshutinsky et al., 2007). There is a positive sea-level trend along Arctic coastlines of 1.94 ± 0.47 mm/year for 1954–89 (not shown in Fig. 12), after correction for GIA. This compares to an estimated rate of 1.85 ± 0.43 mm/year over the same period, based on the 40 longest and most complete records of the 71 Arctic coastal stations available to Proshutinsky et al. (2004). The addition of 1990–2009 data increases the estimated rate of SL rise for the nine stations in the Siberian Seas, beginning in 1954, to 2.57 ± 0.45 mm/year after correction for GIA (Proshutinsky et al., 2010). This is considerably larger than the rate of 1.94 ± 0.47 mm/year for the entire region. Both estimates are higher than the mean rate of sea-level rise for the global ocean estimated by the Intergovernmental Panel on Climate Change (IPCC) as ~1.8 mm/year for 1961 to 2003 (IPCC, 2007a), more recently revised to 1.6 ± 0.02 mm/year (Domingues et al., 2008). Note the time period included in our estimate (1954-2007) is longer than the IPCC time interval and sea level in the Arctic rose significantly during 2000-2008, with a slight reduction in 2009 (Proshutinsky et al., 2010).

From the beginning of the record until 1996, sea level correlates relatively well with the time series of the Arctic Oscillation (AO) index and sea-level atmospheric pressure at the North Pole (Fig. 12). In contrast, from 1997 to 2007, sea level generally increased despite the relatively stable behavior of AO and sea-level pressure, indirectly indicating that after 1996 something other than the inverted barometric effect dominated sea-level rise in the region. Among possible candidates are ocean expansion due to heating, freshening, and wind-driven effects.

Glacial isostatic adjustment and implications for relative sea-level change in the Arctic

Relative sea-level (RSL) change occurs through a combination of changes in the volume of water in the oceans and local vertical land motion. Changes in the ocean volume (eustatic changes) occur by addition or removal of water and by changes in water density (steric effects). In the Arctic, glacial isostatic adjustment (GIA) is the dominant source of vertical land motion, although tectonics also play a role. GIA is the continuing response of the Earth to past changes in glacier and ice-sheet loading. Where the ice was thick, causing subsidence of the Earth's crust, mantle material flowed outwards and caused uplift outboard of the ice sheet. Upon deglaciation, the central depressed region

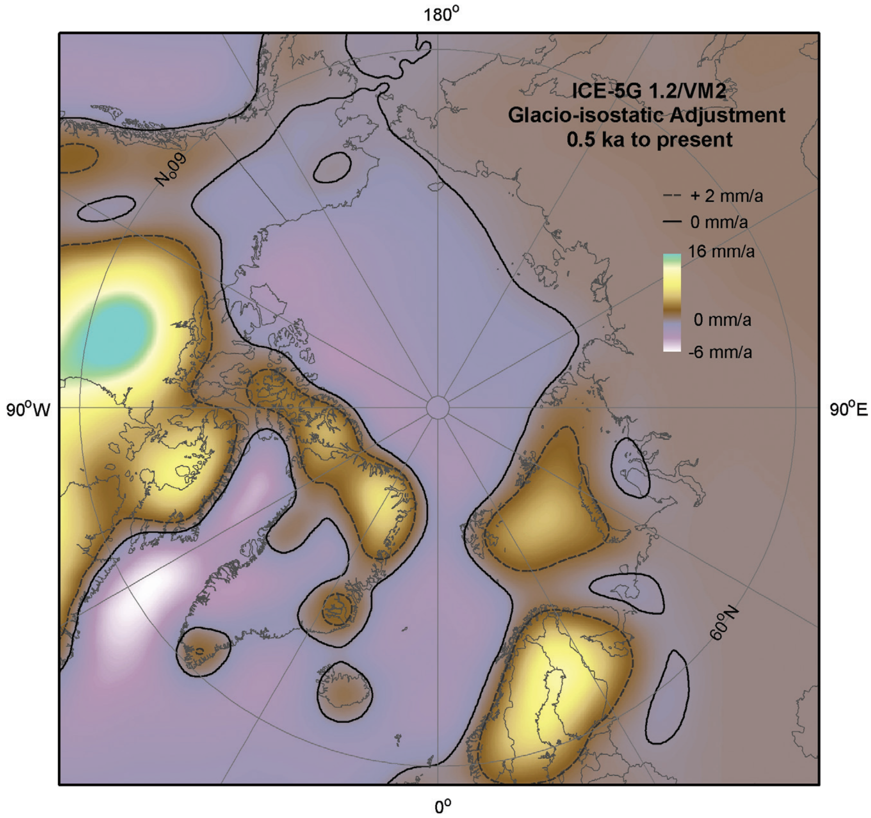


Figure 13. Rates of crustal uplift from glacial isostatic adjustment predicted by the ICE-5G 1.2/VM2 model.

began to rise and uplifted areas began to subside. Because the Earth's mantle behaves like a very viscous fluid, GIA is still continuing today (Fig. 13).

ICE-5G is a global GIA model spanning the last glacial-interglacial period (Peltier, 2004). It is based on geological information on ice-sheet history and on past sea-level change. The map shows vertical motion from Ice-5G averaged over the last 500 years. The solid line separates areas of subsidence (purple to white tones) and uplift (brown to green tones). Notable areas of uplift such as the central Canadian Arctic and Scandinavia correspond to centres of ice accumulation during the last glaciation.

Globally, eustatic sea-level rise is expected to accelerate from increased meltwater addition and thermal expansion over coming decades. Rates of eustatic sea-level change will vary regionally because of the gravitational effects of changing ice sheets ('sea-level fingerprinting', Mitrovica et al., 2001; James et al., 2011) and spatial variability in the steric effect. Where crustal uplift rates exceed the regional rate of accelerated sea-level rise, RSL is projected to fall. Regions that are subsiding will experience RSL rise larger than the projected regional eustatic rise. Where uplift is slower than 2 mm per year (dashed line in Fig. 13) – the approximate 20th century global mean sea-level rise – continuing RSL rise is expected; regions rising more rapidly may experience RSL rise or fall, depending on the regional eustatic sea-level change and the speed of land uplift.

Future projections

IPCC (2007a) projects from 0.18 to 0.59 m globally averaged sea-level rise at the end of the 21st century (mean for 2090-2099 relative to mean for 1980-1999), depending on the climate-change scenario. There is growing evidence for accelerated contributions of water from ice sheets, ice caps and mountain glaciers (Alley et al., 2005, 2008; Velicogna and Wahr, 2006; Rignot et al., 2008; Dahl-Jensen et al., 2009; Pritchard et al., 2009; Radić and Hock, 2011). A number of papers have been published since the cutoff for the Fourth Assessment Report (AR4) of the IPCC (2007a), many projecting rates of global mean sea-level rise considerably higher than the AR4 (Rahmstorf, 2007; Horton et al., 2008; Pfeffer et al., 2008; Grinsted et al., 2009). The most extreme projection (Vermeer and Rahmstorf, 2009) ranged from 0.75 to 1.90 m (1990-2100), but Pfeffer et al. (2008) also showed that a sea-level rise greater than 2 m by 2100 is physically implausible. At the time of this report, there are no estimates of sea-level rise specifically for the Arctic Ocean.

It is important to note that projections relevant to communities, infrastructure, or habitat impacts need to incorporate vertical land motion, in other words the impacts depend on the relative sea level change. In addition, parts of the Arctic are particularly sensitive to the gravitational 'finger-printing' effect of the Greenland Ice Sheet (Mitrovica et al., 2001) and this needs to be taken into account in developing relative sea-level projections for the Arctic (James et al., 2011).

2.1.6 Freshwater, solute, and suspended particulate fluxes to the Arctic Ocean

It is now widely recognized that the Arctic Ocean and its surrounding seas receive disproportionate inputs of fresh water and dissolved organic matter from rivers compared to other major ocean basins around the world (Aagaard and Carmack, 1989; Serreze et al., 2006; Opsahl et al., 1999; Dittmar and Kattner, 2003; Rachold et al., 2000; Raymond et al., 2007), while inputs of total suspended sediments, particulate organic matter, and dissolved nutrients are relatively low (Holmes et al., 2000, 2001; Gordeev, 2006; Emmerton et al. 2008b). However, estimates of water and water-borne constituent fluxes from the pan-Arctic watershed are currently undergoing major revisions. Several studies have documented changes in the timing and magnitude of Arctic river discharge that may be linked to climate change (Déry and Wood, 2005; Déry et al., 2005; McClelland et al., 2004; Peterson et al. 2002; Yang et al., 2002, 2003, 2007; Shiklomanov and Lammers, 2009; Overeem and Syvitski, 2010). At the same time, estimates of solute and suspended solid fluxes from Arctic rivers are being revised to account for seasonal variations in constituent concentrations (Raymond et al., 2007; Cooper et al., 2008). While seasonality has long been acknowledged as a defining feature with respect to Arctic river export, recent efforts such as the Pan Arctic River Transport of Nutrients Organic Matter and Suspended Sediments (PARTNERS) project have improved seasonal data coverage and thus facilitated better estimates of export (McClelland et al. 2008).

Annual river discharge to the Arctic Ocean increased by an average of ~7 km^3 each year over the 1964-2000 time period, with a large increase from Eurasia tempered by a small decrease from North America (McClelland et al., 2006). On the other hand, Overeem and Syvitski (2010) report an increase of +2% over 1964-2000 for the Canadian Arctic. Shiklomanov (2010) reports an increasing trend of discharge in both regions, amounting to 2.9 ± 0.4 km^3/year for the six largest Eurasian rivers over the 1936-2008 time interval, with a higher rate of increase in the past 20 years. The trend for four North American rivers (Yukon, Mackenzie, Peel, Back) was positive for 1970-2008 interval but with a large uncertainty [this selection of rivers should perhaps be revisited to exclude the

Figure 14. Plumes of suspended sediment in outwash discharge to Eclipse Sound from Bylot Island, eastern Canadian Arctic.
Source: D.L. Forbes, Geological Survey of Canada, 2009

Yukon, which discharges to the Bering Sea]. Changes in precipitation, evaporation, and a variety of permafrost characteristics have been identified as potential contributors to the changes in annual river discharge, with the relative importance of these different drivers varying across watersheds (Ye et al., 2003; McClelland et al., 2004; Hinzman et al., 2005; Yang et al., 2007). Changes in the seasonality of river discharge are also dependent on the above mentioned drivers. However, snow cover characteristics (i.e. extent, water equivalent, and timing of melt) are particularly important with respect to the timing and magnitude of the spring freshet (Kane et al. 2000; Woo, 1986; Yang et al. 2003). Warming caused snowmelt to begin earlier in northern regions during recent decades (Yang et al., 2002, 2003; Zhang et al., 2000) and melt month discharge increased considerably (Overeem and Syvitski, 2010). Furthermore, enhanced melting from Arctic glaciers and ice caps will enhance the discharge of fresh water and sediment from glacial sources (Fig. 14). It is noteworthy that the freshwater discharge record shows a high negative correlation with sea ice extent in the Arctic Ocean ($r = -0.72$ for the Eurasian rivers 1979-2008), suggesting that both are affected by large-scale hemispheric climate patterns (Shiklomanov and Lammers, 2009).

Seasonal variations in constituent concentrations are tightly linked to seasonal variations in water flow, with some constituents becoming diluted during high flow while others are enriched (McClelland et al., 2008). For example, nitrate concentrations often exceed 10 μM during later winter (minimum flow) but decrease by 50 to 90 percent during the spring freshet and remain low throughout the summer. Silicate also shows a strong dilution effect, as do many of the major ions and trace elements associated with mineral weathering. In contrast, dissolved organic carbon (DOC) concentrations increase by 1.5 to 4.5 times between winter low flow and spring peak flow causing a large percentage of the annual DOC flux to occur over just a few weeks (Rember and Trefry, 2004; Finlay et al., 2006; Neff et al., 2006; Raymond et al., 2007; Holmes et al., 2008). Particulate organic matter (carbon and nitrogen) concentrations are also positively correlated with discharge.

Along with revised estimates of organic matter export that account for higher concentrations during the spring freshet, there is mounting evidence of seasonal changes in organic matter quality. Several previous studies that focused on summer conditions concluded that DOC in Arctic rivers was refractory, at least over time-scales relevant to the coastal zone and transport across the shelf. However, recent work demonstrated surprisingly high lability of DOC during the spring high-flow period (Holmes et al., 2008). This has far-reaching, yet unknown consequences for Arctic Ocean productivity, as this organic matter is a direct source of energy for secondary production and a potential important indirect source of nutrients fueling new production once remineralized. Furthermore, studies have indicated that the DOC exported during the spring freshet has a higher UV absorbance (Spencer et al., 2008) and therefore will compete with phytoplankton for light and impact remote sensing interpretation.

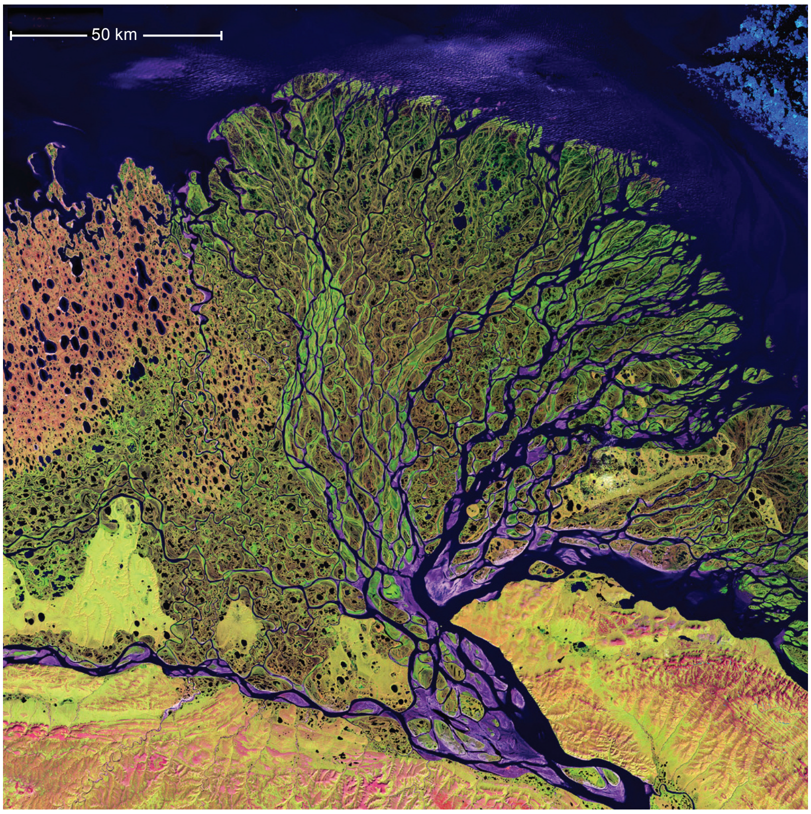
While estimates of river export from the pan-Arctic watershed are improving, studies of nutrient and organic matter dynamics in Arctic river deltas and nearshore ocean waters (Carmack et al., 2004; Dunton et al., 2006; Emmerton et al., 2008a) remind us of the importance of the marginal filter in determining what is ultimately supplied to offshore waters (Lisitsyn, 1995). Very few studies have focused on river delta and nearshore environments in the Arctic to date, particularly with respect to seasonal dynamics. More studies focusing on these important transitional environments are essential for improved understanding of Arctic river-ocean linkages in the future.

Carbon export to the Arctic Ocean also results from coastal erosion, which in some cases is comparable to or greater than nearby fluvial sources. Quantification of this component was a major objective of the ACD Project (Rachold et al., 2005b). A number of detailed studies were undertaken in support of this objective, quantifying contributions from several parts of the Arctic coast (e.g. Rachold et al., 2000; Brown et al., 2003; Jorgenson and Brown, 2005; Vasiliev et al., 2005; Streletskaya et al., 2009; Couture, 2010). A major driver of the ACD circum-Arctic coastal classification and mapping activity was to support estimates of total carbon flux from coastal sources for the entire basin (e.g. Lantuit et al., 2009, 2011). Lantuit et al. (2011) provide data on total carbon content in coastal sediments and on coastal erosion rates, permitting a first-order estimate of the contribution from coastal erosion, but they highlight the high spatial variability and extensive stretches of coast with low carbon content as complications in developing a robust estimate. The mean organic carbon content in Arctic coastal deposits is approximately 2% (by mass) but ranges from near 0% to >15%, with the highest proportions along the US Beaufort and Chukchi coasts. Of 22 segments with organic carbon content >10%, 16 were on the US Beaufort Sea coast, 4 on the Canadian Beaufort Sea coast, and 2 bordering the Kara Sea in northern Russia (Lantuit et al., 2011).

2.1.7 Arctic deltas

Arctic deltas share many similarities with their counterparts in temperate regions, but the presence of ice in the form of permafrost (on land and in the shallow nearshore) and seasonally persistent sea and river ice have a significant influence on hydrological and sedimentological processes. Reviews of Arctic deltas (e.g. Walker, 1998, 2005; Forbes and Hansom, in press) emphasize the extreme seasonality of processes, with very low flows throughout the winter season and a large proportion of the annual discharge delivered during the spring freshet.

Figure 15. The Lena River delta in the Laptev Sea, northern Russia, is the second largest delta in the world and the largest in the Arctic.



The Lena is the largest Arctic delta, with an area of 29 000 km^2, and forms a broad lobe about 260 km wide, projecting more than 100 km seaward of the general line of the coast in the region (Fig. 15; Aré and Reimnitz, 2000; Schneider et al., 2009). This morphology attests to long-term dominance of delta sedimentation over wave reworking, which may in part reflect the influence of sea ice in limiting wave action, but lack of accommodation space may have played a larger part and adjacent coasts are known to have rapid rates of shoreline retreat (Aré et al., 2008; Lantuit et al., 2008a; Sánchez-Garcia et al., 2009). Fronting on the southeastern Beaufort Sea in northwestern Canada, the Mackenzie Delta is the second largest Arctic delta, with an area of about 13 000 km^2 (Burn and Kokelj, 2009). In contrast to the Lena, the Mackenzie Delta occupies a glacially-scoured trough and does not project seaward. It forms a roughly rectangular alluvial plain 210 km long and about 60 km wide. The active delta front is wider because the delta aggraded under rising sea levels and spread over older deposits to the east in its outer reaches (Hill et al., 2001).

While smaller deltas in areas of isostatic rebound are the modern active components of raised-delta sequences representing full postglacial time (e.g. Lavoie et al., 2002; Lønne and Nemec, 2004; Briner et al., 2006), most Arctic deltas in regions of isostatic subsidence are relatively recent features (Walker, 1998; Aré and Reimnitz, 2000; Hill et al., 2001). These formed as the rates of Holocene sea level rise slowed about 5000 years before present. As with other deltas, their stability depends on a fine balance between sediment supply, subsidence, relative sea level and wave and tidal forces. Despite the fact that the Mackenzie River is the largest source of sediment to the Arctic Ocean (Rachold et al., 2000; Gordeev, 2006), most of the subaerial delta front is eroding at rates from 1-2 m/year, and more than 16 m/year locally (Solomon, 2005). This has been attributed to a late-Holocene expansion of the delta front as described above (Hill et al., 2001).

All of the deltas which are fed by the larger rivers (e.g. Lena, Yenisey, Ob, Mackenzie) are characterized by vast southern drainage basins which experience spring thawing well in advance of that at the river mouths. Thus, spring melt water reaches the Arctic Ocean when temperatures there are still below freezing and thick ice (1-2 m) covers the river and ocean surface. As a result, breakup of the ice on the delta and adjacent ocean occurs earlier than on adjacent coasts that are unaffected by river influences. Prior to the onset of the spring freshet the shallow portions of the subaqueous delta are characterized by ice frozen directly to the seabed and channel-mouth cross-sectional areas beneath sea ice are reduced. Aré and Reimnitz (2000), following Dupré and Thompson (1979), suggest that the extensive shoal fronting several Arctic deltas, controlled by the extent of bottom-fast ice (typically about 2 m deep), is a characteristic feature of Arctic deltas. During the rising limb of the spring hydrograph, the preconditioning by ice development during the winter results in upwelling of river water along the boundaries between bottomfast and floating ice and extensive overflow onto the surface of the sea ice. While there are few measurements of current velocity in ice-constrained channels, it is believed that high velocity and erosion can occur beneath the ice. Overflow waters extending many kilometers over the sea ice can deposit thick layers of sediment on the ice (Walker 1998; Forbes et al., 1994), but initial spring overflow off the Mackenzie Delta is typically clear water and little sedimentation on ice was observed there (Solomon et al., 2008b). Overflow waters drain through cracks and holes in the ice, where the flow is focused on the seabed to create 'strudel scours' (Reimnitz et al, 1974), as much as 4 m or more deep (below seabed) and tens of metres in diameter (Solomon et al., 2008b; Hearon et al, 2009). Spring breakup of the river is accompanied by ice jams which can cause backwater flooding hundreds of kilometres upstream from the jam. Flood waters inundate the surface of the deltas for days at a time and river banks are undercut causing erosion by failure of frozen blocks of silt. In much of the Arctic, the tidal range is small (<1 m) and the impacts of storm surges (generating combined tide-surge water levels 2-3 m above mean) can be felt many km upstream from the coast (Walker, 1998; Marsh and Schmidt, 1993).

Permafrost and ice-bonded sediments are ubiquitous in the Arctic deltaic environment. Sediments deposited on the delta surface become frozen and are buried in that state once their depth exceeds that of the active layer. As opposed to the burial of unfrozen material in temperate deltas, this may prevent full compaction of these materials until they reach a depth where average annual temperatures are greater than freezing. Permafrost processes also include the development of ice wedge polygons due to thermal contraction cracking, development and drainage of thermokarst lakes and formation of pingos in drained lake basins. Lakes and channels that are deeper than the seasonal ice thickness develop thawed zones (taliks) in the sediments beneath and adjacent to them. In larger features these taliks may penetrate the entire thickness of permafrost allowing compaction of the previously frozen sediments and creating the potential for differential subsidence beneath lakes and channel versus the surrounding subaerial delta surface. The potential for differential subsidence will be exacerbated in cases where the delta has overtopped older surfaces where permafrost may be much colder and deeper.

Although there are no comprehensive studies of the changes to Arctic deltas, they are at risk from a variety of natural processes and human activities. Accelerating rates of sea level rise will raise base levels and threaten to increase erosion rates, especially when combined with the potential for increased wave and storm surge activity caused by decreasing sea ice extent and duration. The extent to which this effect may be offset by increased river run-off due to precipitation increases is not known. Development resulting from an increase in demand for resources, especially oil and gas, is an increasingly important factor affecting delta stability.

2.1.8 Unlithified coasts (erosional and depositional systems)

Unlithified, ice-bonded sediments characterize 65% of the coast facing directly onto the Arctic Ocean (Lantuit et al., 2011) and smaller proportions of other coasts in the Canadian Arctic Archipelago, Greenland, and elsewhere. Unlithified sediments exposed at Arctic coasts formed mainly under permafrost conditions during the Quaternary. Often relatively low in elevation and flat lying, these are preferred locations for the development of permanent settlements on the coast. The presence of ice-bonded permafrost in the sediments lends them a transient strength, but they are highly susceptible to erosion and redistribution upon thawing (Fig. 16). Rates of shoreline change vary considerably around the Arctic and even very locally due to combinations of geological and biological properties of the coastal materials (e.g. ice content, vegetation and sediment type), coastal morphology (e.g. exposure, elevation, slope) and the way that they mediate the response of the coast to climate and oceanographic forcing (e.g. waves, sea and air temperature). Accumulative features (beaches, spits, and barriers) are also common along many Arctic coasts and represent the transport of the coarser erosion products along the shoreline (Forbes and Hansom, in press). As on temperate coasts, waves, currents and water levels are major forcing parameters. However, in the north, sea surface temperature and salinity are also very important in that high values of both contribute to thaw of the ice-bonded sediment in the shore-zone and shallow seabed (Anderson et al., 2009).

Rates of coastal change have been monitored and measured along most of the populated Arctic shores using a combination of in situ and remotely sensed observations. Data on retreat rates usually suffer from some degree of temporal aliasing in that frequency of

Figure 16. Undercut cliff in ice-bonded sediments and massive ice following August 2000 storm surge, Tuktoyaktuk, Northwest Territories, Canada.
Source: S.M. Solomon, Geological Survey of Canada

site visits may not be sufficient to adequately define the processes affecting a coastal reach. Thus, data from monitoring sites can best be described as providing an averaging or integration of multiple events and processes. Some of these data along with relevant information about coastal characteristics have been collated by the Arctic Coastal Dynamics Project and will soon be available on-line (Lantuit et al., 2011).

Long-term (decadal) rates of coastal change are typically in the 1-2 m/year range, but vary up to 10-30 m/year in some locations (e.g. Aré, 1988; Reimnitz et al, 1988; Harper, 1990; Jones et al 2009a, 2009b; Jorgensen and Brown, 2005; Solomon, 2005; Vasiliev et al, 2005; Barnhart et al., 2010). Most of the literature notes that storm events play a significant role in controlling the short term rate of coastal change. Solomon and Covill (1995) describe the impact of a severe event at several sites along the Canadian Beaufort Sea coast. Maximum retreat rates resulting from the storm exceeded 20 m at one location and spits migrated landward. Single events may cause erosion at rates of 2-3 times the longer term average.

Parts of the Arctic coastal plain have large numbers of lakes, variously of kettle, thermokarst, or other origins, which are intersected by marine transgression and shoreline retreat. This results in a transformation from freshwater lakes to lagoons or bays, often involving the coalescence of multiple basins, with spits or barrier islands developed along the outer coast (Zenkovich, 1985; Ruz et al., 1992; Hill et al., 1995; Solomon et al., 2000; Mars and Houseknecht, 2007; Jorgenson and Shur, 2007). Hypersaline conditions may develop under ice in winter (Forbes et al., 1994) and occasionally persist through the summer (Smith et al., 2006). The barriers generally have low crest elevations resulting from frequent and extensive overwash under storm-surge conditions, with sediment transport into the back-barrier lagoons, although sites with higher backshore terrain exhibit seaward sediment losses under storm conditions (Héquette and Hill, 1995; Héquette et al., 2001).

Large-scale spits, barrier beach complexes, and forelands have developed in a number of places throughout the Arctic (Zenkovich, 1985; Mason and Jordan, 1993; Ogorodov, 2003). These represent major sediment sinks, may host important archeological sites, are important nesting sites for some bird species, and in some cases are occupied by seasonal or permanent communities. With rising sea levels and more open water and storm impacts, some such communities in Alaska are facing the possibility of relocation (see below).

To date it remains difficult to discern the impacts of changing climate on Arctic coasts. Some studies report no statistically significant change between decadal averages since the 1970s (e.g. Solomon, 2005), others report a cyclic pattern which may be attributable to regional or global climate oscillations (Vasiliev et al., 2005). Some recent papers have reported significant rapid increases (e.g. doubling of the rate over about a 40 year time-frame – Brown et al., 2003; Mars and Houseknecht, 2007; Arp et al., 2010; Jones et al., 2009b). There is growing evidence that accelerated erosion may be attributed to retreating sea ice, changes in storm wave energy, and increased sea-surface temperature (Jones et al., 2009b; Overeem et al., 2010; Barnhart et al., 2010; see Section 2.1.9) or also to increases in the frequency and severity of storms (Brown et al., 2003; Arp et al., 2010).

Coastal erosion in the Arctic is threatening community and industrial infrastructure. The plight of several communities in Alaska has been widely documented pointing to the need to move to safer sites (Bronen, 2009; Oliver-Smith, 2009). A report on the erosion status of Alaskan villages by the US Army Corps of Engineers (2006) states that for several of the villages along the Chukchi coast (Shishmaref and others; Fig. 2), sea ice is forming later in the season, exposing the villages to more frequent or more damaging storms. Coastal erosion is also affecting industrial infrastructure. Besides the threat to buildings, many landfills, sewage lagoons and water sources are located in locations where they can be impacted by erosion which could cause environmental damage as well as threatening human health.

Coastal erosion in the Arctic is not a new phenomenon and many Arctic communities have been dealing with it for years. However, there are no comprehensive global assessments of the vulnerability of Arctic communities and infrastructure to accelerated coastal erosion. The US Army Corps of Engineers (2006) report provides a synopsis of the situation for threatened Alaskan communities. The situation in some communities is sufficiently dire that they are considering immediate relocation (e.g. Shishmaref (http://www.shishmarefrelocation.com/). In other cases (e.g. Tuktoyaktuk – Johnson et al., 2003; Catto and Parewick, 2008), phased retreat to a new location is an option which is now being considered (http://www.cbc.ca/technology/story/2009/09/08/climate-change-tuktoyaktuk-erosion.html; http://hosted.ap.org/specials/interactives/_science/tuktoyaktuk/). 'Hard' protection in the form of sea walls and revetments is costly and because funds are limited, the design and/or construction may not be adequate. Even wealthier communities in temperate regions are faced with the need to reconstruct protection measures following severe events (e.g. levee failures during Hurricane Katrina). Hard protection also has consequences for the stability of adjacent locations without protection. Softer forms of protection such as beach nourishment have been attempted in some communities. In Barrow, Alaska, this form of protection was implemented, but was terminated following the destruction of the dredge during a storm. In general, the successes or failures of protection options have not been well documented, if at all.

2.1.9 Permafrost and ground ice

Ground ice is a distinctive feature of polar coastal systems with important implications for the development of Arctic coasts (Fig. 16). Its distribution is highly variable, based primarily on the regional environmental history and its impact on permafrost formation. Specifically, the distribution of continental and alpine glacial ice masses during stadials determined the spatial distribution and temperature at depth of modern permafrost (Fig. 17). Where the land surface was unglaciated, land-atmosphere energy exchange led to the deep penetration of cold permafrost. In regions with a strongly continental climate, thermal contraction cracking and annual meltwater produced large volumes of ground ice, exceeding 80 vol% in many regions. The most significant of these is spread across central and eastern Siberia, and is often referred to using a stratigraphic designation *Yedoma Suite* or *Ice Complex* for late Pleistocene (80 000 to 13 000 years old) polygenetic, organic-rich and ice supersaturated deposits (Schirrmeister et al., 2010). Sea-level rise since the last glacial maximum has elevated the modern coastline around 120 m. In regions where isostatic rebound does not occur, the coastline has generally moved inland, meaning that the current coastline developed under cold subaerial conditions. In this context, recent increases in sea surface temperature throughout the Arctic (Steele et al., 2008), in large part driven by increased solar heating as a result of sea-ice retreat, may play a prominent role in accelerating coastal erosion (Overeem et al., 2009, 2010; Wobus et al., 2008, 2009, 2010). At the same time, the persistence of bottomfast ice helps stabilize ice-bonded sediments and can significantly impact the state of the coast (Reimnitz, 2000; Solomon et al., 2008a, 2008b). While Solomon and co-workers have made great progress in mapping bottomfast ice extent in the Mackenzie Delta region, its distribution and potential changes in the pan-Arctic are poorly understood. Where transgression resulted in the inundation of permafrost, ground ice can also persist beneath the water column, as submarine ground ice (Mackay, 1972).

The presence of ice distinguishes coastal dynamics in the Arctic from temperate and tropical systems. Sea ice and ground ice can both limit and enhance erosion processes. The high ground ice content and the generally fine-grained unlithified material in some areas render the coast sensitive to waves and storm surges in the short summer, and annual erosion rates are relatively high (Aré et al., 2008). Historical data on coastal change in the Arctic are not as widely available as in the more heavily populated south. The critical and relevant question along much of the Arctic coast is the current trajectory and rate of coastline change.

Nonetheless, how these processes play out on different time and spatial scales is not straightforward. Previous studies have sought a correlation between coastal retreat rates and ground ice content (Lantuit et al., 2008b; Héquette and Barnes, 1990; Kobayashi et al., 1999). These studies suggest that the presence of ground ice can enhance coastal erosion, but find at best weak correlations between the two. Others have suggested that consequences of ground ice thaw in the coastal zone, such as thermokarst features,

Figure 17. Circum-Arctic distribution of terrestrial and submarine permafrost, highlighting the coasts affected by the presence of subsea permafrost.
Source: Brown et al. (1997)

Figure 18. Ground ice exposure in the headwall of a coastal retrogressive thaw slump on Herschel Island, Yukon coast, Canada. The greyish layers are composed of more then 90% ice.
Source: M. Fritz, Alfred-Wegener-Institute. 2009

render the coast more susceptible to erosion (Lantuit and Pollard, 2005, 2008, Wolfe et al., 2001). The ice-rich coastal cliff is sensitive to increased air and sea surface temperatures, which increase thermo-abrasion (the combined action of waves and thawing of the permafrost) and thermo-denudation (erosion due to the warming and thaw of ground ice) (Fig. 18). Increased ground heat flux on the terrestrial side of the coast can thaw ground ice at the top of permafrost, leading to subsidence (a process called thermokarst). Subsidence due to thaw of excess ice is not being systematically observed, but is known to occur at rates exceeding 5 cm/year (Overduin and Kane, 2006). With warmer air and ground temperatures, deepening of the active (seasonal thaw) layer can result in thaw subsidence, with important implications for flood risk in low-lying coastal areas such as the Mackenzie Delta.

New insights are emerging from recent field studies combined with numerical modelling of bluff erosion in ice-rich silts along the Alaskan Beaufort Sea coast (Anderson et al., 2009; Overeem et al., 2009, 2010; Wobus et al., 2009, 2010; Barnhart et al., 2010), where 5-year mean coastal erosion rates (2002-2007) of ~14 m/year in ice-rich silt bluffs are double the long-term mean for 1955-1979 (Mars and Houseknecht, 2007). These studies point to the interaction between high sea-surface temperatures (reaching record levels in 2007 – Proshutinsky et al., 2010), which drive thermal abrasion and undercutting, and the timing of ice break-up and freeze-up in combination with storm dynamics. In contrast to results from gravel coasts in the eastern Arctic and other sites without permafrost (e.g. Forbes et al., 2008), later freeze-up exposing the coast to more fall storms with cooler water temperatures may be less effective in the Alaskan study area, where summer heating and thermal abrasion dominate the erosion process (Wobus et al., 2010) – in this case, earlier retreat of sea ice would be more effective in accelerating erosion rates (Overeem et al., 2010).

Inundated permafrost, separated from the atmosphere by a layer of sea water with a comparatively warmer mean annual temperature, is unstable and begins to degrade. Degradation occurs from below through geothermal heat flux and from above via heat transfer and penetration of salt water into the sediment, which results in a shift in the freezing point of the pore space fluid. The initial result of degradation from above is a decrease in sediment-column ice content and resulting subsidence, analogous to thermokarst processes on land. Dallimore et al. (1996) suggested that thaw settlement of ice-rich sediments in the nearshore zone could increase wave efficiency during storms by lowering the shoreface profile.

2.1.10 Gas hydrates

Gas hydrates are ice-like crystals comprising water and low-molecular-weight gases, usually microbial methane, which form within sediments under conditions of low temperature, high pressure, and adequate gas concentrations (Kvenvolden and Lorenson, 2001; Makogon et al., 2007). Methane hydrates are common in many Arctic settings in association with thick terrestrial permafrost (generally more than 250 m) and beneath Arctic shelves where terrestrial permafrost was submerged by marine transgression (Collett and Dallimore, 2000). Gas hydrate can occur both within ice-bonded permafrost (Dallimore and Collett, 1995) and many hundreds of metres beneath it. One ubiquitous feature of gas hydrates in nature is that they are often very close to their pressure-temperature equilibrium point where a modest increase in temperature or decrease in pressure can result in decomposition of the hydrate and release of the formerly hydrate-bound methane.

Because the global inventory of methane trapped as gas hydrates is thought to be enormous, there is concern over the potential for excess methane emissions if these deposits are destabilized by temperature and pressure changes (McGuire et al., 2009), such as might be induced, for example, by coastal retreat. In addition the dramatic strength loss when gas hydrates are dissociated with the release of free gas is recognized as a geohazard to offshore exploration and a possible factor influencing seabed processes. Assessing the importance of gas hydrates in coastal settings of the Arctic is challenging because they are difficult to detect using seismic data and for the most part can only be identified on industry well logs or in scientific core holes. Recently Paull et al. (2007) have suggested that degrading gas hydrates may be a factor influencing the formation of pingo-like features (PLFs) on the Beaufort Sea shelf. To date several hundred PLFs have been identified on this shelf.

Recent observations from the East Siberian Shelf point to large emissions of methane from seabed sediments (Shakhova et al., 2010a). They note that the "vulnerability of the subsea permafrost methane pool may lead to an unfortunate coincidental timing with anthropogenic greenhouse gas releases" (Shakhova et al., 2010b: 1647).

Northern peatlands and thaw lakes are also recognized as potential major sources of methane emissions to the atmosphere (Roulet et al., 1994; Zimov et al., 1997; Walter et al., 2006). Large numbers of methane seeps and considerable fluxes of CH_4 have been reported from Arctic deltas, notably the Lena Delta (Wagner et al., 2003, 2007) and the Mackenzie Delta, where a conical depression (pockmark) 10 m deep was formed by methane release in an outer-delta lake (Bowen et al., 2008).

2.1.11 Bedrock coasts

Bedrock coasts represent about 35% of the Arctic coastline (Lantuit et al., 2011; Fig. 2). On a circum-Arctic scale, bedrock coasts are most abundant in the central and eastern

Figure 19. Rock cliff near Longyearbyen, Svalbard.
Source: Hanne Chistiansen, University Centre in Svalbard

parts of Arctic Canada, Greenland, the Barents Sea region including Svalbard (Fig. 19), and the Taymyr Peninsula. The occurrence of Pleistocene glaciations is clearly a control on the large-scale distribution of bedrock coasts in the Arctic regions. Most of the Siberian lowlands and western part of the Alaskan coastal plain were non-glaciated during the Pleistocene and modern coastlines in these regions rarely have exposed rock.

Millimetre-centimetre accuracy is needed to measure expected coastal cliff retreat rates. Terrestrial photography/photogrammetry or terrestrial laser scanning are potential methods to quantify the volume of retreat with satisfactory spatial and temporal resolution (Rosser et al., 2005; Wangensteen et al., 2007). Air or space-borne data collection meanwhile has the disadvantage of vertical or oblique viewing angles of the sensors, thus reducing the ability to detect the spatial pattern of erosion. Due to these methodological constraints there are few data available on Arctic coastal bedrock retreat rates. Marine cliffs in general show a variety of erosion rates as a function of lithology, in extreme cases more than 1 metre per year down to millimetres per year for medium to hard rocks (Young and Saunders, 1986). Sunamura (1992) listed worldwide linear cliff retreat rates and found the following average rates: 1 mm per year for granite, 1-10 mm per year for limestone and 10 mm per year for shale. Cold regions generally have higher retreat rates and Allard and Tremblay (1983) found rates in the order of 10 mm per year for basaltic bedrock coast in Hudson Bay in northern Quebec, Canada. Wangensteen et al. (2007) measured rates of approximately 3 mm per year in dolomitic limestone in Svalbard. This rate is more the twice the estimates of non-coastal rock wall retreat in the same area (0-1.58 mm per year, Rapp, 1960; André; 1997; Berthling and Etzelmüller, 2007).

Resistant rock cliffs are generally considered stable over time-scales of 50 to 100 years. Even on a time scale of 100 years coastal erosion more than 1 metre is probably rare in medium to hard rocks. However, these estimates are uncertain. In Holocene lacustrine environments much higher rates of weathering in bedrock cliffs have been reported (Matthews et al., 1986; Aarseth and Fossen, 2004).

The appearance of the rock walls together with the quantity of angular rock fragments accumulating on the snow- and ice-foot below the cliffs during spring show that subaerial weathering is active and important together with the marine processes. The efficiency of marine processes is reduced by the ice-foot and sea ice protecting the coast during the cold season and shallow waters reducing the amount of wave energy reaching the shores in the ice-free period. This complicated interaction of subaerial and marine processes makes it difficult to make projections about the stability and development of bedrock coasts in the Arctic regions. It is even possible that coastal erosion may be reduced in a warmer climate if mechanical frost weathering processes become less effective (Ødegård and Sollid, 1993; Ødegård et al. 1995).

2.2. Ecological State of the Circum-Arctic Coast

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Contributing authors: B. Collen, T. Barry, D.L. Forbes, J. Loh, M. Gill, L. McRae, L. Sergienko

Key Findings

- Arctic coastal habitats are the prime lifeline for Arctic communities and provide a wide range of ecosystem services.
- They support very large populations of fish, mammals and birds that are harvested by Arctic and non-Arctic communities.
- The Arctic coastal zone provides habitat to an estimated 500 million seabirds alone.
- Arctic coastal habitats are highly vulnerable to changing environment conditions, including climate change and growing human activities such as oil and gas exploration and development.
- Arctic river deltas are biological hotspots on the circumpolar Arctic coast. They have high biodiversity and are extremely productive in relation to adjacent landscapes. The high biodiversity remains poorly understood, but may be related to the complex natural patterns of water level fluctuation that occur in these vast lake-rich systems.
- Arctic ice shelf microbial mat cryo-ecosystems are severely threatened by ice shelf collapse, with some of the richest examples already lost.

The assessment of coastal aquatic and terrestrial biodiversity is an important component of coastal zone management and the design of marine protected areas (Cogan 2003). This report aims to assess the available knowledge from previous regional and global assessments and more recent published literature on the status, trends and prognosis of Arctic coastal ecosystems. Sources include the Arctic Climate Impact Assessment (ACIA, 2005), the AMAP Oil and Gas Assessment (AMAP, 2007), the Arctic Marine Shipping Assessment (PAME, 2009a), the Millennium Ecosystem Assessment (UNEP, 2003, 2005), and the Arctic Biodiversity Trends -2010 (CAFF, 2010), as well as a selection of global assessment reports and the Circumpolar Biodiversity Monitoring Programme (CBMP) (AMAP, PAME, and CAFF being working groups of the Arctic Council - see Section 3.4.2).

The CBMP is an international network of scientists and local resource users working together to improve detection, understanding and reporting of important Arctic biodiversity trends. To achieve these objectives, it is developing a number of ecosystem-based, pan-Arctic integrated monitoring plans to coordinate Arctic biodiversity monitoring. The CBMP is the cornerstone program of the Arctic Council's Conservation of Arctic Flora and Fauna Working Group (www.caff.is) and represents the biodiversity component of the Sustaining Arctic Observing Networks initiative. The CBMP aims towards an integrated and sustained monitoring program and is based largely on a network of networks approach with expert monitoring groups, organized by biomes, including the coastal biome (Gill and Zöckler, 2008).

2.2.1 State of knowledge – habitats and species

Coastal seas

Much of the Arctic coast borders coastal seas or inter-island passages with varying degrees of enclosure, in some cases quite shallow with significant inputs of fresh water,

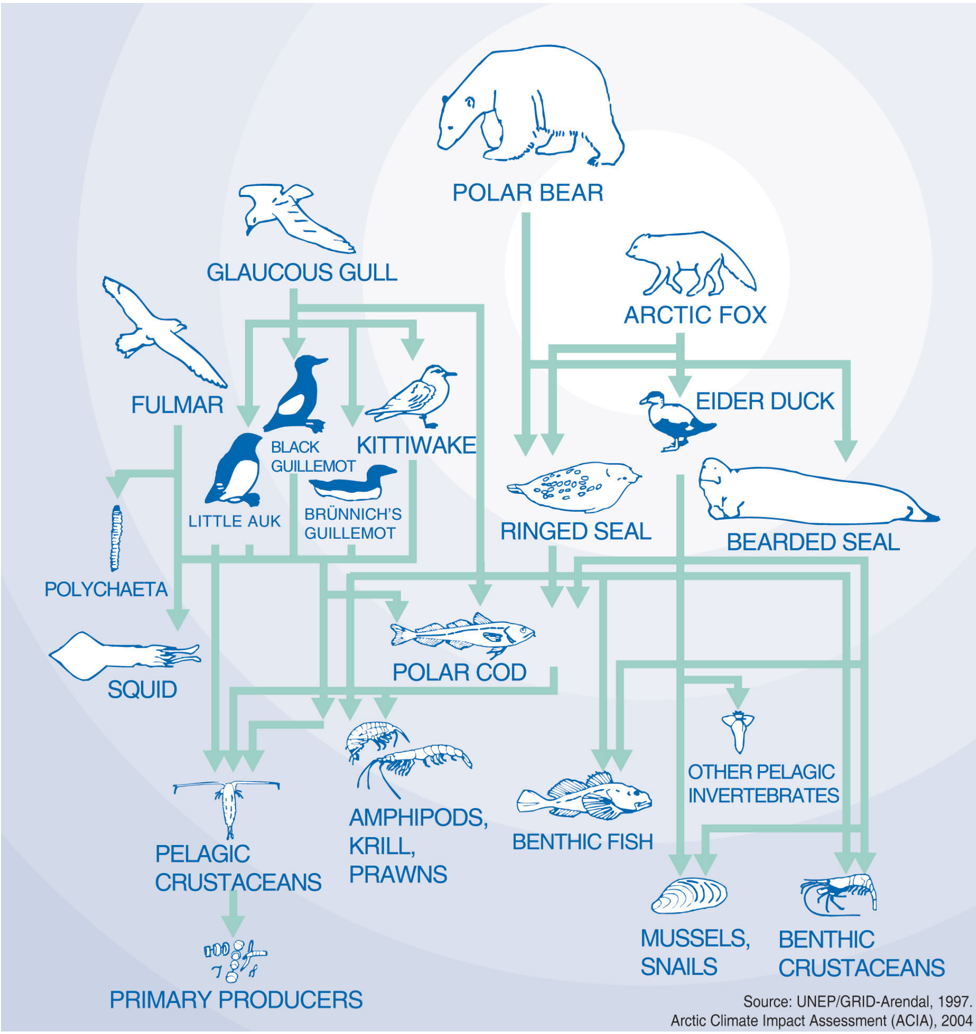


Figure 20. The coastal Arctic food web is closely related to drift ice conditions and seasonal use of shorelines by both terrestrial and marine mammals. Numerous species depend upon each other and on the transport of food between marine, coastal, and inland habitats.
Source: UNEP/GRID-Arendal.

nutrients, carbon, sediment, and contaminants (AMAP, 1997, 2002; Rachold et al., 2000). These coastal waters are critically important for northern coastal ecology and can be highly productive (Table 1) (e.g. Carmack and Macdonald, 2002; Clarke and Harris, 2003). Changes in circulation, temperature, salinity, productivity, and sea ice, among other factors, may have important implications for species success or survival, species invasion, ecological function, and biodiversity. Changes in sea ice, in particular, may also have impacts on ice-dependent or ice-limited species (Loeng et al., 2005; Mueter and Litzow, 2008) (Fig. 20).

Projected salinity changes in the Nordic Seas are generally small, except for areas influenced by coastal runoff and the melting of sea ice. If warming occurs within the Barents Sea over the next hundred years, thermophilic species (i.e., those capable of living within a wide temperature range) will outcompete others and become more prevalent. This is likely to force changes in the zoobenthic community structure and, to a lesser extent, in its functional characteristics, especially in coastal areas (Loeng and Drinkwater, 2007; Cochrane et al., 2009). Similar concerns have been identified for Baffin Bay and other Arctic coastal waters.

Area (103 km²)	Total primary production (g C/m²)	New primary production (g C/m²)	Grazing rate of zooplankton (g C/m²)
Alaskan coastal	50 –75	<20	32–50
Siberian coastal	>400	>160	>90

Table 1. Estimated levels of primary production, defined as the integrated net photosynthesis (corrected for respiration) over at least 24 hours, plus the grazing rate of mesozooplankton (compiled by Sakshaug, 2004, on the basis of data from several authors).

Past changes in northwest Atlantic circulation related to the North Atlantic Oscillation (NAO) have resulted in warmer water in southern Baffin Bay in the 1920s and associated recruitment and local spawning success of Atlantic cod (*Gadus morhua*), followed by a change of sign in the NAO, resulting in cooler temperatures, diminished spawning success, and less recruitment of juvenile cod from the 1970s to 1990s (Vilhjálmsson, 1997), with major impacts on the commercial fishery and economies of coastal communities (Hamilton et al., 2003).

Coastal wetlands (salt marshes, laida, estuaries and intertidal flats)

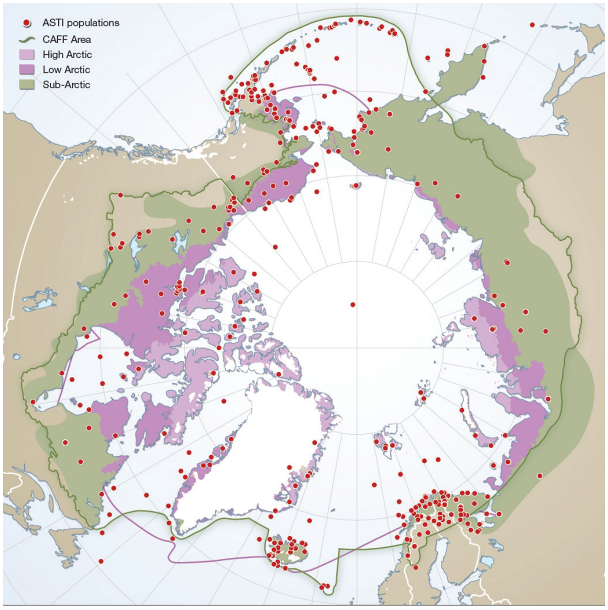
Coastal wetland habitats of open coasts, deltas, and river estuaries are an important element of the overall Arctic ecosystem (Martini et al., 2009). Representing the littoral halophytic floristic complex, salt marsh communities are among the most sensitive to environmental change. The most likely drivers of change in this region include rising sea level and the introduction of sediments and biogeochemical components due to coastal erosion from storm surges and warming-induced permafrost degradation (Rachold et al., 2000; Lantuit et al., 2009). Studies of the interactions between abiotic and biotic processes enable us to determine the impacts of development on coastal biology and geomorphology, facilitating efforts to project the response of the Arctic coastal zone to future changes.

Arctic coastlines are subject to extensive disturbance through processes such as thermal abrasion, wave erosion, storm-surge flooding, and sea ice grounding in the shore zone, with implications for species distribution and abundance. Genetic, range, or other adaptations by plant and animal populations require time. If environmental

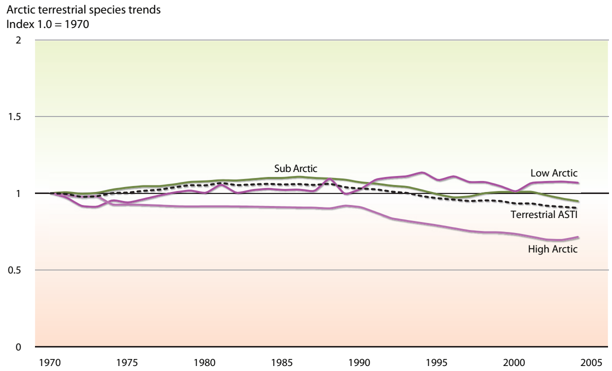
The Arctic Species Trend Index: A Barometer for Arctic Wildlife

Michael J. Gill, Christoph Zöckler, Louise McRae, Jonathan Loh and Ben Collen

The CBMP is the cornerstone program of the Arctic Council's Conservation of Arctic Flora and Fauna Working Group (www.caff.is). The Arctic Species Trend Index (ASTI) is a headline indicator for the CBMP and was developed to provide a pan-Arctic perspective on trends in Arctic vertebrates. Tracking this index will help reveal patterns in the response of Arctic wildlife to growing climatic, encroachment, development and landscape change pressures. It is also envisioned that the ASTI could be used to facilitate our predictive understanding of trends in Arctic ecosystems. A total of 965 populations of 306 species were used to generate the ASTI (see map), of which 390 relate to coastal and marine populations. Overall, the average population of Arctic species rose by 16% between 1970 and 2004, although this trend is not consistent across biomes, regions or groups of species (see graph). Although both freshwater and marine indices show increases, the data behind the freshwater index are currently too sparse in terms of species and populations, while the marine index is not spatially robust. More trend data are required, especially from marine and coastal areas in the Atlantic and central High Arctic coasts in both North America and Siberia.



Location of datasets in the Arctic Species Trend Index.



Index of terrestrial species disaggregated by Arctic boundary for the period 1970-2004. (High Arctic, n=25 species, 73 populations; Low Arctic, n=66 species, 166 populations; Sub Arctic, n=102 species, 204 populations)

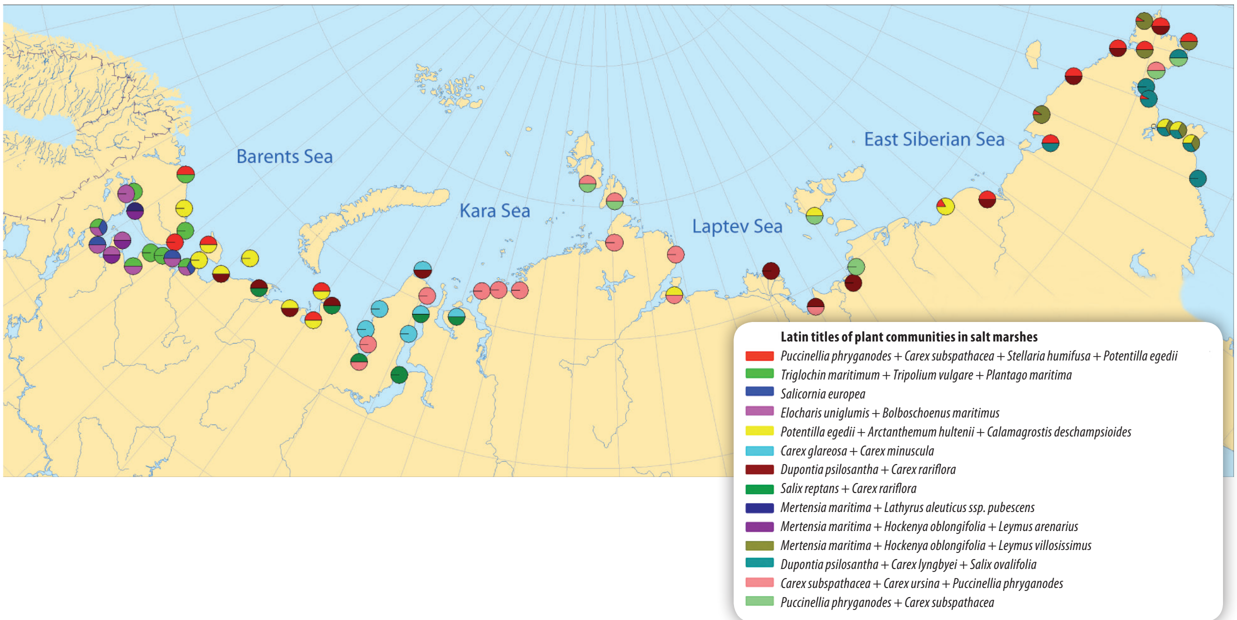


Figure 21. Distribution of salt marshes in the Russian Arctic. Colours represent variability in salt-marsh plant communities.
Source: L. Sergienko, unpublished data, 2009.

changes occur too rapidly, a population may be unable to adjust by migrating or altering its reproductive behaviour. This, in turn, could lead to deleterious changes in ecosystem functioning if the population in question is a keystone species. The total number of coastal species in various Arctic regions ranges from 18 in the plains of the Lena region to 58 species in the Kola Peninsula (L. Sergienko, pers. comm., 2009). Regions with fewer species may be more susceptible to climate changes.

During the Last Glacial Maximum, salt marshes spread along the unglaciated coasts of Chukotka and Alaska at lower sea levels. During this time, surviving coastal communities consisted only of the cold-tolerant Arctic forms. These mainly adapted to the northern climate by growing in the relatively warm estuarine zones of Arctic rivers. In the vicinity of the Taymyr Peninsula, such species as *Arctanthemum arcticum, Mertensia maritima, Senecio pseudoarnica, Salix ovalifolia, Saxifraga arctolitoralis,* and *Saxifraga bracteata* disappeared from the salt marsh communities. Under present-day conditions, some characteristic Arctic coastal species have been transferred from the Chukchi Sea to the Pacific Ocean by cold currents and spread mostly along the eastern coast of Chukotka. At the same time the warmer current from the Bering Sea transports boreal warm-preference species of salt marsh communities along the Alaska coast to spread to the coast of Siberia (Fautin et al., 2010).

The full distribution of Arctic salt marshes has not been documented, although a few regional overviews exist. Some regions with minimal tidal range, such as parts of the Beaufort Sea coast and the Canadian Arctic Archipelago have minimal salt marsh development, largely confined to low deltas and supratidal marshes (inundated during storm surges) along the margins of estuaries and thermokarst embayments (Forbes et al., 1994; Hill and Solomon, 1999). These are often dominated by *Puccinellia* spp. (Martini et al., 2009). Figure 21 shows the distribution of salt marshes across the Russian Arctic coast.

Flooding of coastal buffer zones is already occurring in some areas. Accelerated sea-level rise could lead to further destruction or rapid redistribution of existing salt marsh

Figure 22. Inundated polygonal tundra, western Banks Island, Arctic Canada.
Source: D.L. Forbes, Geological Survey of Canada

complexes (or both). The limited species diversity of the Arctic coastal zone means that the ecosystem is extremely vulnerable to rapid changes whether they are induced by climate change, resource development or a major spill. Over the past 4000-5000 years, some coastlines of the Russian Eastern Arctic have retreated as much as 30 to 50 km (Romanovskii et al., 2005; Overduin et al., 2007). The coastline of the Yamal Peninsula for the same period receded about 18 to 20 km. Deltas of the Dvina and Pechora rivers no longer expand outward. Similarly, the delta front of the Mackenzie River in the western Canadian Arctic is predominantly erosional (Solomon, 2005) (see Section 2.1.7).

Changes in species composition due to sea-level rise will be experienced most in buffer zones (sandy and silty supratidal meadows, mud flats and marshes) periodically inundated at high tides. Circumpolar saline margin species such as *Puccinellia phryganodes* and *Carex subspathacea* will migrate slowly landward with marine transgression (Martini et al., 2009). Although many salt marshes in temperate regions keep pace with slow sea-level rise through inorganic sedimentation and organic production (e.g. Allen, 1990; Plater et al., 1999), there are many observations of flooded tundra along Arctic coasts, where vertical accretion is clearly not keeping pace (Fig. 22). It is important to determine the dynamics of these processes and their responses to a changing climate if we wish to understand the nature and rate of adaptation in salt marsh communities. In some places, species or communities that cannot respond to change may disappear or be replaced by more hearty adaptors or perhaps by invasive species.

Biogeochemical responses to changing ocean and coastal dynamics are equally important. For example, changes in pH or chloride concentration in lower marshes lead to increased success for grasses and sedges, such as *Carex* spp. During colonization of the mudflats ancient species with different levels of ploidy prevail. Ploidy, the number of chromosomes in a plant, is dependent on the evolution and hence the co-evolution of the vegetation. Thus it is indicative of the species richness and, perhaps, its viability in evolving ecosystems. Based on the diversity and density of coastal species and on their floristic composition we can determine the origins of the coastal and estuarine biogeochemical characteristics and can make assessments of the timing of coastline formation in the Arctic.

Apart from the salt marsh and supratidal marsh habitats described above, Arctic intertidal habitats cover a wide range of environments from wide silt and sand flats in the vicinity of large deltas or other areas of abundant sediment supply to boulder-strewn tidal flats in other areas with tidal ranges from <1 m to 16 m (Lauriol and Gray, 1980; Nielsen, 1994; Samuelson, 2001; Zajaczkowski and Włodarska-Kowalczuk, 2007). There is a modest body of research on benthic communities in Arctic intertidal habitats (e.g. Aitken et al., 1988; Ambrose and Leinaas, 1988; Weslawski and Szymelfenig, 1997; Samuelson, 2001; Powers et al., 2002; Bick and Arlt, 2005). Reworking by sea ice has been proposed as one explanation for low productivity (Hamel and Mercier, 2005), a view challenged by some (e.g. Weslawski and Szymelfenig, 1997). Nevertheless the Arctic intertidal benthos has limited biodiversity, with typically 30 to 50 species (Loeng et al., 2005). Soft-bottom tidal flats are found locally in a wide range of settings from Hudson Bay embayments to Svalbard fjords to Chukotka (Fig. 23). In areas of rapid isostatic uplift, former intertidal flats emerge slowly and the upper limit of marine flooding gradually recedes seaward (Hansell et al., 1983). Bottomfast ice can develop over tidal flats with limited tidal range, while areas with higher tidal range may see the formation of an icefoot at the landward margin of the flats and mobile ice to seaward. On boulder-strewn tidal flats, the ice moves boulders, rearranging and disturbing the substrate (see references in Forbes and Taylor, 1994).

Deltas

Arctic river deltas support highly productive ecosystems (Squires et al. 2009) with high biodiversity (Lesack and Marsh, 2010; Galand et al., 2006) compared to the surrounding landscape. The high biodiversity may result, in part, from the complex natural patterns of water level fluctuations that occur in these vast lake-rich systems, with their complex networks of interconnecting channels (Lesack and Marsh, 2010). Rising sea levels and delta subsidence with limited overbank sedimentation are driving progressive inundation of some delta areas and likely contributing to delta-front retreat (see Section 2.1.7).

Other habitats

It is important to note here the unique microbial mat communities and other ecosystems on Arctic ice shelves, as well as those associated with sea ice (Vincent et al., 2004). Given the 90% loss of ice shelf extent along the north coast of Ellesmere Island over the 20th century (Vincent et al., 2001) and the more precipitous loss in recent years (Fig. 11), these remarkable cold-adapted communities are highly vulnerable (see Section 2.1.4). Recent losses include complete disappearance of the Ayles Ice Shelf in 2005 and the Markham Ice Shelf in 2008 (Copland et al., 2010). Just four years before its demise, Vincent et al. (2004) described the Markham Ice Shelf as having the richest of the Arctic ice shelf cryo-ecosystems, with a total standing stock of 11 200 tonnes (11.2 Gg).

Marine mammals (seals, polar bears, whales)

In the Arctic coastal zone, many marine mammals form a direct connection between land and sea. They link the ocean and land in the summer and the sea ice and land in winter. Their viability is dependent on nutrient flows between coasts, upwelling and river discharge and its food chains. Different species respond in different ways to disturbance, either induced by climate or human development (Laidre et al., 2008; Sjare and Stenson, 2010). The Polar Bear *Ursus maritimus* is a top-level predator, an iconic Arctic marine and coastal species that is particularly vulnerable to changes in sea ice because it is fundamentally dependent upon the ice as a platform for hunting seals, traveling, finding mates, and breeding (Regehr et al., 2007). Changes in the distribution, duration, and extent of sea ice cover and in the patterns of freeze-up and break-up have the potential to significantly influence the population ecology of polar bears (Stirling and Derocher 1993; Derocher et al. 2004).

It has been established that the timing of sea ice development, river discharge and nutrient flow has shifted markedly. Seasonal ice forms later in the fall and multiyear floes are smaller and retreat farther offshore in the summer (Serreze et al., 2002; Stroeve et al., 2005). As such, climate change poses risks to marine mammals in the Arctic that are dependent on the ice ecosystem for survival. With ports remaining ice free for longer and with potential shipping routes opening as summer ice extent decreases there will undoubtedly be an increase in human traffic and development in previously inaccessible, ice-covered areas. This poses additional stresses for ice-associated mammals. Bearded seals use regions of thin, broken sea ice over shallow areas with appropriate benthic prey communities (Burns, 1981). Their distribution, density, and reproductive success are dependent on the maintenance of suitable sea ice conditions in shallow, often coastal, areas. Walruses, another predominantly benthic feeder, also have quite specific sea ice requirements. They overwinter in areas of pack ice where the ice is sufficiently thin that they can break through and maintain breathing holes (Stirling et al., 1981), but is sufficiently thick to support the weight of groups of these highly gregarious animals. Ice retreat may result in much of the remaining Arctic sea ice being located over water that is too deep for these benthic foragers. Bowhead whales are known to inhabit the boundary between landfast ice and pack ice 2 km off the coast of Barrow, Alaska. This ecologically rich coastal zone also includes ringed seals, birds and fish. Native Alaskans have inhabited the Barrow area for about one thousand years because of this close proximity to ice-dependent subsistence foods.

In East Greenland, the narwhal together with minke whale, walrus, polar bear and ringed seal, bearded seal, harp seal, and hooded seal, are the most important living marine resources for the communities of Scoresby Sund and Angmagssalik (see Section 2.3.4). This hunt is shore-based and takes place in coastal waters. Many of these animals are bound to the ice pack. In West Greenland, the quota species humpback and fin whale are hunted. As the bowhead stock is increasing, it may also be possible that Inuit will receive a quota for bowhead in the near future. Ringed seal is hunted mostly for dog food, which is economically important because polar bear hunting requires the use of dogs.

Harp, ringed and harbour seals are hunted from shore, boats, or the floe edge in various other parts of the Arctic and these animals are dependent on the ice edge. Harp and hooded seals are hunted by Norwegians around Jan Mayen; harp, ringed, and bearded seals are taken in Svalbard. Beluga and narwhal are important species for Inuit communities

Figure 23. Tumlat mudflat in Chukotka, Russia.
Source: C. Zöckler, UNEP

in Arctic Canada. Minke whales (quota 650 per year) are hunted by Norwegians (from the whaling station Skrova Westfjorden, Lofoten) and Icelanders in the North Atlantic Ocean. Fin whales are hunted by Icelanders (from the whaling station located in Hvalfjörður).

Fish distribution and changes in species diversity and abundance

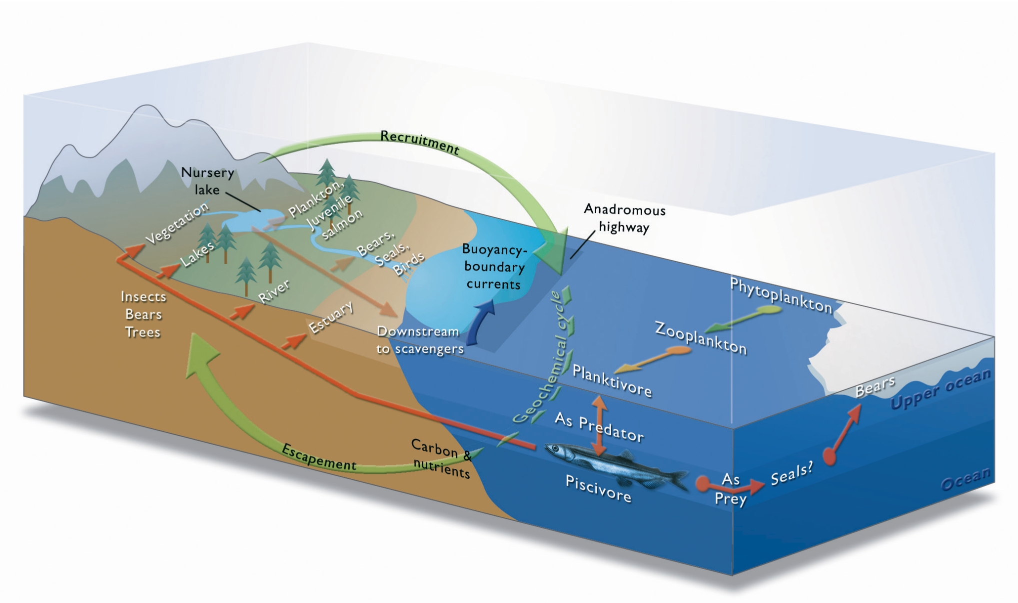
The Arctic marine coastal zone is largely inhabited by Arctic fish fauna consisting mainly of euryhaline species. Eleven of these are of circumpolar distribution, including *Lycodes pallidus, L. polaris, Artediellus scaber* and some endemic to the Arctic such as *Triglops nybelini, Lycodes jugoricus, Artediellus scaber* (Chernova 2003).

Inside the circumpolar Arctic marine coastal zone, estuaries of numerous large and small rivers host specific ecosystems. Fish complexes inhabiting these zones include about 20 anadromous, and semi-anadromous fishes, as well as those freshwater species which can enter brackish estuarine waters (Fig. 24). These fish (*Acipenser baeri baeri, Coregonus autumnalis, Stenodus leucichthys nelma* and others) usually do not occur in the waters of higher salinity.

The littoral zone in the high Arctic is a harsh environment because of ice presence most of the year. Benthic species predominate in the Arctic. In the high Arctic mid-water so-called cryopelagic fish species, depending on sea ice, are widely distributed (*Boreogadus saida, Arctogadus borisovi*). Only a few of the Arctic species have very large populations, and most of those are heavily exploited by marine fisheries.

Changing water temperatures, water levels and ocean currents are expected to alter fish migration patterns and new species will likely enter Nordic and Arctic seas (e.g. Reid et

Figure 24. Schematic portrayal of the use of estuaries and the keystone role of anadromous fish in the trophic dynamics of Arctic nearshore estuarine and marine ecosystems.
Source: Wrona et al. (2005), © Arctic Climate Impact Assessment, 2005



al., 2007). In the northern Bering Sea, a change from ice-dominated Arctic conditions to sub-Arctic conditions with more open water tends to favor pelagic species like pollock (*Theragra chalcogramma*) over benthic and bottom-feeding species. With the recent shift to a cold period, the pollock population in 2009 is in collapse (Grebmeier et al., 2006; Overland, 2009). Global analyses of marine biodiversity response to projected climate change suggest the potential for substantial changes in the distribution of numerous exploited fish and invertebrate species, with the most intense species invasions at high latitudes (Arctic and Southern Ocean); these changes may entrain species turnovers of as much as 60% of present biodiversity, with impacts on marine and coastal ecosystems and potential disruption of ecosystem services (Cheung et al., 2009). In Hudson Bay and the Canadian Arctic Archipelago, some important food species such as Arctic char (*Salvelinus alpinus alpinus*) may see contracted distributions, with diminishing numbers in the southern part of the present range and limited expansion to the north (Cheung et al., 2010). The ice-dependant Arctic cod is projected to suffer severely by climate change as modeled for the next 30 years. Although not a harvested fish itself it is an important prey for larger fish important for human consumption (Bluhm and Gradinger, 2008). Anadromous species such as char integrate climate change effects between freshwater and marine environments and the impacts will vary between regions in the Arctic as a function of numerous factors affecting habitat suitability, growth, and survival (Reist et al., 2006a, 2006b, 2006c; Todd et al., 2008).

Freshwater fish relate to coastal waters in a different way than salt water fish. Deltas and estuaries have a complicated relationship with ice that controls salinity. If ice is present during spring melt flooding, it helps drive freshwater and nutrients offshore. This process and the water temperatures of the rivers and coastal ocean control stratification which in turn drives the deposition and assimilation of nutrients into the coastal zone. This has ramifications for fish such as Arctic char, as well as waterfowl, shorebirds and marine mammals that are part of the food web (e.g. Gaston et al., 2002; Chaulk et al., 2007; Dawe et al., 2007; Gaston, 2008; Regular et al., 2009). Many anadromous fish (Arctic cisco, Dolly Varden, rainbow smelt) may overwinter in freshened coastal or estuarine waters and then migrate upstream in the freshwater systems to spawn. Thus the fish are a transfer mechanism for nutrients linking coastal and inland ecosystems. Figure 24 depicts the coastal and terrestrial linkages driven by freshwater with a focus on fisheries and how climate change may affect fisheries dynamics. The figure suggests that many unknowns remain in predicting the future response to climate warming across a broad range of parameters.

Seabirds (breeding and non-breeding concentrations)

Seabirds comprise mostly cliff-breeding birds on rocky outcrops and islands or on low coastal wetlands. They nest in huge coastal colonies, often on remote islands free of ground predators. They are among the most numerous colonies in the Arctic, if not at a global scale. Some account for several million birds, like the little auk (*Alle alle*) in Greenland or the Puffin (*Fratercula arctica*) in Iceland. In the North Atlantic between Greenland and Svalbard alone an estimated 50 million pairs of seabirds (Bakken et al., 2006) nest in the coastal zone of this area, comprising in total more than 100 million seabirds that use the North Atlantic waters. Similar numbers are estimated for the Eastern Barents and Bering Sea (Isaksen and Gavrilo, 1996; Dragoo et al., 2010), followed by fewer numbers in the Kara, Laptev, Chukchi and Beaufort Sea, totalling an estimated 500 million seabirds nesting at Arctic coasts.

Indirect changes in the food chain can be expected through changes in salinity and temperature, with implications for diversity and abundance of invertebrate and fish prey (Durant et al., 2003). These may severely impact seabird communities in critical locations relative to breeding grounds. Sea surface temperatures impact the abundance of seabirds (Irons et al., 2008) with warming waters pushing the distribution of some such as the thick-billed murre to the north (Fig. 25).

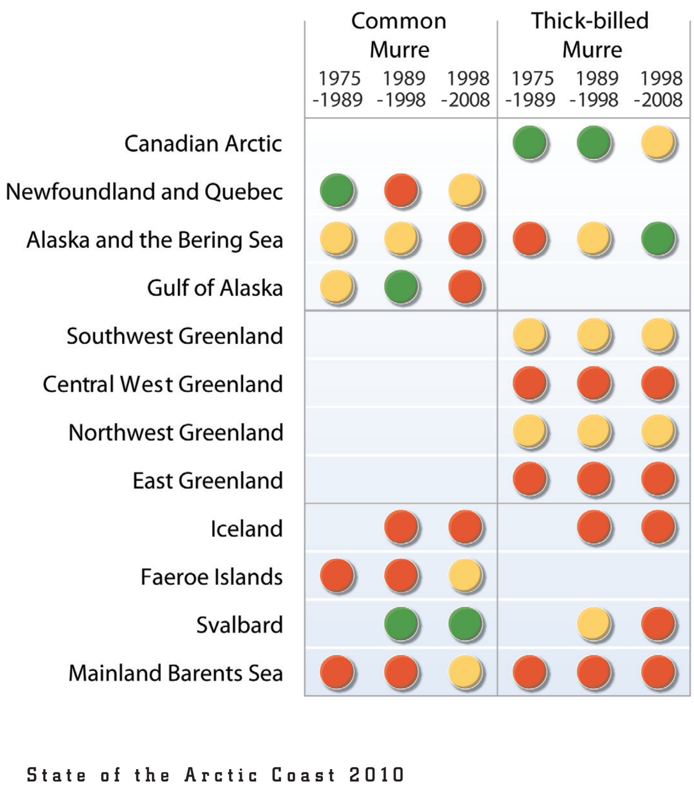


Figure 25. Changes in murre populations since 1975 by region and 'decade' (as defined by regime shifts in the Pacific Decadal Oscillation; see Irons et al., 2008). Green indicates positive population trends, yellow indicates stable populations, and red indicates negative population trends (http://web.arcticportal.org/en/caff/cbird).

Those seabird species that predominantly breed in coastal lowlands, such as eider ducks, gulls and terns may lose some breeding habitat to rising sea levels and may experience breeding failures from storm surges, but are likely to be able to adapt. Additionally, common eiders and other species have been subjected to over-harvesting in many parts of the Arctic (e.g. Merkel, 2004) (Table 2).

Table 2. Status and trends of seabird harvest in the Arctic (including sea ducks). Information from Merkel and Barry (2008)

Country/ Region	No. of species harvested	Most important species	Est. annual seabird harvest	Est. annual egg harvest	Overall trend in harvest	Reason for change
USA/ Alaska[1]	>25	Auklets, Murres	30,000 (2001-2005)	145,000 (2001-2005)	Variable annually, no trend evident (1995-2005)	Survey methods may not be comparable
Canada	8	Murres, C. eider	260,000 (2002-2008)	Some	Decreasing (1980-2002)	Regulation and fewer hunters
Faroes	9	fulmar, puffin	65,000-240,000	1,000-12,000	Decreasing (1980-2006)	Regulation and fewer hunters
Finland	6	oldsquaw, C. eider	31,000 (2000-2004)	Banned since 1962	Decreasing (1995-2005)	Regulation and fewer hunters
Greenland	19	C. eider, dovekie terns? (eggs)	153,000-220,000 (2002-2006)	6,600 (2006)	Decreasing (1993-2006)	Regulation and fewer hunters
Iceland	19	puffin, C. murre, C. eider (down, eggs)	158,000-285,000 (2002-2007)	Many	Decreasing[2] (1995-2007)	Decreasing pop[2].
Norway/ Svalbard	5/4	gulls/ B. guillemot	4,000/150 (1995-2008)	Some	Stable (1995-2008)	-
Russia West	~10	Eiders, murres, gulls	?	Some 1000s (<10,000) (illegal)	Increase in 1990s, now stable or decreasing	Changing law enforcement and social-economic situation
Russia East	~20	Eiders, alcids, gulls, terns, comorants	Eiders (50-62,000), other seabirds (~100,000, mainly illegal)	~100,000 (mainly illegal)	Decrease in early 1990s and gradual increase in 2000s	Changing law enforcement and social-economic situation

Shorebirds and waterfowl

Arctic and sub-Arctic intertidal mudflats serve as vital feeding and stopover sites for migratory waders (shorebirds) (e.g. Gill and Handel, 1990). Gill and Senner (1996) identified 15 sites of hemispheric importance in Alaska. Other sites in northern Norway and on Kolguev Island in the Russian Arctic serve as stopovers for thousands of migrating shorebirds (Kruckenberg et al. 2008). For such migratory species, the greatest challenges may relate to climate change, development pressures on habitat, or contaminants encountered at critical sites along the migration routes or in the southern winter range (Boyd and Madsen, 1997; Baker et al., 2004).

Many swans, geese, ducks, waders (shorebirds), loons (divers) and other water birds

[1]Studies focused on coastal zone management are exceptions here.

rely on salt marsh habitats for breeding and for accumulating body mass and nutrients to sustain them on their winter migration. Swans, geese, and other waterfowl and shorebirds in the outer Mackenzie Delta (including the Kendall Island Bird Sanctuary) occasionally experience breeding failure caused by early summer storm surges. In the long term, a more serious threat may come from loss of habitat through delta front erosion combined with sea-level rise and delta subsidence (Forbes et al., 2010). The brent (brant) goose (*Branta bernicla*) with an almost circumpolar distribution makes extensive use of coastal salt marsh habitats (Zöckler, 1998), which the high Arctic goose also uses on migration in temperate Europe, America and Asia. Barnacle geese (*Branta leucopsis*) have similar characteristics and their 400,000 strong Russian population relies on salt marsh habitats for breeding and grazing in the Arctic. Likewise, the emperor goose (*Anser canagica*), endemic to Beringia, is entirely confined to coastal salt marshes in northeastern Siberia and Alaska. Among the loons (divers), the red-throated loon (diver) (*Gavia stellata*) has its maximum distribution in Arctic salt marsh areas and deltas. The Sabine's gull (*Xema sabini*) and to some extent the Ross's gull (*Rhodosthetia rosea*) breed predominantly in salt marshes. The globally critically threatened spoon-billed sandpiper (*Eurynorhynchus pygmeus*) breeds exclusively near coastal habitats utilizing salt marshes and mudflats (Tomkovich et al., 2002). All of the aforementioned water birds are examples of species highly vulnerable to sea-level rise and other coastal changes, including changes in vegetation that alter the breeding habitat, so that populations either abandon or shift their distribution. This has already been noticed for the site-faithful spoon-billed sandpiper, which abandoned some of its most southern breeding territories due to vegetation changes in its coastal habitats (Zöckler et al. in press).

2.2.2 Ecosystem services

Ecosystem services have been defined by the Millennium Ecosystem Assessment (UNEP, 2005) as provisioning, cultural, supporting, regulating and preserving services for human well being. These services refer to the Arctic local people but also to the global community (e.g. carbon sequestration and mitigation). From an Arctic coastal perspective, fish stocks are most prominent and also coastal breeding birds and other coastal animals that are regularly harvested. From a cultural perspective, the variety of peoples and traditional lifestyles as well as the touristic value of coastal habitats and their communities are of great importance (Huntington et al., 2009a; Huntington and Pungowiyi, 2009). Coastal zones also provide services in protecting the coast line and buffering the impact of storm surges and ice flow. These services are expected to be in greater need with warming seas and increased storminess. Seabirds are an excellent example to illustrate the regional differences but also the challenges, when it comes to managing the harvesting of coastal biodiversity.

The common eider (*Somateria mollissima*) is a coastal breeding bird with an almost circumpolar distribution. This duck and two other Arctic eider species of the same genus are highly valued living resources in the Arctic. The birds or their products are harvested throughout most of the circumpolar region. As the largest duck in the Northern Hemisphere, the eider is important for traditional food and lifestyle in many Arctic communities (Merkel and Barry, 2008; Syroechkovskiy and Klokov, 2007). In some countries, especially Iceland, down feather collection constitutes a significant commercial industry (Bédard et al., 2008). Common eiders have a circumpolar distribution and are dependent on benthic organisms in shallow marine waters for food throughout the year, making them a potential indicator of the health of marine coastal environments (http://maps.grida.no/go/graphic/distribution-of-common-eider-breeding-and-wintering- ranges-in-the-arctic).

Table 3 summarizes the various ecosystem services in relation to coastal ecosystems.

Table 3. Examples of ecosystem services provided by different Arctic coastal habitats (✓ indicates the habitat provides a significant amount of the service, modified after UNEP, 2005).

Ecosystem services

	Estuar-ies and Marshes	Lagoon and salt ponds	Inter-tidal mudflats	Kelp	Rock and shell reefs	Sea-grass	Inner Shelf
Biodiversity	✓	✓	✓	✓	✓	✓	✓
Provisioning services							
Food	✓	✓	✓	✓	✓	✓	✓
Fibre, timber, fuel	✓	✓					✓
Medicines, other resources	✓	✓		✓			
Regulating services							
Biological regulation	✓	✓	✓		✓		
Freshwater storage and retention	✓	✓					
Hydrological balance	✓	✓	✓				
Atmospheric and climate regulation	✓	✓	✓		✓	✓	✓
Human disease control	✓	✓	✓		✓	✓	
Waste processing	✓	✓				✓	
Flood/storm protection	✓	✓	✓	✓	✓	✓	
Erosion control	✓	✓				✓	
Cultural services							
Cultural and amenity	✓	✓	✓	✓	✓	✓	✓
Recreational	✓	✓	✓	✓			
Aesthetics	✓	✓	✓				
Education and research	✓	✓	✓	✓	✓	✓	
Supporting							
Biochemical	✓			✓			
Nutrient cycling and fertility	✓	✓	✓	✓	✓		✓

2.2.3 Processes, drivers and pressures

Compared to global coasts in general, Arctic coasts largely still escape the pressure of human impact. Based on a global research effort evaluating the impact of 17 combined anthropogenic marine stressors, including coastal runoff and pollution, warming water temperature due to human-induced climate change, oil rigs that damage the sea floor, and five different kinds of fishing, most of the Arctic coastline shows low to very low impact (Halpern et al., 2008). However some areas in the Barents Sea and Bering Sea are considered highly or even very highly impacted and the sea around West Greenland shows a medium high impact.

Tourism is increasing across the Arctic and the number of cruise ships has been growing rapidly in recent years, particularly in the Canadian Arctic, Labrador, and Greenland, but also in longstanding cruise destinations in Svalbard and northern Norway (Hall and Saarinen, 2010a, 2010b). Tourists are now landing in places where they have never landed before, placing added stress on popular sites and increasing ship traffic with concomitant added risks of accidents, oil spills, and biological invasion (Hall, 2010; Hall et al., 2010).

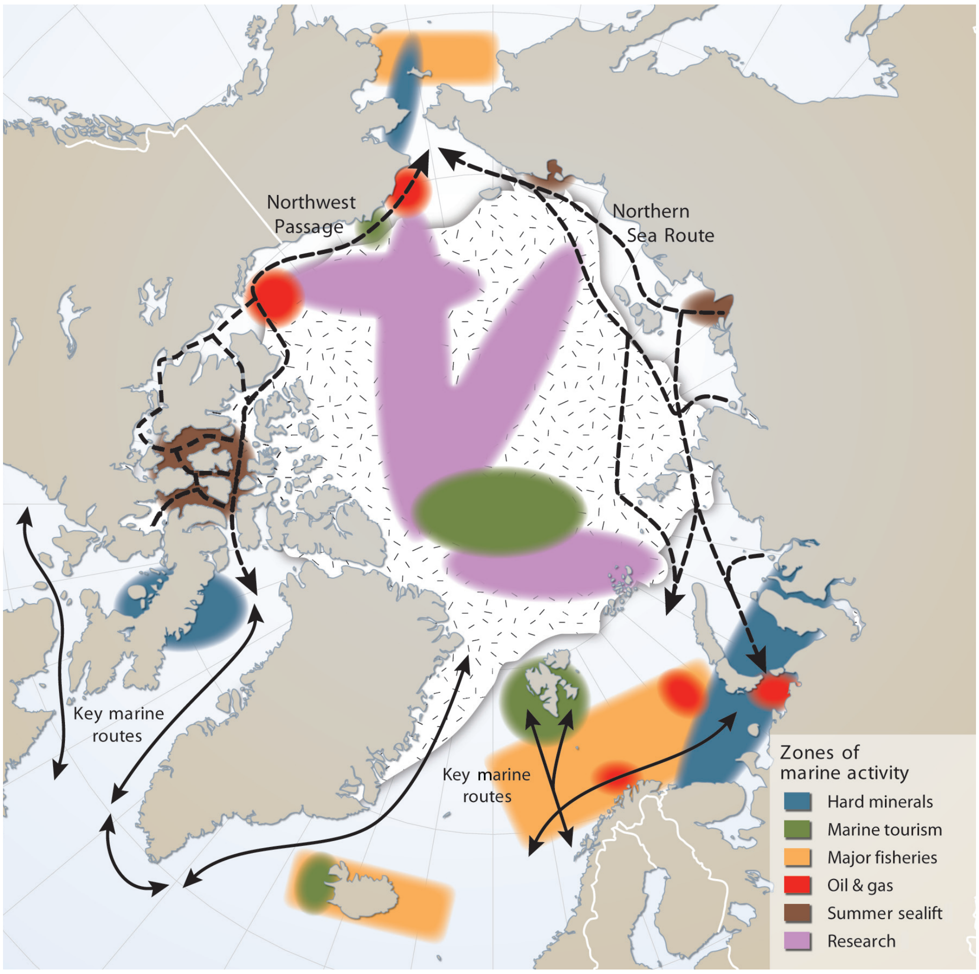
Oil spills present the greatest anthropogenic risk for the marine and coastal environment in the Arctic. Seasonality is a major driver for how pollutants can affect ecosystems. The impact of an oil spill on ice covered waters is of particular concern due to limited options in containing or responding to a spill in open or shifting pack ice. In the event of a spill in the open ocean the oil will inevitably end up at the coast when winds and currents drive it in a predominant direction. The dispersion of an oil spill would inevitably lead to extensive contamination of coast line as was evident in the Exxon Valdez spill in Alaska's Prince William Sound. Birds and other animals are most affected by a spill if they are physically coated with oil. Seals and whales are not as sensitive due to their blubber coating. Oil spills in aquatic environments are particularly dangerous because they can spread over large areas and distances. Clean up of any oil spill in the Arctic would be difficult due to the remoteness. Ice-edge communities would be the most difficult to remediate.

Climate change is likely to open or expand shipping routes, particularly north-east and north-west trans-Arctic shipping routes, or ever 'over-the-top' trans-ocean routes (Fig. 26). This, in turn, expands the range of locations where spill, recovery, and rescue response will be required. Seasonal patterns of migration and breeding determine vulnerability in Arctic systems and add importance to the timing of oil and gas activities and their impacts. Following breeding, shorebirds, ducks and geese congregate in coastal habitats where they feed and prepare for their southbound migration. Many indigenous cultures rely on the harvesting of these seasonal migrators. Near shore facilities and ship routes pose a great risk for coastal impacts. The timing of spills in relation to when fish are spawning or marine mammals are present is thus of major importance. The marginal ice zone is a location where animal aggregations are common.

Overfishing and over-exploitation of coastal marine resources pose another increasing threat (UNEP, 2007; ICES, 2008). With increasing accessibility and more and more modern technology even remote regions can be accessed for fishing and hunting, leaving more limited areas for recovery. Strict law enforcement and fishery and hunting restriction are required but not always implemented across the Arctic region (see also Table 2).

For many Arctic mammals and seabirds, changes in the extent and timing of sea-ice cover over the past several decades (Stirling and Parkinson 2006; Gaston et al. 2005) are leading to changes in phenology and reproduction with adverse consequences on breeding success. These changes seem likely to intensify. Aside from climate change, problems also include fisheries interactions, contaminants, and oil spills (PAME, 2009b) and hunting (CAFF, 2009). Levels of some contaminants, especially mercury, have increased in seabird eggs in the North American Arctic since the 1970s, although they remain at sub-lethal levels (Braune et al. 2001). If climate change leads to increased shipping and oil and gas exploitation in Arctic waters, the increased risk of spills would pose an additional stress and potential hazard to coastal marine biodiversity (Wiese and Robertson, 2004; AMAP, 2007; PAME, 2009a, 2009b) , some of which are extremely susceptible to mortality from oil pollution.

Figure 26. Current marine shipping uses in the Arctic.
Source: PAME (2009a)



Reductions in sea ice extent, duration, and thickness will likely increase human presence and activities in the Arctic (Hovelsrud et al. 2008, Ragen et al. 2008). Longer ice free seasons and reduced ice coverage could increase shipping activity and enhance resource exploration, development, and production impacting vulnerable coastal species, such as polar bears, walrus, seals and many seabird species. Potential effects of shipping include pollution, noise, physical disturbance related to ice-breaking, and waste. The number and range of cruise ships moving further north, reaching coastal areas previously untouched, may also increase the pressure on coastal ecosystems (Hall, 2010; Hall et al., 2010). Potential effects of increased tourism include pollution, disturbance, and increased risk of defence kills and biological invasion. The Arctic Marine Shipping Assessment (PAME, 2009a) mapped the distribution of shipping activities under various use classes (minerals, oil and gas, major fisheries, summer sealift, marine tourism, and research) (Fig. 26).

2.2.4 Management responses

Oil spill response facilities spaced along transportation corridors and near port facilities

Oil spill response is a major challenge, especially where ice is present. Many coastal locations that are vulnerable have limited response equipment available. Increased tanker traffic and platform installation, particularly in the Norwegian and Russian fields, is likely to continue. It is desireable that transportation and infrastructure development use the best environmental and engineering practices; be designed using adequate methods for the potential location(s) affected; and be designed to reduce the risk of marine and terrestrial spills but particularly spills on or near sea ice.

The loss of sea ice is likely to improve access to locations in the Arctic (including current port facilities) and to lengthen the shipping season. A negative consequence of having more open water is the potential for increased wave action and coastal erosion. Coastal and offshore based facilities thus must be designed to withstand the predicted increase in wave and erosion energy and activity.

PAME (2009b) developed a set of guidelines for Arctic offshore oil and gas exploration. These comprise safety management, compliance monitoring, methods, practices and standards as well as operating practices and training requirements and the level of preparedness for spill response. As is evident in the response to the Gulf of Mexico oil rig explosion and spill in 2010, oil spills in readily accessible areas can pose substantial control and remediation challenges. A similar mishap in an Arctic marine location with sea ice could be far more challenging.

Coastal Protected areas

Protected areas are still considered a key element for maintaining and conserving Arctic biodiversity and the functioning landscapes upon which species depend. Arctic protected areas have been established in strategically important and representative areas, helping to maintain crucial ecological processes, habitats and species, e.g., caribou migration and calving areas, shorebird and waterfowl staging and nesting sites, seabird colonies, and critical components of marine mammal habitats. Arctic marine and coastal areas are increasingly protected, yet still cover less than 5% of the Arctic coast line and below the average of all the other Arctic habitats (see Box).

Coastal zone management

By the early 1990s common eiders along with other eider species had generally declined over the past two to five decades, and the need to stabilize and manage eider populations was increasingly recognized. As part of the Arctic Environmental Protection Strategy, signed in 1991, the Circumpolar Seabird Working Group under CAFF developed a Circumpolar Eider Conservation Strategy and Action Plan (CSWG 1997). The factors behind several eider population declines reported in the 1980s and 1990s were often unknown, but in some cases involved human disturbances, excessive harvest, and severe climatic events (Robertson and Gilchrist, 1998; Suydam et al., 2000; Merkel, 2004). The current trend of common eider populations varies but at least some populations in Alaska, Canada, and Greenland are now recovering with improved harvest management as a likely contributing factor (Chaulk et al. 2005, Gilliland et al. 2009).

Further details on institutional arrangements for Arctic coastal zone management can be found in Section 2.3.7 below.

Protected Coastal Areas *C. Zöckler (UNEP)*

The first protected areas dataset for the Arctic was created by the Conservation of Arctic Flora and Fauna (CAFF) Working Group of the Arctic Council in 1994. It has recently been updated as part of CAFFs ongoing Arctic Biodiversity Assessment (ABA) (www.caff.is/aba), which is a follow-up to ACIA (2005). The term 'Protected areas' is included in the suite of indicators included within the first ABA report, *Arctic Biodiversity Trends 2010: selected indicators of change.* This new dataset contains data officially submitted by each of the Arctic Council countries (Canada, Sweden, Norway, Denmark, Greenland, Faeroe Islands, Iceland, Finland, Russia, USA).

A key finding from the *Arctic Biodiversity Trends 2010* report was that, since 1991, the extent of protected areas in the Arctic has increased, although marine areas remain poorly represented. The analysis found that 11% of the area of the Arctic as defined by CAFF (see map) has protected status. This represents a doubling of the area protected in the last 30 years. The initial results also indicate that over 40% of the protected areas recorded have a coastal component. However for the majority of these areas it is not possible at present to determine the extent to which they incorporate the adjacent coastal/marine environment. To redress this gap in knowledge, CAFF has launched a project led by Iceland to consider the extent that protection extends into the coastal environment. This project will further develop the information on these areas and compile a dataset detailing the nature and extent of the protection afforded.

This project reflects but one aspect of CAFFs activities addressing protected areas in the Arctic. Other activities include establishment under the Circumpolar Biodiversity Monitoring Programme (CBMP) of an expert group with members from all Arctic countries to develop an Arctic Protected Areas Monitoring Plan. In addition, CAFF is actively following up on the Arctic Marine Shipping Assessment (AMSA) recommendations to consider marine sensitive areas in the Arctic and is also cooperating with the International Union for Conservation of Nature (IUCN) to address related aspects of protection in the coastal/marine environment.

Protected areas in the Arctic classed after their IUCN category

2.3 Social, Economic, and Institutional State of the Circum-Arctic Coast

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Contributing authors: L. Hacquebord, B. Poppel, J.N. Larsen

Key Findings

- Social, cultural, health and demographic conditions, economic systems, industrial structure and the relative importance of subsistence activities vary across the spectrum of communities on the circumpolar Arctic coast.
- The Arctic economy as a whole is dominated by four major characteristics: the continuing importance of traditional subsistence activities and local living resources in most regions, the lack of manufacturing industries, the local and regional impacts of large-scale natural resource extraction or exploitation projects, and the major importance of the public sector for service provision and transfer payments from the south.
- Disposable household income (DHI) is largest in the Arctic regions where large-scale resource extraction occurs. These are, however, also the regions where the discrepancy is largest between DHI and gross regional product, demonstrating that actors outside of the region reap a large portion of the benefits from the economic activities there.
- Even though the Arctic has a relatively large proportion of people living in a near-traditional manner, close to nature and utilizing the resources there for food and subsistence, it is also well linked to the global economy, in particular as a large supplier of natural resources. The same processes we see in the advanced industrialized regions, of a knowledge-based economy with a focus on innovations, are also taking place in the Arctic.
- Although climate change and other processes affecting natural resources and environmental conditions impose large impacts on quality of life and economic activity for communities on the Arctic coast, other factors and processes will often be more important, especially in the short run. Where communities are already stressed, even small changes in the availability or quality of natural resources may be critical.
- Recently established integrated marine regional plans, as for example in the Barents Sea, are milestones in the implementation of ecosystem-based management. Laudable as these efforts are, however, it is clear that more work needs to be done, particularly on societal impacts of industrial activities and on the socio-economic impacts of ecosystem changes in the Arctic coastal zone. In each case, a multifactor perspective is essential.
- The Arctic Human Development Report found that, for people in the Arctic, fate control, cultural integrity and contact with nature are central for well-being and should be included in future statistical data collection efforts. The Arctic Social Indicators project has proposed a suite of indicators for these factors, in addition to aspects considered in the United Nations Human Development Index, and is working toward the implementation of these indicators in the Arctic.

- Statistical data specific to coastal regions are difficult to obtain, at least for circumpolar comparisons. Economic, social and demographic connections between coastal and inland areas hinder a clear delineation of what should be included, or excluded, in a coastal-based study such as this.
- At a time of incipient rapid changes in the Arctic coastal zone resulting from climate change and other factors, there are growing health challenges in Arctic communities. Monitoring of the human health situation across the Arctic is critically important, especially for indigenous people in rural areas and remote communities.

Human interests in the coastal zone involve the socioeconomics of communities, including social and cultural traditions, institutions, and governance systems. The coastal zones are extremely important for communities with a subsistence economy. The distribution of the settlements in the Arctic shows that at least 80% of the people in the Arctic live along the coast. They depend on the living marine resources for a great part. The subsistence economy depends on the presence of terrestrial and particularly marine living resources and greatly influenced by sea-ice conditions. All of these are immensely complex and impossible to cover in detail. The purpose here is to give an overview, applying the lens of the coastal zone to that material, and having a special focus on scientific work done or published after the Arctic Human Development Report (AHDR) and the Arctic Climate Impact Assessment (ACIA) were published. An important objective is to identify gaps in knowledge of changes affecting indigenous communities and subsistence activities in the coastal zone.

The following are presented for the Arctic and its regions:

- the social situation for humans on the Arctic coast, including the diversity of lifestyles;
- economic resources and economic systems;
- subsistence economies; and
- a brief overview of governance and political systems of relevance for the management of coastal and marine resources in the Arctic.

Boxes are included on cultural heritage sites on the Arctic coast, and on the projects SLICA (Survey of Living Conditions in the Arctic) and ASI (Arctic Social Indicators), both which aim to help remedy the lack of data on social and economic conditions in the Arctic

We take as a starting point that changes in climate and ecosystems may affect Arctic communities across a broad range of conditions from cultural heritage to social resilience, health, economic status, governance and institutions. We focus primarily on social conditions, the economy, and governance systems, as they are relevant to the ability of individuals, communities and regions to adapt to these external changes and ensuing socio-economic adjustments.

The people on the Arctic coast depend on natural resources and natural conditions in the area in many ways (Glomsrød et al., 2009). Changes in resource availability and in

Cultural heritage sites on a changing Arctic coast

Louwrens Hacquebord

The coast has always played an important role in the exploration, exploitation and habitation of the Arctic regions. Originally, ancient peoples followed the coastline searching for game and shelter. With a relatively simple toolkit, containing only the essential tools to extract enough food resources and to build effective shelters these Arctic hunters managed to survive in one of the most severe environments of the world. Travel and movement were essential aspects in the survival process of these hunters. This can be a short-distance seasonal camp shift or a long-term migration (Schledermann 1990). Around 4000 years BP, small groups of Palaeo-Eskimo Independence-I hunters migrated over a long distance along the coast from Alaska to the Canadian Arctic Archipelago and northern Greenland. They traveled under relatively good climate conditions, with much driftwood on the beach for heat, light and cooking, many terrestrial mammals such as muskoxen, and enough sea mammals such as seals, which were easy to kill and delivered all-round food (McGhee 1996, 2004).

Around 4000 BP, in a period that was warmer and more humid than to-day, muskoxen migrated to the north to survive the winter. To get their food in the wintertime the animals need a stable climate with dry circumstances in the fall like that in Northern Greenland. The hunters of the Independence-1 culture followed the muskoxen migration to the polar desert region in Northern Greenland. Thanks to the muskoxen, they managed to survive the harsh high Arctic environment. Some sites on the north coast of Greenland indicate that the warmer conditions in that period enabled hunters to settle down along the polar sea for a period. As soon as the environmental circumstances changed they migrated to the south again (Grønnow and Jensen 2003). Because of the certain presence of sea mammals, the coastal areas on the islands of the Canadian Arctic Archipelago near polynia were very attractive campsites for Arctic hunters. In Broomans Point Village on Bathurst Island, archaeologists have discovered remains of two later high Arctic cultures, Dorset and Thule, meaning that ancient people visited certain places several times and it shows that migration as part of the nomadic lifestyle was used as a successful strategy of survival (McGhee, 1981). Archaeological studies demonstrate that flexibility and seasonality have always been important in the survival strategy of Arctic cultures making the nomadic subsistence system the key to survival and sustainability of Arctic cultures. Archaeological research of Woollet and Kaplan (2000) on 18th century Inuit sites along the east coast of Labrador (Canada), on the other hand, showed sedentary aspects and the resilience character of Arctic cultures. Here Inuit were able to stay at the Labrador coast for a long time thanks to their social and economic structure and the food resources available to them. Change in climate and even the arrival of Moravian missionaries in Labrador did not force the hunters to go away. They did not have to change their hunting strategy in the winter, which shows another quality of hunters to survive environmental change. Other archaeological studies (McGhee 1996, 2004) show that change has always been a major aspect in the livelihood of Arctic people and that they have a rich heritage of cultural adaptation to deal with change.

Later explorers from the south penetrated the region along the coast with ships and regularly established their base-camps on the coast. After the exploration, the exploitation of natural resources took place in the coastal area as well. Buildings and installations were constructed on the coast, very often near the place where the resources were found. Recent research in the framework of the IPY project LASHIPA has made clear that these constructions were very vulnerable for environmental change and on the other hand essential in the European colonization of the Arctic (Hacquebord and Avango, 2009).

Most Arctic residents still live on the coast and for their subsistence many of them depend on marine resources present in the coastal zone. From a long time ago, the coast has been a transitional zone between dwelling and hunting, because it connects the settlements on the coast with the hunting and fishing grounds in the sea near the edge of the ice pack. This connection is called the Inuit coastal system (Parewick, 2008). This system has always been, and still is, crucial for the Inuit subsistence economy, which is based on the formal and informal economy on a fifty/fifty base in many places. Nowadays, the coast also gives Inuit the possibility to participate in the global market economy.

Beside its economic importance, the coast also plays an important role in the spiritual world of the Inuit. Sacred places and cemeteries show the prominent position of the coastal zone in their life.

Until now, the permafrost preserved the cultural remains at these sites, showing the history of exploration and exploitation of Arctic Regions very well. However, due to the recent climate modifications, coastal erosion and permafrost thaw are threatening the historic sites (Jones et al., 2008). Some of them should be protected and others excavated to preserve the data they contain.

states of nature can have large impacts on the livelihoods, industries, transportation, settlements, recreation activities and spiritual life of the inhabitants. In some areas, rising sea levels and increased wave energy may enhance rates of coastal erosion, threatening settlements (see e.g. http://www.shishmarefrelocation.com/) as well as archeological and cultural heritage sites (see Box). Climate change will result in altered abundance of different fish species and other subsistence food resources in various regions of the Arctic. It will also affect other economic activities such as mining and hydrocarbon production on- and offshore. Reduced sea ice extent will open up the Northwest and Northeast Passages, not to mention the increasingly ice-free Arctic Ocean itself, with effects on global maritime shipping patterns, tourism, and exploitation of natural resources, but ice withdrawal will have negative consequences for indigenous hunters who mainly hunt from the ice. Clearly, there can be both benefits and losses associated with such changes, and they may be different for different groups, settlements and industries.

2.3.1 Data challenges

A challenge for this chapter on human issues is that studies of political, social and economic conditions rarely focus only on the coastal zone (studies focused on coastal zone management are exceptions here.). Consequently, datasets on socio-economic conditions are available for regions which are not demarcated by their inclusion in the coastal zone. We will deal with this in this chapter in two different ways. For presentation of data that can give a broad picture on human conditions for different regions of the Arctic, we use the administrative units that have a coastline (Fig. 27). From the map of Arctic sub-national units (counties, states, oblasts, okrugs, territories, and indigenous land-claim areas) it is clear that almost all Arctic regions have a coastline. The only exceptions are the Russian regions of Khanti-Mansii Autonomous Okrug, and the Republic of Komi, Norrbotten in Sweden, and Kainuu in Finland. When we use the term 'Arctic regions' later in this chapter, we refer to the administrative units in Figure 27, unless otherwise stated.

There is large variation among the Arctic regions across a range of dimensions. We return to many of these below, but here note just a few demographic characteristics. In 2006 the population size ranged from 10 000 in Nunavik to 1.3 million in Arkhangelsk Oblast, the share of indigenous people varied between 0% and 90%, and the share of children 0-14 years age in the population was from 15% to 36% (Duhaime and Caron, 2009). The objective of this section is to provide an overview and explanation of this, but to provide an overview of the variability in human economic and political conditions throughout the circumpolar Arctic coastal zone.

National statistics agencies collect a number of statistics relevant to the human populations in the various Arctic countries. Attempts to gather and compare such statistics across the Arctic regions are limited. The AHDR (2004) was the first comprehensive attempt. The ECONOR project, led by Statistics Norway, focused on comparing mainly economic data (Glomsrød and Aslaksen, 2006). The follow-up, ECONOR-II, updated the first report, and elaborated on social conditions, and also focused on some specific themes (Glomsrød and Aslaksen, 2009). ArcticStat is a database on Arctic circumpolar data. It was set up as a major Canadian contribution to the International Polar Year. The database covers socio-economic data for 30 Arctic regions in the 8 countries around the circumpolar north, including population, migration, education, employment, language,

Figure 27. Arctic regions.
Source: Arcticstat (www.arcticstat.org)

economy, health and more. Partly it helps locate datasets in the web pages of the bureaus of statistics of the Arctic countries, and partly it presents comparisons that have been made especially for ArcticStat. It is available at www.arcticstat.org. Two other projects that specifically aim to improve the collection and availability of data on social conditions in the Arctic must be mentioned. The SLiCA (Survey of Living Conditions in the Arctic) is gathering data mainly on indigenous peoples' living conditions (see Box). The Arctic Social Indicators project (Larsen et al., 2010) is a direct follow up to the AHDR-report (see below).

2.3.2 Social conditions and human development

As we have already noted, the human condition varies considerably across the Arctic. Duhaime and Caron (2009) provide some key figures to illustrate this (with data for 2006): life-expectancy at birth in the Arctic regions varies from 56 to 80 years; Infant mortality from 1.4 to 33 per thousand live births; the share of the population with tertiary education varies from 9% to 25%.

SLICA: Survey of Living Conditions in the Arctic

Birger Poppel

The partnership between international researchers and indigenous representatives (Inuit and Sami) resulted in 2001 in an agreement on a common 'core questionnaire' for all regions included in the Survey of Living Conditions in the Arctic, SLiCA. The content of this box is based on Kruse et al. (2008), Poppel (2010) and progress reports on SLiCA to the Arctic Council's Sustainable Development Working Group.

The major objectives of the joint research effort were: 1) to measure living conditions in a way relevant to Arctic residents; 2) to document and compare the present state of living conditions among the indigenous peoples of the Arctic; 3) to improve the understanding of living conditions to the benefit of Arctic residents; and 4) to provide local, regional, national, and international organizations an improved basis for decision-making.

Following these objectives it was the ambition not only to measure living standards of individuals and households but to focus on all resources - material as well as non-material - that individuals can apply to enhance their living conditions and thus to develop indicators reflecting the welfare priorities of the Inuit, the Sami and the indigenous peoples of Chukotka and the Kola Peninsula. It was, at the same time, the goal to increase the understanding of relationships among both new and traditional living conditions. Thus it was decided to develop indicators within each of the following dimensions: 'communication and technology', 'community viability', 'discrimination, education', 'employment/harvest', 'environment/resource management', 'family relations and social networks', 'health, household economy', 'housing', 'identity management', 'justice/safety', 'language', 'mobility', 'political resources', 'religion/spirituality', 'work/leisure'. The international core data dictionary with information also about analytic variables is accessible at http://classic.ipy.org/development/eoi/ • Science Plans: SLiCA data description.

The SLiCA target population is defined in three elements: (1) indigenous individuals aged 15+ in Canada and Greenland, 16+ in other regions (in Greenland the sample includes immigrants, mostly individuals who have migrated to Greenland from Denmark); (2) residing in households; (3) in a traditional settlement region. The results cited below are based on the first part of SLiCA including Inuit and the indigenous peoples of Chukotka. The settlement regions are defined as: Alaska (North Slope, Northwest Arctic, Bering Straits census areas); Canada (Inuvialuit, Nunavik, Nunavut, Labrador Inuit land claims regions); Greenland (North Greenland; Disco Bay region; Middle Greenland; South Greenland; East Greenland); and Chukotka (Anadyrskij, Anadyr, Shmidtovs, Beringovskij, Chukotskij, Iujl'tinskij, Bilibinskij, Chaunskij, Providenskij, Uel'Kal' districts).

The indigenous peoples represented by the data include Inuit in Northern Alaska, Arctic Canada, Greenland and Chukchi, Inuit, Evan, Chuvan, and Yukagir in Chukotka. All Inuit in Northern Alaska and Greenland and most of the Inuit of Chukotka (i.e. Siberian Yupik) live in coastal areas. Furthermore, all but two Canadian Inuit communities are located on the coast, and these two exploit coastal resources.

Response rates exceeded 80 percent in all regions. The sampling procedures applied ensure that the SLiCA sample is representative, and the subsequent weighting procedures (taking into account differences in regional and community sampling probabilities and differences in response rates by gender) make it possible to generalize responses to entire populations by: 'country', 'region', 'region/place size', 'gender' and 'age groups'. Such population breakdowns are reported on the project website, www.arcticlivingconditions.org.

Results for Arctic indigenous settlement regions as a whole are subject to a maximum estimated sampling error of plus or minus one percentage point. Regional comparisons have sampling errors of one to four percentage points. Breakdowns for subpopulations and more refined geography are subject to larger sampling errors. A more thorough elucidation of the methodological and theoretical aspects of the study as well as the development of the process can be found in Andersen and Poppel (2002), Andersen et al. (2002), Kruse et al. (2008) and on the project web-site: www.arcticlivingconditions.org.

Key SLiCA findings

SLiCA findings and analysis results are published on the project web site and in a number of articles (e.g. Kruse et al., 2008; Poppel and Kruse, 2009). The following key findings are responses to research questions posed by the indigenous partners within SLiCA. At the same time the results indicate the range and variety of data.

- A combination of traditional activities and cash employment is the prevailing lifestyle among Arctic Inuit and indigenous peoples of Chukotka. It takes money to pursue traditional activities; households with higher incomes can, and do, choose to spend income on these activities. Nine out of ten Inuit think traditional activities are important to their identity.

- Health conditions vary widely in the Arctic: Most of the Inuit rate their own health as good or excellent – almost all respondents in Canada and Greenland and three-quarters of those in Northern Alaska. The exception is Chukotka, where more than half rated their health as only fair or poor.
- Even though most are satisfied with life in their communities, indigenous people also cite widespread social problems: unemployment, alcohol abuse, suicide, drug abuse, family violence and sexual abuse are on average considered major social problems by more than six Inuit out of ten. Most problems are reported from Chukotka, as at least eight out of ten cite most of these problems.
- In the face of rapid changes in the Arctic, most indigenous peoples have maintained their traditional subsistence activities. Many also continue to speak their native languages – in addition to Western languages. More than 90% of Greenlanders and Inuit of Nunavut and Nunavik – young and old – report that they are fluent in their native language. In Northern Alaska and Chukotka, indigenous people of all ages are much less likely to speak their native languages — and those who can are more likely to be 55 or older. In Northern Alaska, just 5% of those aged 16 to 19 say they are fluent in a native language.
- The indigenous peoples of Chukotka, Northern Alaska and Greenland were asked about environmental concerns, if any. On average three out of four perceive climate change to be a problem in their communities and more than half of all Inuit mention local contaminated sites, pollution of local lakes and streams and pollution from industrial development as problems in the region. A significantly larger proportion of the indigenous people of Chukotka are concerned with these problems. In Greenland pollution from other countries and in Chukotka and Alaska erosion of coastal areas or riverbanks are cited as problems by vast majorities.

Young and Einarsson (2004a) in the Introduction to the AHDR ask what human development is, and how we should measure it. A measure such as the UN Human Development Index is clearly limited, as it only includes three factors: life expectancy at birth, education (a combination of adult literacy and school enrolments), and material standard of living measured by GDP (Gross Domestic Product) per capita. A major point from the AHDR is that for the Arctic a measure of human development should include elements on *fate control* (to what extent it is possible to guide one's own destiny), *cultural integrity* (belonging to a viable local culture), and *contact with nature* (interaction with the natural world) (Young and Einarsson 2004b). The project on Arctic Social Indicators (ASI) is a direct answer to this call, and from the completed Phase I of the ASI-project a large number of indicators also including these elements are being proposed, in addition to a smaller suite of indicators that, taken together, are expected to do a good job of capturing key elements of human development in the North (see Box).

Another attempt to look at human development in the Arctic with a somewhat wider set of indicators than the ASI uses is presented in *The Economy of the North 2008* (Glomsrød and Aslaksen 2009). Chapter 2 in the report (Duhaime and Caron 2009) gives an overview and comparison of economic and social conditions across regions in the circumpolar Arctic, expanding on the original *Economy of the North*-report (Glomsrød and Aslaksen 2006). They construct indicators based on the regions' score on these six data sets: (1) female proportion, (2) life expectancy, (3) infant mortality, (4) tertiary education, (5) disposable income, and (6) dependency ratio. The female proportion-index is highest when there is balance between the numbers of males and females. Tertiary education is the proportion of the population that has completed tertiary education. The dependency ratio tells us how many people are unemployed or outside of the labour force per employed person. Note that a seemingly high dependency ratio may not necessarily imply a large dependence on transfer payments. If the subsistence economy is large and important compared to the market economy, we will also see this pattern. Disposable income is measured per person by purchasing power parities (PPP). This is a better measure of material well-being than Gross Regional Product (GRP) per person, as it accounts both for the fact that much of GRP does not devolve to the region's inhabitants, and that the cost of living varies between regions. PPP attempts to equal out the differences in the cost of living by adjusting the disposable income in the region with the cost of a "standard" basket of goods. Larsen and Huskey (2010) present a number of alternative indicators to GRP that are, they argue, doing a better job of capturing the level of material wellbeing in the region.

Although the differences between regions' average values for these variables can be quite dramatic, the variation in shares of women in the population varies only from 47% to 54%. On a finer geographical scale, the differences are more dramatic however (as also for other variables). Data on the regional level will of course mask differences within the regions. Comprehensive data collection across "all" small communities is hardly feasible. When regional data cannot be broken down in a meaningful way, case studies should be performed to supplement these.

Several publications post-AHDR have an explicit health focus. Young and Bjerregaard (2008) gives an overview of health issues in the Arctic, by major Arctic regions, (selected) indigenous peoples, major determinants of health conditions, and consequences for health. Among the groups of determinants the authors discuss are *Environment and living conditions* (chapter 10), and *Cold exposure, adaptation and performance* (chapter 14). Some of these factors may be influenced by environmental change on the Arctic coasts. Also, socio-economic conditions in general have a very strong influence on the health of people. Changes in the natural environment on the Arctic coasts that lead to altered socio-economic conditions are thus likely to also give health effects.

Van Oostdam et al. (2005) give a review of the human health implications of environmental contaminants in Arctic Canada. For these regions, with large indigenous populations (about 50%, Duhaime and Caron 2009; but much higher proportions in remote coastal communities), they point to how country food (as opposed to southern/market food) is the major source of contaminants. However, they also point to how country food is important both as a source of protein and essential minerals and metals, and for cultural, spiritual, social and economic reasons. Balancing the risks and benefits of a traditional diet is thus challenging, raising problems that cannot be resolved by simply considering health and food substitutions alone.

2.3.3 Economic conditions and economic systems

There is a wide range of community size and economic conditions on the Arctic coast; from large urban settlements to small hamlets (population <100 in some cases) and nomads following herds on their migration through the year. Traditional indigenous ways of life dominate in some areas, but not entirely without influence from the "modern" world. Global communications (satellite television, mobile phone services, and high-speed internet) are making rapid inroads even to small isolated northern communities (Poppel, 2006; Poppel and Kruse, 2009). Social organisation ranges from family- and tribe-based to urban with inhabitants from different ethnic groups, regions

ASI: Arctic Social Indicators

Joan Nymand Larsen

Rapid change challenges Arctic communities, with globalization, economic and political transformations, changing cultural landscapes, and climate change, all of which require adaptations. In recognition of these social challenges, the Arctic Council supported the documentation of Arctic residents' well-being around the Circumpolar North, and commissioned the *Arctic Human Development Report* (AHDR). The AHDR emphasized the need to develop a system for tracking trends in human development in the Arctic over time, through the identification of a set of indicators. It identified a number of key domains as determinants of wellbeing in the Arctic that reflect particularly prominent features of human development in the Arctic, and that have not been systematically considered: *Fate control* – guiding one's destiny; *Cultural integrity* – belonging to a viable local culture; and *Contact with nature* – interacting closely with the natural world (AHDR 2004:11). The AHDR contended that measuring human development in the Arctic would require a distinct set of indicators reflecting these domains. Simply using the UN Human Development Index to measure human development in the Arctic would result in a distorted picture.

The Arctic Social Indicators (ASI) project (2006-2011) responded to the AHDR, in aiming to develop a set of indicators to track changes in human development in the Arctic. ASI is endorsed by the Arctic Council, and is developed under the auspices of the Sustainable Development Working Group (SDWG). ASI chose six domains in which to develop indicators for monitoring human development, the three domains identified by the AHDR:

- fate control,
- contact with nature, and
- cultural wellbeing,

and three domains constituting the UN Human Development Index, adapted for the Arctic context to:

- health/demography,
- education and
- material well-being.

The suite of six domains provides an approach that is broad and inclusive while remaining manageable. The challenge was then to find a concise set of indicators that could practicably depict trends of development (positive or negative) for the domains in an intelligible manner.

The three domains highlighted by the AHDR have proven particularly challenging for indicator construction: *Fate Control* refers to people's ability to guide their own destiny, and is a concept that is highly linked with the more common term "empowerment". To capture the complexity of this domain, the ASI team settled for a composite index. Similarly, *Cultural Integrity* is a particularly challenging concept for indicator construction. The complexity of the concept of culture makes it a significant challenge to determine an appropriate indicator, one which can provide a universally intelligible measure of cultural wellness across circumpolar populations. Language retention, cultural autonomy, and sense of belonging are all elements that influence cultural integrity and are important for cultural wellbeing in the Arctic. And lastly, *Contact with Nature* is a somewhat intangible attribute of human development in the Arctic and indicators are extremely challenging to develop and difficult to measure. One major constraint to measuring indicators for this domain is the lack of current data.

The ASI team developed a common list of key selection criteria. Criteria chosen were data availability, data affordability, ease of measurement, robustness, scalability and inclusiveness. These criteria were adopted as a set of principles to guide indicator selection, recognizing that the criteria themselves were not precisely defined, and that trade-offs in their application had to be considered.

In creating a tractable set of social indicators for the Arctic, the team were faced with choosing, from a large number of possible indicators, a small, manageable subset that were robust, user-friendly and straightforward to interpret. The ASI working group placed special emphasis on the selection criteria of data availability and ability to access data currently. 'Data availability' refers to whether the data required for an indicator exist, and whether they are retrievable. A number of indicators considered could draw on data collected by national agencies. Other considerations in terms of availability included whether nationally collected data are comparable across countries, and whether the data are accessible in hard copy or electronic format from the collecting agency, or whether data could be compiled by researchers from other existing information.

Also, it is important that the chosen indicators receive wide support, so that they will not be changed regularly, just as it is critical that the chosen indicators are consistent over time and across places, as the usefulness of indicators is related directly to the ability to track trends over time and compare the wellbeing of regions. Based on selection criteria the following suite of ASI indicators was chosen to capture as a collective the state of human development in the Arctic:

- infant mortality;
- net-migration;
- consumption/harvest of local foods;
- per capita household income;
- ratio of students successfully completing post-secondary education;
- language retention; and
- an index of fate control (see Larsen et al., 2010, for in-depth discussion).

The recommended set of indicators is the collection of best-choice indicators representing the best available option from each of the six domains, given the constraints and limitations relating to data availability and to their construction. Once measured, verified and refined through further testing and analysis in the second phase - ASI-II (2009-2011) - this set will help facilitate the implementation of a system for ongoing monitoring and analysis, and will provide critical information on human wellbeing in the Arctic.

Important data challenges, including quality, accessibility, and consistency, results in critical trade-offs in selecting the best indicator among a set of possible indicators. In devising all indicators of human development in the Arctic we face important trade-offs. Such trade-offs will of course always exist to some degree, simply because it is impossible to fully capture the complex reality of some concepts and phenomena in a single measure. Until improvements are realized, in methods and extent of data collection, and data quality and its availability, compromises will need to be made to achieve good indicators that are obtainable at a reasonable cost in terms of both time and resources.

The ASI-II Implementation project (2009-2011) aims to implement the identified indicators, through testing, validating and refining the indicators across the Arctic, and then measuring and performing analyses of select cases, with the ultimate goal of moving to adoption by Arctic governments and the Arctic Council of the indicators for the purpose of long-term monitoring of human development.

of the nation state, and other countries. Commercial aviation, though expensive, enables rapid evacuation for medical emergencies and facilitates provision of services, imports of perishables, and travel for regional administration, political organization, economic and cultural activities, education, and research.

The population of the Arctic lives both on the coast and inland. The coastal population and the coastal region are dependent on activities and resources both at sea and on land. This applies both to subsistence harvesting and the market economy (Hacquebord, 2007). Many reindeer herders migrate between inland and coastal areas between summer and winter. Coastal Inuit communities, while highly focused on marine living resources, also hunt caribou,, muskox, moose, and other terrestrial species where and when available and fish rivers and lakes for anadromous and freshwater fish in addition to coastal fisheries. Some coastal communities are important shipping ports and transport hubs for inland areas, and for many marine fishing is an important industry. Focusing on conditions specifically on the coast, or how the coastal landscape might be affected by changes in natural and/or economic conditions, must therefore be done with an awareness of developments both inland and in the ocean. In this context, the connection to winter ice should also be emphasized. Ice provides a platform for seal, whale, walrus, and polar bear hunting, often at the “floe edge” (the edge of landfast ice) and provides transport corridor to hunting grounds. In some cases, ice provides a winter road for access to southern road networks, extending as far as the Arctic coast (e.g. at Tuktoyaktuk, Northwest Territories).

According to the Arctic Human Development Report (Duhaime et al., 2004, Chapter 4), the Arctic economy as a whole has three major characteristics: large-scale resource extraction, lack of manufacturing industries, and the importance of the public sector due to both the high proportion of service provision and transfer payments from the south. For some regions and groups of people, the subsistence economy is also of large importance (Poppel, 2006; Poppel and Kruse, 2009; Aslaksen et al., 2009). As discussed in the Arctic Social Indicators report (Larsen and Huskey, 2010, Chapter 3), any attempt to measure the size of the northern economy or the level of material wellbeing that excludes the important contribution made by the non-market subsistence sector provides an incomplete measure.

The Arctic is a major provider of natural resources both to national economies and to the world market (Glomsrød et al., 2009; Hacquebord, 2009a). The Arctic also holds a large proportion of known and expected reserves of many non-renewable resources (Lindholt, 2006). Average disposable household income (DHI) per capita in the Arctic regions varies from 6700 US$ (PPP) to 32800 US$ per capita, as can be seen in Figure 28. As many goods and services are imported to the region, and transportation is costly due

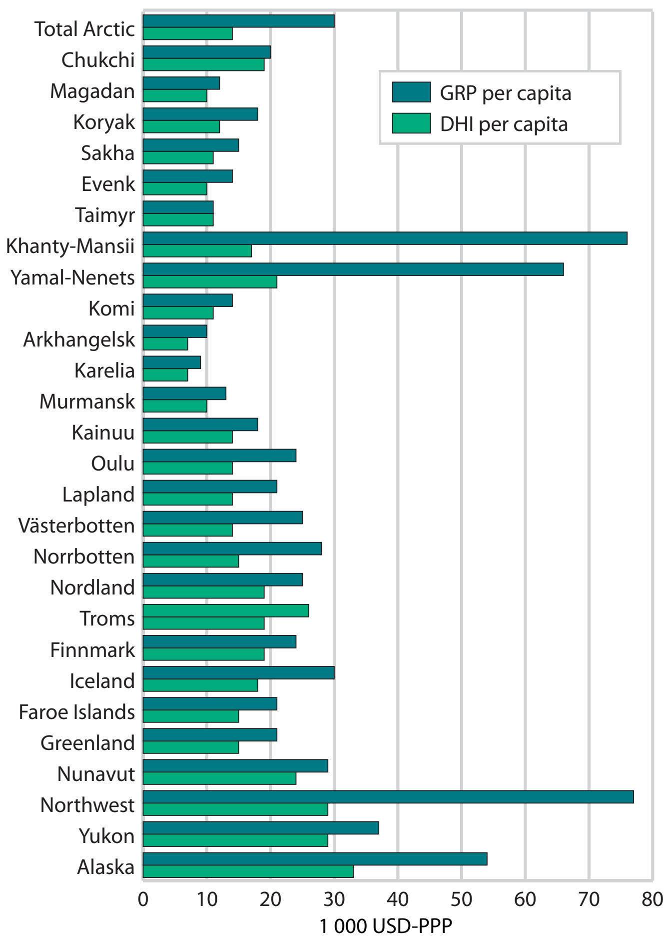

Figure 28. Gross regional product (GRP) per capita and disposable household income (DHI) per capita, by Arctic regions, 2005 (units US$1000-PPP).
Source: Glomsrød and Aslaksen (2009) and Marit Vågdal

to the long distances, limited infrastructure and often bad weather conditions, there is a high cost of living in general (Glomsrød et al., 2009).

Note how the Gross Regional Product differs dramatically from DHI for many regions (Fig. 28). For all Arctic regions, except one, GRP per capita is much larger than DHI per capita. This reflects that often large parts of the value creation that occurs in these regions accrue to people and institutions outside of the Arctic because of outside control and ownership of resources. The largest discrepancies between GRP and DHI per capita are in regions where oil or gas production or large-scale mining occurs.

The regions with the largest value creation per capita are also the regions that regularly experience the largest shifts in economic situation (Glomsrød et al., 2009) (Fig. 29). A strong dependency on raw material production, in particular non-food items such as oil and gas, metals and minerals, leaves the regional economy vulnerable to shifts and cycles in the prices of these commodities. During the last 10 years the prices of some of these have varied over 500% (in nominal terms). For communities with economies based on non-renewable resources, boom and bust may be a characteristic that can be used to describe their economic development pattern, particularly as the resource may run out (or extraction and transport may become cost-prohibitive). Both boom-periods and bust-periods place strains and create negative effects for local administrations, people and the economy. While a relatively high dependence on transfers from the federal level "in the south" may act as a cushion in times of regional or local economic downturn, it also makes the Arctic regions vulnerable to political regime shifts that result in reduced transfers.

While natural resource extraction is a major component of the economic and industrial structure of the Arctic regions, the overall industrial structure of these regions is not too dissimilar to that of regions further south or the Arctic countries as a whole. It

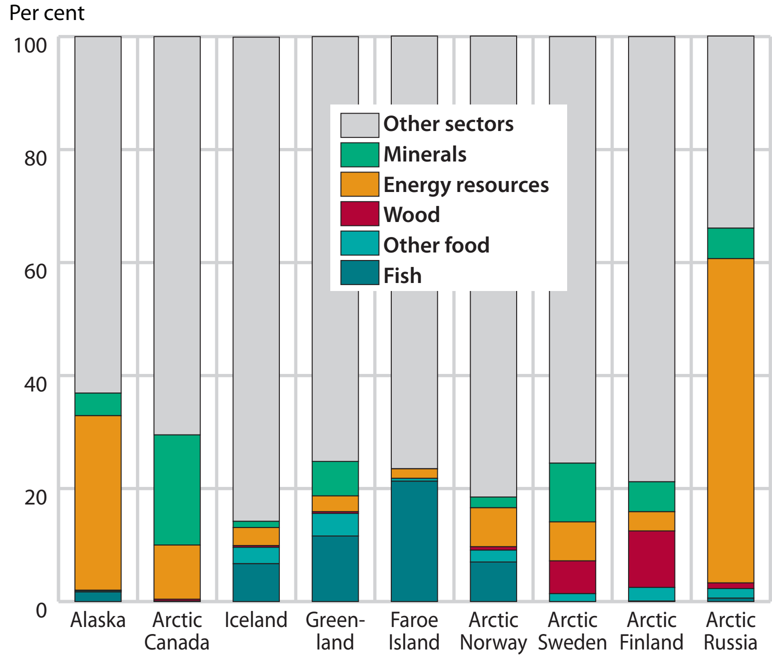

Figure 29. Value added in natural resource based industries in Arctic regions, 2005 (units US$1M).
Source: Glomsrød and Aslaksen (2009) and Marit Vågdal

is still the tertiary sector (services) that dominates in terms of both employment and value creation in these regions. Considering the industrial structure of each of the Arctic regions in somewhat more detail is useful to gain a further understanding of how they may be affected by changes in the natural systems on the coast. We focus here on market-driven industries that either depend on living natural resources on the coast, industries that depend on non-renewable resources, or industries which are otherwise likely to be affected by climate change or policies relating to it. Here we have considered industries to be important if they are important either for value creation or for employment. There is not always a correspondence between the two. The description is based on Glomsrød et al. (2009).

In Alaska, petroleum activities dominate value creation to a large degree. Other important sectors are mineral extraction, seafood production and tourism. The latter has been growing rapidly in latter years. In Canada, mining and oil and gas are the predominant industries, with limited commercial fishing but a growing tourism industry. In Arctic Russia oil and gas constitutes more than 50% of value creation (including Khantii-Mansi), but mining is also important. Reindeer herding has been and may still be important in Arctic Russia for food production marketed to industrial and mining settlements.

The Faeroese and Icelandic economies are strongly dominated by fisheries. In Greenland, fishing (particularly shrimp fisheries) and mining are important, and offshore oil and gas exploration in Baffin Bay is ramping up. Tourism is also of growing importance in Greenland. For northern Norway, fishing is an important industry, as are offshore oil and gas, agriculture, tourism (particularly in terms of employment) and hydroelectric power production (in terms of value creation, not employment). Some commercial whaling continues to be practiced in Iceland and Norway.

For Arctic Sweden, mining, forestry and manufacturing based on forestry, as well as hydroelectric power production are important. Northern Finland constitutes an exception to the picture of an Arctic with very little manufacturing. In addition to forestry and forestry-based industries, there is important electronics manufacturing and a metals industry. Figure 29 gives an overview of most of these characteristics, in terms of natural resource-based industries' value creation. Note that it does not include the value creation related to subsistence activities, except for Alaska.

Some important keywords for modern economic theory related to economic development are innovation, competence, networks and collaboration. Research on Arctic economic conditions and development has to a limited degree included the perspective linked to these keywords. Technologically advanced and competence-intensive industries are being developed in the Arctic. This is often based on natural resources available in the region, and not only linked to the multinational companies that do large-scale resource extraction. An example is the marine biotechnology industry established in Northern Norway (Normann, 2007). The links between people and businesses in urban and peripheral centres, and between higher education institutions, research institutions, existing industries and public authorities and public policies, should be investigated further. A recent contribution from Russia related to this is Pelyasov (2009).

2.3.4 Subsistence economies

Both for indigenous peoples and other residents of the Arctic, subsistence production (hunting, fishing, gathering for own household's consumption and for sharing and thus not for the market) is important (Poppel, 2006; Poppel and Kruse, 2009; Aslaksen et al., 2009; Larsen et al., 2010; Larsen, 2010a). To different degrees it is combined with participation in the ordinary market economies. Hunting, fishing and gathering is important for large parts of the Arctic population both for food (and thus economic reasons), nutrition, cultural identity and social relationships (Fig. 30).

Reindeer herding is another important subsistence activity in the region, and it is the main economic activity for several tens of thousands of people across the Arctic. While to a large degree it utilizes inland areas far from the coast, in some regions summer pastures by the coast are important. Climate change, even if it should directly affect inland winter pastures more seriously than the summer pastures, may give strong effects on the coastal regions due to temporal and geographical displacement of reindeer herds placing a heavier burden on the summer pastures there.

Indigenous rights to land and natural resources in the Arctic are important as a material basis for their cultures (Aslaksen et al., 2009). Threats to the access, abundance or quality of these resources are thus not just a threat to the subsistence of a people of the circumpolar north, but also a threat to their cultures and very identity as indigenous people. This is the reason why protection and securing of the material basis for indigenous peoples' cultures are emphasised both in international declarations and conventions (e.g. United Nations Declaration on the Rights of Indigenous Peoples, 2007), and in some states' national legislation.

Subsistence activities are largely invisible in official statistics, with the exception of Alaska (Aslaksen et al., 2009). Reliable statistics on the importance and extent of

Figure 30. Traditional fish-drying in Arctic Canada.
Source: David Hik, University of Alberta and IASC

subsistence activities are therefore mainly based on case-studies, and attempts at synthesising and comparing, such as the *Survey of Living Conditions in the Arctic* (SliCA) (Poppel, 2006; Poppel and Kruse, 2009; Rasmussen, 2005; Aslaksen et al., 2009; see Box).

Based on a comparison of subsistence activities in Greenland, Chukotka and Alaska (and partly Canada), Poppel (2006) and Poppel and Kruse (2009) show that for more than 40% of households, household-harvested food accounts for 50% or more of consumed meat and fish. Sharing traditional foods with other households is done by more than 90% of households, and more than 90% of households think that subsistence activities are *important* or *very important* for their indigenous identity.

Even for those people in the Arctic that are not dependent upon hunting, fishing or gathering for their subsistence, it is an activity that many take part in for recreation.

Even though data on the importance of subsistence economies are scarce, the report *The Economy of the North 2008* includes some descriptions of the situation in Alaska, Canada and Russia, as well as a description of reindeer herding in the whole Arctic region. Other accounts (e.g. Poppel, 2006) include other regions. We present a selection of findings from these studies just to illustrate the variability in extent and material basis of subsistence activities, their importance, as well as the legal/governance framework for these activities in the Arctic. These examples are based on Aslaksen et al. (2009).

In Alaska, there is not just one type of subsistence economy: there are several, with different emphasis on fishing different fish species, hunting game or sea mammals, and gathering food. The amount of food collected per person varies considerably between regions. The largest differences are between persons in urban and rural settlements, ranging from 10 to 390 kg per person per year. Practically 100% of the households in Alaska have members that harvest from nature in one way or another during the year. For people in communities where subsistence activities are important, extensive sharing (giving or receiving) fish, meat etc. is common, and also with people in other communities (Poppel and Kruse, 2009).

In Canada, the material and legal basis for indigenous peoples' subsistence activities is largely secured through land claims settlements between the federal, provincial, or territorial governments, aboriginal governments, and/or aboriginal organizations. Temporary participation in ordinary wage activities is common, at least at the household level. The consumption of country food typically ranges from 90 to 300 kg per person per year. Substantial variations exist across indigenous communities in Arctic Canada.

In Russia, 40 small northern ethnic groups have special legal status (increased from 26 since 2002). It is acknowledged that they require special protection to sustain their culture. Indigenous groups comprising more than 50 000 people are not given the same privileges, as their cultures are considered more viable by virtue of their sheer size. Outside urban areas in the Russian Arctic, indigenous people often make up the majority of the population. Among the provisions are land set aside for traditional use, and special quotas for fishing. The data on the subsistence economy is generally not reliable, except for a few case studies. It is however clear that for some groups the value of the subsistence production is several times larger than their monetary income from other sources (wages, pensions, transfers).

2.3.5 Social-ecological couplings in the Arctic

To what degree people and communities in the Arctic depend on natural resources and environmental conditions, and conversely how changes in resources and environmental conditions may affect industries, regions and people, is important for policy formulation and adaptation, and particularly interesting when large changes are possible due to climate change. Other factors are the effects of expanding human populations and the application of 21st century technology for subsistence harvesting on ecological systems and the populations of harvested species. Some recent contributions have considered this for Arctic regions.

Fisheries are important for the north-Norwegian economy (see Section 3.3). Fish stocks in the Barents and Norwegian Seas, especially cod, but also herring and capelin, are central. These major commercial species are also linked ecologically, so harvests on one of them also affect the future possible harvests on the other species. Heen and Flaaten (2007) estimate the spatial employment effects in northern and south-western Norway of different fisheries management regimes for these three fisheries. They couple a multi-species fisheries model with a regional input-output model, and find that fisheries management decisions can have large regional employment effects in Norway. The same ecological links are true for other species. Norway is still taking minke whales (circa 600 per year), influencing the composition of the zooplankton, shrimps, and fish populations in the northern seas (Hacquebord, 1999).

Studies by Eide (2007, 2008) consider possible economic impacts of climate change on the Barents Sea fisheries in a 25-30 years perspective. The economic and employment effects are given for the whole fishery, and not for different geographic regions. The effects of climate change are found to be much less important than the choice of management regime. This is in accord with earlier studies, and assumes that the ecosystem is not altered dramatically due to climate change. Link and Tol (2009) model effects of a change in the thermohaline circulation (caused by climate change) on Barents Sea fisheries in a 100-year perspective. They find that a substantial weakening of the thermohaline circulation can give an impaired cod stock to the degree that the fishery becomes unprofitable. Concurring improvements in the capelin fishery are not enough to offset the effects on the cod stock. Such changes would lead to substantial regional redistribution of income and employment in Arctic countries, and possibly also between the nation states.

Huntington et al. (2007a, 2009a) investigate links between human demography and environmental conditions on the Pribilof Islands, off Alaska. For more than two centuries the people on the Pribilof Islands have relied strongly on fur seal hunting for their income. The commercial hunting ended in 1984. Since then the islands' inhabitants have searched for other activities that could provide a lasting economic basis for them. Fishing, mainly for halibut and snow-crab, has been important, but has not been a reliable source of income for the whole period. Analysis of data on employment, household income and population numbers, led Huntington et al. to suggest that there have not been strong and obvious linkages between population levels and environmental and economic conditions on the Pribilof Islands in this period. There has been a decline in population on the islands, but it does not correlate significantly with employment or household income, nor is it significantly different from the population dynamics of other communities in Alaska. Hence, the linkage between population and environment has been loose on the islands in this period. Huntington et al. (2009a) discuss many reasons why this is the case. One is that the social-ecological connection is rather resilient, and has not yet been pushed far enough. Economic conditions have not yet reached the point where it strongly affects peoples' choice of moving or staying. Attachment to place, culture, people and society are still more important. Benefit transfers to individuals and communities from the government also weaken the linkage between migration patterns and economic activities on the islands that are based on the area's natural resources. These factors that explain limited detectable social-ecological coupling on the Pribilof Islands are also present in many other parts of the Arctic, to different degrees. For example, for some indigenous people in Russia the safety net provided by transfers from the federal level may be weaker than on Pribilof, but the attachment to land, culture and lifestyle may be equally strong or stronger.

For communities and people that are already stressed, even small changes in the availability or quality of natural resources may be enough to threaten their very existence.

The studies above demonstrate the need for having a multifactor perspective when considering the likely societal effects of changes in biological resources and/or environmental conditions, whether these are due to climate change or other processes.

2.3.6 Changes in industrial activities due to climate change

Climate change can also be a catalyst for expanding industrial activities in the Arctic. Retreating sea-ice will make new areas available for shipping and offshore oil and gas activities, while increasing wave erosion hazards to coastal infrastructure (Fig. 31). Whether, or to what extent, these activities actually will increase depends on a number of factors. Technological challenges that remain unresolved may mean production will not expand due to either safe and reliable operation not being possible, or due to

Figure 31. Wave-cut coastal scarp near the Varandei oil terminal, Pechora Sea, Russia.
Source: S. Ogorodov, Arctic Coastal Dynamics Coastal Photo Collection, Potsdam

the costs of operation being too high relative to the prices that can be fetched on the world market for the products/services. Legal and political decisions may also limit the expansion of these activities, particularly in case of indigenous concerns about the effects of shipping activity on sea-ice stability and the risk of spills.

If petroleum production is to move further offshore and poleward in the Arctic, operating costs are expected to increase due to harsher climatic conditions and a lack of infrastructure. Lindhold and Glomsrød (2009) discuss how oil production in the Arctic will depend on the development in world market prices for oil and gas, based on model simulations. They consider both the effects for the total Arctic production and the geographical pattern of production. Relative to a reference scenario of 80 US$ per barrel oil equivalents (boe), the total Arctic production of oil and gas will be about 50% lower in 2030 if the price is 40 US$ per boe, and 50% higher if the price is 120 US$ per boe.

Military and industrial complexes are common features along many parts of the Arctic coast. The Distant Early Warning radar system was built in the 1950s and operated by the United States in cooperation with Canada until the 1980s. The majority of these sites were coastal and decommissioning has involved considerable expense for cleanup of contaminants (including hydrocarbons, polychlorinated biphenyls, organic pesticides). One of the methods for cleanup was excavation and reburial of the more stable materials in landfills that would be safe from coastal erosion. Other industrial facilities potentially at risk include ports and harbours supporting hydrocarbon and mineral extraction. The Varandei coast on the Pechora Sea has experienced significant erosion along the waterfront of a large oil storage facility, although this is caused by human activities on the beach – principally sand mining for aggregate (Ogorodov, 2005). Coastal erosion has also threatened potentially contaminated soils at other sites such as Komakuk Beach on the Yukon coast and in Alaska (Warren et al., 2005).

While retreating sea ice may lead to expansion of large-scale industrial resource extraction, both geographically and seasonally, other effects of climate change may act as constraints. It is not obvious whether the total ecological footprint on the whole Arctic will increase or diminish. What seems likely, though, is that the extent of industrial activity on Arctic coasts will increase. Another crucial issue is the extent to which a possible increase in large-scale industrial activities gives development opportunities and improvements in living conditions for local Arctic communities or merely benefits investors and other stakeholders living outside the Arctic.

2.3.7 Governance, planning and politics

In accounting for the status of Arctic coastal zones, two points of departure are worth noting:

First, all coasts in the Arctic are under the jurisdiction of a country (Fig. 32). There are almost no disputed land boundaries, although possession of Hans Island remains unresolved between Canada and Greenland (Denmark). Of the potential marine boundaries, more than half have been resolved. In contrast to many other areas in the world, the boundaries in the Arctic have been resolved peacefully (with the exception of the Finland – Soviet Union border along the Finnish Barents Sea corridor).

Second, there are enormous differences between the various regions of the Arctic in terms of population, economies, climate, cultures, and a number of other factors. The diversity is so vast that one could question the use of the term ‘Arctic’ as applied by many today (cf. the AMAP definition). Arctic economies range from modern market capitalism to mixed subsistence and cash economies. Political systems vary across all shades of what goes under the term “democracy”, with consequent implications for governance.

Also, there are a number of definitions of what is meant by ‘Arctic’. The issue of definitions is important because the wider the understanding of the region, the more diverse it

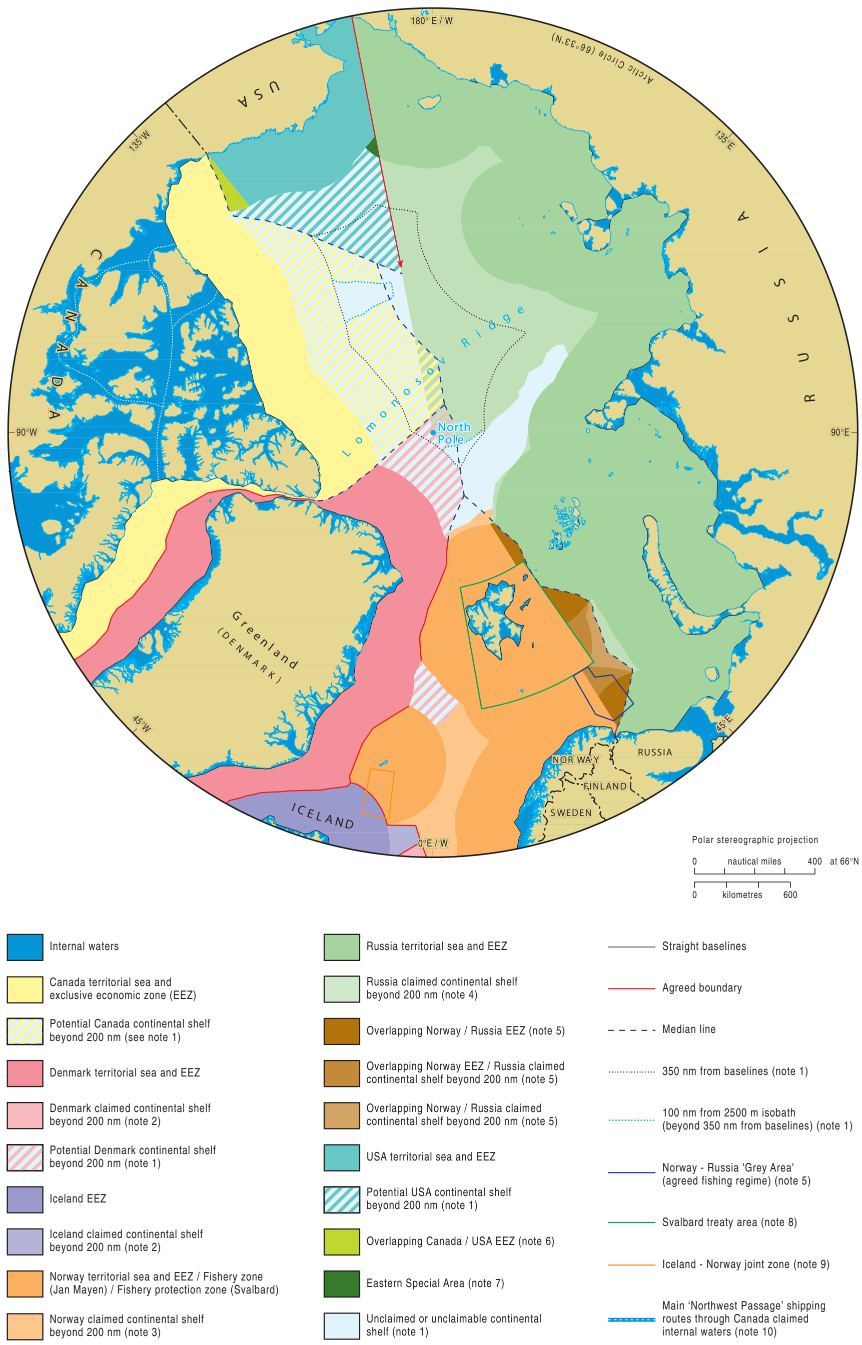

Figure 32. Maritime jurisdiction and boundaries in the Arctic region. Source: International Boundaries Research Unit, Durham University, UK (www.dur.ac.uk/ibru/resources/arctic)

is and the more varied and complex the challenges related to coastal zone management.

Because all coastal zones are in the territories of countries, their governance is essentially a matter for the relevant governments. Countries are however bound by international treaties on the one hand, and often have domestic arrangements for delegating authority to regional and/or local levels on the other. So an account of governance systems has to consider international obligations as well as multilevel decision-making systems at the domestic level.

At the international level, the most important global treaties pertaining to coastal zones are the Law of the Sea in general and the 1982 Law of the Sea Convention in particular, the 1992 Biodiversity Treaty, and the 1992/1997 global climate regime. These agreements give states a number of rights and obligations on the use, conservation and management of coastal zones. A regional treaty of great importance in the North Atlantic is the OSPAR Convention, which regulates marine pollution in that region.

The five littoral states in the Arctic have 200 mile EEZs (or corresponding) in the Arctic Ocean, leaving an area in the middle that is high seas (international waters; Fig. 32). As to the sea floor, the continental shelves belong to the coastal states – a process is under way under the Law of the Sea Convention to determine the outer limits of the shelves. The deep seabed in the central Arctic Ocean is the common heritage of mankind.

The Arctic Council serves as a high-level forum for international cooperation in the Arctic but has no legal status as a governance organization (Hacquebord, 2009b). It was formally established in 1996 under the terms of the Ottawa Declaration to promote cooperation, interaction and coordination among the eight member Arctic states with the involvement of six Arctic indigenous organizations as permanent participants. Much of the Arctic Council's work is carried out in six working groups (http://www.arctic-council.org/section/the_arctic_council).

The eight Arctic states vary immensely in size, culture, governance systems, and other aspects. Four are federal states (Russia, Canada, USA, Iceland), three are democratic republics (Russia, USA, Iceland), four are constitutional monarchies (Norway, Sweden, Denmark, Canada), two are self-governing autonomous territories (Greenland, Faeroe Islands), and three are members of the European Union (Denmark, Sweden, Finland), while Norway is associated with the EU.

There is a wide variety of coastal zone management systems implemented across the Arctic. The coastal zone management program implemented in Alaska's North Slope Borough is based on the Alaska Coastal Management Act of 1977 (http://www.co.north-slope.ak.us/programs/coastal_management/about.php, accessed 2010-01-15), which provides for shared state and local responsibilities for coastal areas and resources. The three EU countries are obliged to follow EU regulations for coastal management. Norway uses planning legislation, with strong interaction between the municipal level and regional sectoral state authorities (particularly for fisheries, environment, and health). In 2006, Norway established an integrated marine regional plan for the marine environment of the Barents Sea areas off the Lofoten Islands. It was seen as a milestone in establishing ecosystem based management of Norwegian marine areas. These efforts and attempts at holistic approaches are important steps, but it is clear that particularly on understanding societal risks of industrial activities and socio-economic impacts of ecosystem-changes, more work needs to be done.

In Canada, federal, provincial and territorial governments all play a role in managing coastal areas. Thus there is a tendency for the management to be fragmented (NTK, 2008), although resources in some areas are managed under co-management arrangements pursuant to the terms of land-claim agreements (e.g. Suluk and Blakney, 2008). In the coastal zone, this follows from the recognition of various indigenous treaty and non-treaty rights related to ocean and coastal activities. According to Kearney et al. (2007), the Canadian coastal zone management system has taken "some steps toward participatory governance but has not adequately provided the mechanisms for a strong role for communities in integrated coastal and ocean management". Some nevertheless see indications of a better inclusion of indigenous people in oceans and coastal management in northern Canada than on the North Slope of Alaska (Baker, 2010a, 2010b).

2.3.8 Summary discussion

Quality of life, health, demographic status, economic and political systems, industrial structures and the role of subsistence activities vary considerably between and within Arctic regions, and between indigenous and non-indigenous populations.

The Arctic economy as a whole is dominated by four major characteristics: the continuing importance of traditional subsistence activities and local living resources in most regions, the lack of manufacturing industries, the local and regional impacts of large-scale natural resource extraction or exploitation projects, and the major importance of the public sector for service provision and transfer payments from the south. Disposable household income is typically largest in the regions where large-scale resource extraction occurs, particularly petroleum extraction and mining. These are however also the regions where the discrepancy is largest between disposable household income and gross regional product, demonstrating that actors outside of the region reap a large portion of the benefits from the economic activities there. For many regions and groups of people the subsistence economy is of large importance, but relevant statistical data are still sparse for many regions, as demonstrated by the work on measuring Arctic Social Indicators (Larsen et al., 2010).

Even though the Arctic has a relatively large proportion of people living in a near traditional manner, close to nature and utilizing the resources there for food and subsistence, the Arctic is also well linked to the global economy. The same processes we see in the advanced industrialized regions, of a knowledge-based economy with a focus on innovations, are also taking place in the Arctic. The links between people and businesses in urban and peripheral centres in the Arctic, and between higher education institutions, research institutions, existing industries and public authorities and public policies, should be investigated further.

Climate change, and other processes that can affect natural resources and environmental conditions, can have large impacts on living conditions and quality of life in the Arctic; Renewable natural resources important for human activities may become less or more abundant, and new areas may be opened up for economic activities, representing both new opportunities and threats to existing activities. The importance of changes in environmental conditions for communities on the Arctic coast and Arctic industries should however not be overstated. Other factors and processes will often be more important, especially in the short run. For communities and people that already have a stressed situation, even small changes in the availability or quality of natural resources may be enough to threaten their very existence. The importance of a multifactor perspective when considering the likely societal effects of changes in biological resources and/or environmental conditions is critical. This includes, among others, government policies in the social, regional and natural management areas, international market and trade conditions, and cultural and demographic changes caused by other factors, like cultural globalization. Methods and tools to perform such integrated assessments, and to make scenarios that include physical, ecological and social changes, need further development and refinement.

The implementation of integrated marine regional plans, such as Norway's plan for the Barents Sea and the area outside the Lofoten Islands, is a milestone in establishing ecosystem-based management. Laudable as these efforts are, however, it is clear that particularly on understanding societal risks of industrial activities and socio-economic impacts of ecosystem changes, more work needs to be done.

In the period since the Arctic Human Development Report (AHDR, 2004) was released, the availability of statistical data on social, human and economic conditions in the Arctic has improved, and important projects are underway to improve this further. The AHDR found that, for people in the Arctic, fate control, cultural integrity and contact with nature are central for well-being, and should be included in future statistical studies. The Arctic Social Indicators project has now proposed a suite of indicators for these issues, in addition to those included in UN Human Development Index, and will work towards implementing a total set of indicators for the Arctic. Statistical data specifically on coastal regions is difficult to obtain, at least for circumpolar comparisons. Economic, social and demographic connections between coastal areas and inland areas also make it hard to make a clear delineation of what should be included, and what should be left out, in a coastal-based study such as this.

In a time of possible rapid changes in the Arctic due to climate change, monitoring of the human health situation across the Arctic is important, especially for indigenous people in rural or remote areas. They are particularly dependent on natural resources for food, and traditional food is very important for a wholesome diet and for cultural integrity, but at the same time may increase exposure to contaminants.

The various impacts, positive and negative, of large natural resource extraction projects (mining, oil and gas, hydro, or others) at local and regional levels need further study with attention to actions and effects on the operators (companies or utilities), regulatory and other government agencies, residents and other stakeholders, including effects of and on the natural environment.

More attention is needed on strategies to develop businesses, industries and communities in the rural north that support social, cultural, economic and ecological sustainability (see e.g. Larsen, 2010b).

3 Integrated assessment and response to Arctic coastal change

Following the thematic approach adopted in Chapter 2, this chapter introduces an alternative perspective, highlighting the need for integrated approaches to environmental and other changes in the Arctic coastal zone. There are four sections addressing the following topics:

- *integrated approaches to assessment of Arctic social-biophysical systems,*
- *monitoring, detecting, and modelling change,*
- *vulnerability, adaptive capacity, impacts and resilience, and*
- *the need for integrated governance mechanisms to support adaptation.*

3.1 Integrated Approaches to Coastal Change in the Arctic

Lead authors: Andreas Kannen and Donald L. Forbes
Contributing Authors: R. Cormier, J. Salamon

Key Findings

- Arctic coasts may be usefully viewed as complex social-ecological or social-biophysical systems. A social-ecological system is an ecological system intricately linked with and affected by one or more social systems and vice versa.
- The health of Arctic coastal and marine ecosystems is increasingly under pressure, putting at risk ecosystem goods and services that support coastal communities.
- There are major feedback loops in the Arctic system associated with rapid changes in the regional climate. For this reason, the impacts of climate change in the Arctic may extend to a global scale.
- There are two general approaches to more integrated understanding considered in this report:
  - Indigenous communities in general embrace holistic perspectives on the environment and culture.
  - The traditional scientific approach can be applied within a system science framework, with the application of integrated assessments to analyze the interactions in social-ecological systems, as outlined in the risk-based management approach.
- The holistic perspective of indigenous culture suggests that efforts to understand, manage, and respond to change in Arctic coastal systems may benefit from the integration and complementarity of both approaches. Recognizing the value of traditional ecological knowledge may contribute to enhanced resilience and adaptive capacity in coastal communities.

Climate change and expected increasing intensity of anthropogenic pressures such as oil and gas exploration and shipping along Arctic coastlines are generating significant environmental and societal effects. Climate change leads to changes in the physical environment, which then lead to changes in ecosystem conditions, thus affecting resource use and ecosystem goods and services. Thus, the health of Arctic coastal and marine ecosystems is increasingly under pressure, putting at risk ecosystem goods and services that support coastal communities. In the Arctic, both the ecosystem and coastal communities are potentially vulnerable to adverse environmental events. Adaptation of communities to these changes can in turn cause changes in community structures and social cohesion. For management and governance structures, this implies challenges, not only concerning local resource management, but in dealing with new economic sectors and tensions between local, national and global interests and needs.

3.1.1 Arctic coasts as complex social-ecological-physical systems

Much attention has been devoted to the impacts on coastal communities of shoreline erosion and sea-level rise (e.g. Johnson et al., 2003; ACIA, 2005; Manson et al., 2005a; Jones et al., 2008). Nickels et al. (2006) describe, from an Inuit perspective, observations of environmental change, with impacts on the way of life and behaviour for several Inuit communities (Fig. 33). Northern communities have much to lose, given their high dependence on goods and services provided by their local ecosystems. In addition to food and

OBSERVATION, IMPACT & ADAPTATION DIAGRAM FOR ALL REGIONS - UNPREDICTABLE WEATHER

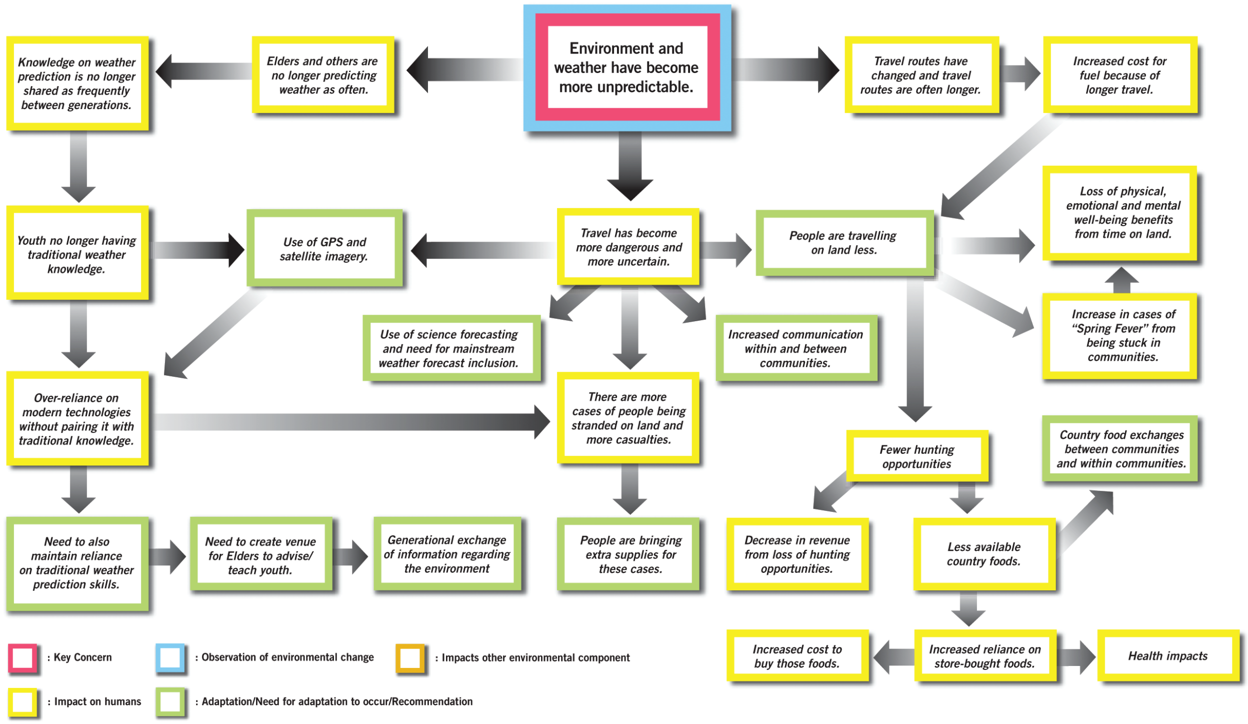

Figure 33. Observation, impact and adaptation diagram for Canadian Arctic regions.
Source: Nickels et al. (2006)

shelter, these goods and services are also tightly linked to the cultural and social fabric of the communities (e.g. Tremblay et al., 2006; Ford et al., 2009, 2010). Economically, ice-free Arctic waters in summer may facilitate increased commercial and industrial access to the Arctic, including petroleum exploration and transport, mining, general shipping, and tourism, but increased volume of traffic will also increase the risk of accidents and release of contaminants. Recognizing the potential for ice-free Arctic summers, two scenario exercises were recently implemented to consider the future of Arctic shipping (Norshipping, 2007; PAME, 2009a). Changing infrastructure needs in response to climate change and variability are widely anticipated (e.g. Canada NRTEE, 2009).

There are major feedback loops in the Arctic system associated with rapid changes in the regional climate. One example is the melting of snow and sea ice due to rising temperatures, which reduces the surface reflectance (albedo) and increases solar absorption, leading to further temperature increase (e.g. Cohen and Entekhabi, 2001; Wang et al., 2006; Zhang et al., 2008). Another example is thawing permafrost and the resulting gradual increase of methane emissions, which could contribute to acceleration of climate change (Lawrence and Slater, 2006; Schuur et al., 2008; Tarnocai, 2009). Due to such feedback loops, the impacts of climate change in the Arctic will not be restricted to local or regional scales, but will extend to the global scale as well.

These processes contribute to the characterization of Arctic coasts as complex social-ecological systems. A social-ecological system is an ecological system intricately linked with and affected by one or more social systems (Anderies et al 2004). Berkes and Folke (1998) used the term social-ecological system to emphasize the integrated concept of humans in nature and to stress that the delineation between social and ecological systems is artificial (Folke et al. 2005), an inherent perspective in holistic indigenous perceptions of the environment (e.g. Nickels et al. 2006; Sable et al., 2007; Huntington and Pungowiyi, 2009).

3.1.2 The need for an integrated approach to Arctic coastal change

As previous chapters have demonstrated, the conventional western science approach in recent years has considerably enhanced our understanding of processes in the Arctic. The strengths of conventional science include a detailed understanding of specific processes and the provision of quantitative assessments and models. On the other hand, the available data and specific knowledge from conventional disciplinary science cannot be readily translated into the understanding of complex system behaviour, and existing models cannot project the complexity of changes in social-ecological systems, including feedback loops between social and natural parts of complex systems (e.g. Janssen et al., 2003; Chapin et al., 2004; Norberg et al., 2008; Armitage et al., 2009; Huntington et al., 2007b). While disciplinary science can generate precise pictures of parts of the whole, a more generalist perspective can focus on the whole, although possibly with lower precision and higher uncertainty (Carpenter et al. 2009). The main problem is how to deal with missing information and uncertainty in the frame of traditional science and its models. Specifically, the conventional approach faces limitations when

- interactions between physical and biological processes need to be understood together for an assessment of ecosystem changes, often including dealing with missing information on specific system components and feedback loops;
- social issues need to be taken into account in order to understand impacts of ecosystem changes for human quality of life, specifically when different customs, values, needs, and cultures are involved;
- institutional issues need to be taken into account in order to understand decision-making and the criteria used by different groups, e.g. groups within indigenous communities or societies, government authorities at various levels, multinational corporations, or society at large;
- projections of changes are required in order to develop mechanisms and tools for adaptation to change including the problem of uncertainty and non-linear relationships.

On the other hand, an integrated approach aims to improve understanding of interactions at the system level in order to inform transparent and scientifically guided decision making. Therefore, integration has to build on results of disciplinary and multi-disciplinary research, but needs to put these results into a wider context. “To understand sustainability in social-ecological systems (SESs) we need to build a coherent understanding of how systems are progressively linked to ever larger systems and how upward and downward causation linkages occur within SES as well as across diverse sectors and scales” (Ostrom, 2008: 249).

Examples of integrated approaches at a global scale include the Millennium Ecosystem Assessment (UNEP, 2005, www.millenniumassessment.org) and the UNEP Global Environmental Outlook (UNEP, 2002). Both apply the DPSIR framework (Driver-Pressure-State-Response) (e.g. Turner et al., 1997; EEA, 1999; Bowen and Riley, 2003;

UNEP, 2005, 2007) to structure information and, like the IPCC, employ a scenario approach in order to frame potential future changes (UNEP, 2002, 2007). Even though the DPSIR framework does not allow full modelling of complex cause-effect chains, it seeks to connect causes (drivers and pressures) to environmental outcomes (states and impacts) and to activities (policies and decisions, response). The approach therefore provides a methodology to structure available information (and based on this, also indicators) into five categories: driving forces (drivers), pressure of use (pressure), a description of the status quo (state), the effects of pressure on that state (impact) and institutional options for taking action (response). Building on the DPSIR approach as well as ecosystem services, the accompanying box describes an analytical integrated risk-based decision-making approach currently under development in Canada.

For the Arctic, the Arctic Climate Impact Assessment (ACIA, 2005), commissioned by the Arctic Council, provides a comprehensive overview of climate-change impacts in Arctic regions including impacts on humans and indigenous societies. Nevertheless, the ACIA focuses on the Arctic as a whole and its subregions, but does not distinguish Arctic coastal areas with their specific pressures, changes and impacts. Other assessments commissioned by the Arctic Council such as the Oil and Gas Assessment focus on single sectors, again not elaborating on the specific vulnerabilities of Arctic coasts and coastal communities. Similarly, the Arctic Human Development Report (AHDR) provides a comprehensive overview of data and information related to human issues including economics, demographics, education and institutional regimes, but at rather broad scales and without looking into land-sea interactions.

An integrated approach to analyze the social-ecological systems of Arctic coasts needs to cover a range of interactions and issues such as

- interactions between physical and biological processes at global to local scales;
- land–sea interactions (e.g. river fluxes, resource use, cultural relations);
- forms of knowledge and information (scientific and traditional);
- timelines from past to present to future (monitoring, modelling, scenarios);
- interactions between ecosystems and humans (impacts on local communities, socio-economics at regional, national and global scales);
- the relations between system change, adaptation and governance structures.

There are two general approaches to more integrated understanding considered in this report:

- Indigenous people in general embrace holistic perspectives on the environment and culture.
- The traditional scientific approach can be applied within a system science framework, with the application of integrated assessments to analyze interactions in social-ecological systems, as outlined in the risk-based management approach (see accompanying box).

Analytical integrated risk-based decision-making

Roland Cormier

Conventional environmental assessments can only project the potential effects of a given project onto its local environment. Mitigation and control measures can then be implemented to reduce or eliminate effects. As development moves forward, the increasing number of projects eventually results in cumulative residual effects even though regional regulatory requirements and best management practices were adhered to. By design, project assessments are not effective at considering cumulative effects. An integrated approach is needed where the pressures of relevant land and aquatic based drivers are assessed as a whole against the vulnerabilities of ecosystem components. Using geo-spatial and temporal analysis, the severity and likelihood of the effects are assessed for each intersecting zone of influence occurring between drivers and components. Here, ecosystem components are valued in terms of their significant function within the ecosystem as well as the goods and services provided to the dependent communities. This level of integration ensures that all risks are considered equitably within a transparent decision-making process. It also facilitates priority setting where mitigation strategies can be developed for the components that are most at risk. A Community Viability Environmental Dependency (CVED) analysis provides the necessary integrated profile of the goods and services that are vulnerable to the drivers occurring within a geo-spatial and temporal unit (Fig. B3). The CVED establishes the pathways of effects between drivers, pressures, stressors of ecosystem health and impacts to goods and services and subsequent impacts to the dependent human activity.

In this discussion, an ecosystem component is considered to be the measurable or observable aspect of the biological, physical or chemical aquatic environment. In an Arctic context, goods and services are resources or processes of the ecosystem that sustain coastal communities. Goods can be considered as food, hunting ranges or ice links between landmasses while services are the natural processes of recycling and renewal. However, some components also have aesthetic and cultural significance. It is at this point of the discussion that values are attached to various ecosystem components. A valued ecosystem component (VEC) is considered as the environmental element of an ecosystem that is identified as having scientific, social, cultural, economic, historical, archaeological or aesthetic importance. A VEC may be determined on the basis of cultural ideals or scientific concern. In an integrated assessment, each VEC is considered on its merit equitably in line with the pathways of effect between the drivers of anthropogenic activities, the pressures caused by the drivers and the vulnerable ecosystem component.

Arctic communities are tightly linked to ecosystem goods and services for their well-being and prosperity. However, these goods and services need to be considered as more than the typical economic values of natural resources. Most of the goods and services have cultural and social values and are dependent on a variety of ecosystem components. In addition, these components are also tied to the geo-spatial and temporal changes of the northern seasons. Although climate change is perceived as having potential impact on the coastal zone resulting in the displacement of people, the impact will also have significant adverse effects on the valued ecosystem components that provide and support economic, cultural and social goods and services to these communities. The intensity of development in the Arctic is at an early stage, but Arctic ecosystems are vulnerable to environmental change. The Arctic will benefit greatly from such integrated assessment and planning.

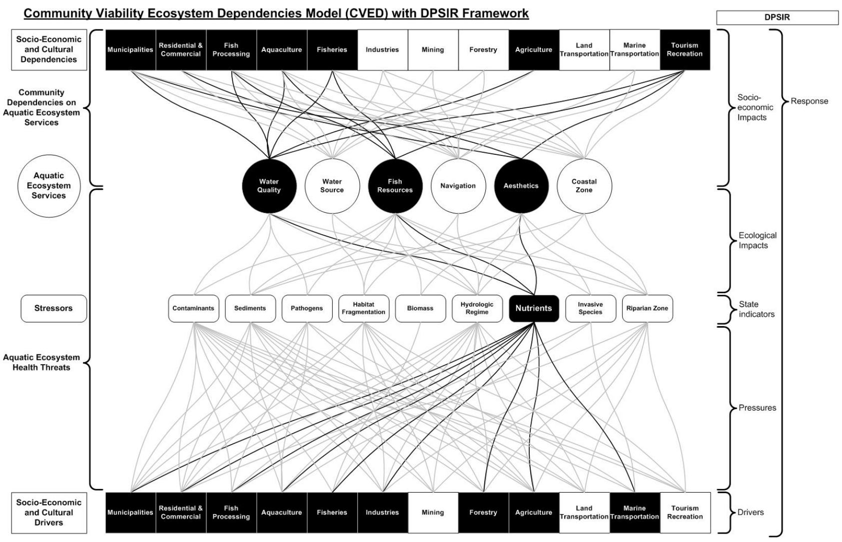

Figure B3. The Community Viability Dependencies Model for the example of impacts of nutrients.

Source: Roland Cormier, Canada Department of Fisheries and Oceans, Moncton

3.1.3 Combining western science and traditional knowledge for enhanced understanding of change

The western scientific tradition provides a powerful approach for understanding the natural world. It involves the testing of theory or hypotheses against objective observations and other data. However the questions asked, the hypotheses developed, and the observations collected inevitably (and often subconsciously) reflect the experience, knowledge, and perceptions of the researchers.

Traditional knowledge, or traditional ecological knowledge (TEK), reflects long-standing personal and cultural experience in a particular biophysical environment, providing insights from a large body of experience and observations (Fig. 34). "Inuit [or other northern indigenous] knowledge did not develop in a context requiring comparison with the parameters of science, but compares well when challenged with these parameters. Inuit knowledge is consensual, replicable, generalizable, incorporating, and to some extent experimental and predictive" (Bielawski, 1992, n.p.). Inuit knowledge has much in common with other traditional knowledge systems in that it is never divorced from moral or practical relevance (Overing, 1985; Bielawski, 1995).

Gearheard et al. (2006: 203) have noted that scientific and indigenous knowledge of sea ice is "generally in agreement or complementary …[but often reflect] different perspectives and emphases" such that drawing general conclusions about impacts may be difficult. *Inuit Qaujimajatuqangit* (IQ, an Inuktitut phrase roughly translating as 'Inuit way of knowing') has emerged over the past decade as an encapsulating term for Inuit TEK in the Canadian Arctic (Tester and Irniq, 2008). An important aspect of this is the recognition that the way in which northern peoples view animal-human relations (or relationship to the land) is as important as what is known (Wenzel, 2004).

Efforts to understand, manage, or respond to change in Arctic coastal systems may benefit from an effort to integrate these two ways of knowing (e.g. Gearheard et al., 2010). They may complement each other, in that TEK or IQ can provide not only a long-term perspective but an understanding of the connections between people and the coastal environment, while western scientific approaches can generate projections of future change in the context of a broader global scientific network and quantitative data analysis and modelling. While scientific knowledge might be better suited to assess future ecosystem changes, traditional knowledge helps to understand (and eventually enhance) the resilience and adaptive capacity of local communities.

Language is a critical component of culture and collective memory, thus it needs to be considered in the context of traditional knowledge. As noted in the box on SLiCA findings (Section 2.3.3), the Inuit language remains strong in Greenland and parts of the Eastern Canadian Arctic. In Canada, the 2006 census showed that 69% of Inuit across Canada had knowledge of an Inuit language, a reduction from 72% in 1996 (Gionet, 2008). The distribution of use was highly variable, with 99% and 91% Inuit speakers in Nunavik (Québec) and Nunavut, respectively, while only 27% retained knowledge of the Inuit language in Nunatsiavut (Labrador) and 20% in the Inuvialuit Settlement Region (ISR) (Northwest Territories). The overall conclusion of that study was that Inuktitut remains strong in Canada but is declining. Use of the indigenous language drops even further proceeding west from the ISR into Alaska and Chukotka (SLiCA box, Section 2.3.3).

Figure 34. King Island Iñupiat elders Gabriel and Edward Muktoyuk (centre and right) clarify place names on a map of King Island, Alaska, with Matt Ganley, an archaeologist, cartographer, and Vice President for Land and Resources with the Bering Straits Native Corporation.
Source: Deanna Kingston

In relation to cognition, language, and orientation, the speakers of Inuit languages use an orientation system that can be classified as a combination of an absolute and a landmark system (Levinson, 2003a). For example, the knowledge of wind directions and navigation in relation to the coastline has played a significant role in the traditional way of living (Levinson, 2003b; Gearheard et al., 2010). This can be considered an inherent part of the indigenous culture in the Arctic. The highly localized systems of demonstratives and the correlation between demonstratives and the natural terrain reflect indigenous knowledge of the surrounding area and highlight the indigenous sense of place.

Huntington et al. (2007a), from an analysis of five case studies in the Arctic, recognized that the answers obtained during surveys and workshops influenced the perception of the analyzed system. "The interactions between researchers and human subjects flow in both directions. For example, project goals must sometimes be modified in order to reflect participant input, insights, or expectations" (Huntington et al. 2007a: 182). On the other hand, seeking input and regular feedback from local leaders and residents helped broaden the research perspective, adding valuable knowledge and insights. They conclude from the example of Barrow (Alaska) that it "was evident early in the project that sound policies to reduce Barrow's vulnerability must go beyond science to incorporate the profound uncertainties, the multiple values of the community, and the resources available. The primary role of the researchers was to bring a broader range of alternatives to the attention of community members to expand the range of informed choice. Some alternatives previously considered became more attractive to community members as the context evolved" (Huntington et al. 2007a: 182).

An emerging development over recent years has been the growth of partnerships and institutions to support the preservation, recognition, and sharing of traditional knowledge. This has ranged from local initiatives such as the Ittaq Heritage and Research Centre in Clyde River, Nunavut (www.ittaq.ca), to web-based, global-scale, data-sharing projects such as ELOKA (Huntington et al., 2008; McNeave et al., 2010; Pulsifer et al., 2010). Arctic-based or oriented centres of knowledge such as universities, cultural and research centres, as well as networks of local museums have evolved as champions and custodians of indigenous knowledge and have contributed to the strengthening of indigenous self-identity in the Arctic.

3.1.4 Integrating science into Arctic policy and decision-making

Integrated assessment approaches such as those described above typically aim to improve understanding of interactions at the system level in order to inform transparent and scientifically guided decision making. An integration effort is needed on one hand to build on results of disciplinary research, but on the other to put these results into a wider context. Specifically in complex unstructured problems for which the available knowledge is uncertain and stakeholders perceptions diverge, classical rational decision-making based on strictly scientific support has limitations (Hommes et al., 2009). While assessments with multidisciplinary perspectives might help to overcome barriers between scientific disciplines, their impact on future policy formulation is often more at a strategic level. Integrative analyses are by their design and nature better suited to trigger ideas and concepts into medium- and long-term policy processes than to provide short-term technical support. Their role is to stimulate debate about policy formulation. A range of barriers to various dimensions of integration exist at different policy levels, including dominating paradigms of development and institutional constraints (Turnpenny et al., 2008) (see Section 3.4).

3.2 Monitoring, Detecting and Modelling Coastal Change

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Key Findings

- Reduction of negative impacts through adaptation to climate change requires new approaches in monitoring strategies to detect and track changes in the Arctic coastal environment. Understanding and prognosis of change is an essential component of resilience in Arctic coastal communities.
- Biophysical and human monitoring both clearly demonstrate that the Arctic environment is changing rapidly – sustained observation and monitoring is essential to document change and validate projections.
- Field-based monitoring in the Arctic coastal zone is challenged by remoteness, accessibility, communications, and instrument performance in extreme cold, but new survey technologies, instrumentation, and higher resolution of remotely sensed data are revolutionizing monitoring capabilities.
- These new techniques, decreasing costs, and higher resolution are enabling better spatial and temporal coverage of coastal change.
- Models represent key tools for understanding current changes and projecting future changes and associated impacts on Arctic coastal ecosystems and human communities.
- Models provide a means of interpolating between periods or locations of observation, a valuable capacity in times of reduced research and monitoring budgets.

Monitoring enables us to determine what changes are taking place in a system and how rapidly they are occurring. Only then can we begin to understand why they are taking place, what the implications are, and what measures may need to be taken to deal with them. In designing and developing coastal monitoring and observing programs, there is a need to consider several systems -- marine, terrestrial, and atmospheric – as well as their impacts on humans and how they are in turn impacted by humans. While Arctic coasts currently may be less affected by anthropogenic activities than their counterparts elsewhere, they can experience greater variation in environmental forcing due to the rapidity and scale of the climatic warming at high latitudes (IPCC, 2007a, 2007b). Monitoring is made more complex by the fact that observations are being made at the boundaries of the systems where interactions with other systems occur.

3.2.1 Monitoring and detecting biophysical Cchanges

Monitoring of biophysical parameters forms the basis of most observation programs because they are the ones which govern most other components of the coastal environment. A variety of monitoring strategies is required in order to capture changes in different elements of the systems, and at different temporal and spatial scales.

Data mining and re-analysis

In coastal monitoring, data collection is carried out in one of three ways: through data mining or re-analysis of existing databases, through direct field-based measurements, or by from analysis of remote-sensing imagery (Fig. 35). Because there is such a continuum in coastal studies, there is considerable overlap between disciplines and geographic areas. From a data gathering perspective, this means that information from existing monitoring activities or programmes can be utilized or refined to address questions directly related to coastal processes. Global and regional programmes collect data such as wind, air and water temperatures, currents, waves, tide and river levels, and sea ice concentrations. Information on phenomena such as storm events and wave energies can then be extracted and used in coastal process studies (e.g. Eid and Cardone 1992; Shaw et al. 1998; Hudak and Young 2002; Atkinson 2005; Manson and Solomon 2007). Currently, much of the data can be located through international or national operational agencies (e.g. WMO, NOAA), on portal web sites such as the Arctic Portal or the Ocean Portal, or downloaded directly from a number of thematic data centres (e.g. NSIDC, AMAP). Relevant data are also increasingly being aggregated by large regional projects such as the European-based DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies), the Canadian-based ArcticNet, and the U.S.-based SEARCH (Study of Environmental Arctic Change). Ultimately, Arctic data should be accessible through pan-Arctic integrated databases encompassing all fields of science. The scientific research community is putting considerable effort into ensuring that existing and future data are widely available, both through making the data as accessible as possible and ensuring that they comply with international metadata standards. Enhanced data access is an area that has been strongly emphasized recently by programmes such as the International Polar Year (IPY) which has generated and continues to generate large volumes of data. Given the interdisciplinary nature of coastal investigations, re-analysis of previously collected data will continue to play an important role in furthering research.

Field-based monitoring

Field based monitoring may involve the collection or inventory of physical samples such as water, sediment, or biota, or direct *in situ* measurement of the variables of interest, such as water temperatures or active layer thickness. Data may also be collected with the goal of ground-truthing remotely sensed observations. Coastal monitoring often involves mapping using remote sensing imagery or repeated ground surveys to determine changes in shoreline position and erosion rates (e.g. Mars and Houseknecht 2007; Aguirre et al. 2008; Forbes 1997; Lantuit and Pollard 2008; Jones et al., 2009a; Solomon 2005; Vasiliev et al., 2005; Ziaja et al., 2009). Recently the use of time-lapse photography has proven valuable in understanding the processes and quantifying rates of coastal change in the Arctic as well as in communicating with the public (Revkin, 2008; Carroll, 2009). Field efforts utilizing autonomous data collection methods such as these could be important in developing models of present and future coastal change. Field activities may also consist of observations of coastal thaw layer, permafrost and ground-ice conditions and shore-zone processes including nearshore dynamics, sediment transport and erosion processes, to help in understanding the dynamics of change. Because a primary goal of monitoring is to detect change, in most cases field measurements are undertaken at the same location, be it a research station, a community, or a specific site of interest. This makes it easier to ensure that there is good baseline data from previous studies. In certain situations however, it may be more suitable to make measurements in different

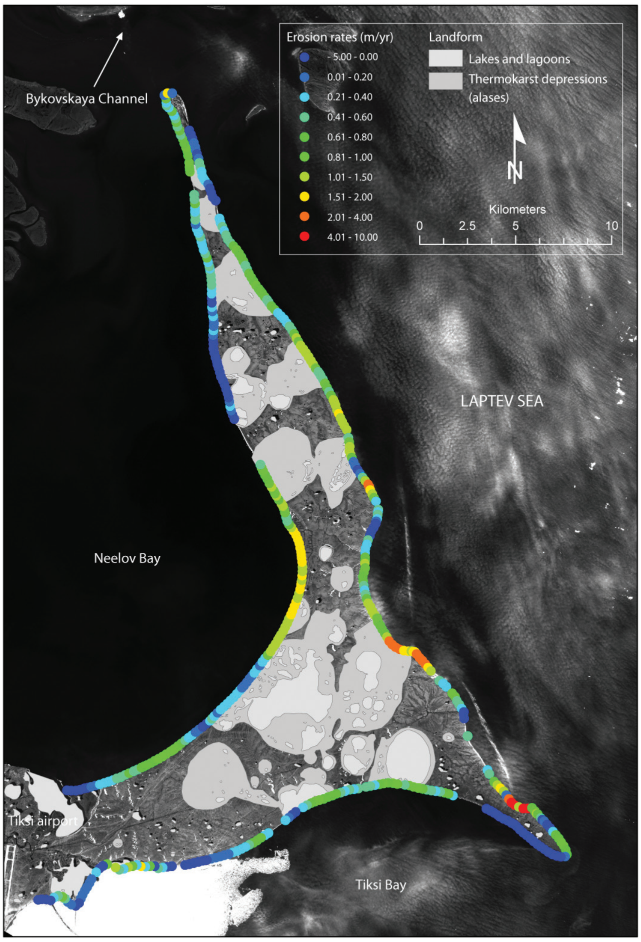

Figure 35. Monitoring of coastal erosion on the Bykovsky Peninsula, Russia, using remote-sensing data from 1951 to 2006.
Source: Hugues Lantuit, AWI

locations. This might be the case, for example, if the research goal is to compare the response of different shore types to a storm event (e.g. cliff vs. beach vs. marsh, or ice-rich vs. ice-poor sediments), or else to examine specific phenomena (such as ice-push events, algal blooms, or iceberg scouring) that do not necessarily occur in the same location. In an Arctic setting, factors taken into account in site selection are often quite different from those in other locations. Considerations can include the remoteness and accessibility of the site and the costs required to transport material and personnel there. This can change dramatically from season to season as conditions for air, land and sea travel are quite variable. These factors will often play a role in the sustainability of the observations over time. Personnel and equipment must be able to withstand the extremes of temperature. The dynamic nature of the coastal interface can have consequences for onshore instrumentation that may be eroded away, or nearshore equipment that can be crushed by ice. Additional challenges and opportunities are presented by variations in daylight length in the Arctic (i.e. solar power for equipment, period of time available for work, aircraft movements).

Remote sensing

Because of its remoteness and the sparseness of *in situ* observations, a particularly valuable tool for monitoring in the Arctic is remote sensing , from satellite, airborne, or surface-based platforms (Lantuit et al., 2010). However, the uptake and utility of remote sensing products can be limited for reasons such as weather, priority acquisitions, prohibitive costs or lack of processing capacity. Several recent initiatives have sought to help offset some of these difficulties, including a program of the European Space Agency (ESA) to provide free earth observation data to IPY projects, and a joint effort ('MORSE') of ESA and the Canadian Space Agency (CSA) to develop earth observation opportunities for monitoring specifically in Arctic coastal regions. The number and wide variety of sensors currently in operation or planned allows for the collection of most of the variables of interest to coastal research (UNESCO, 2006, 15-20), but coverage is not always available or at the desired temporal or spatial resolution. Examples of applications which have yet to be fully exploited in the Arctic include:

- interferometric synthetic aperture radar (InSAR) for coastal subsidence studies (e.g. Sharov et al., 2000; Forbes et al., 2007a);
- Jason-1 and replacement satellite altimetry for sea-level and storm-surge monitoring;
- SeaWIFS and MODIS for coastal productivity measurements (e.g. chlorophyll);
- ICESat laser altimetry for sea ice concentration and thickness;
- Aquarius/SAC-D for sea surface salinity;
- Terra-ASTER and other satellites providing land and sea surface temperatures;
- MODIS data enabling estimation of evapotranspiration;
- satellite-borne SSM/I instruments for measurement of daily rainfall;
- MODIS, SAR, and other sensors for sea ice, river ice, breakup, freeze-up, flooding and other observations.

Coastal change analyses using historical aerial photography and satellite imagery have been undertaken in various Arctic locations (e.g. Solomon, 2005; Manson et al., 2005a, 2005b; Mars and Houseknecht 2007; Lantuit and Pollard, 2005, 2008; Lantuit et al., 2008a; Jones et al., 2008, 2009b; Ziaja et al., 2009). Several space agencies and companies have increased their polar coverage during IPY so that a number of good baselines are being established for future work. Good spatial resolution is particularly important for detecting changes in shoreline position, which can be <1 m/a, or in immediate nearshore areas where conditions within one pixel can be quite variable. Another challenge to such studies is the look-angle of the sensor, because shadows or high coastal cliffs can obscure the land-water interface. With optical sensors, 24-hour darkness in winter or a snow cover can make it difficult to distinguish the terrestrial-marine boundary, and strong temperature gradients between land and water during open water periods mean that clouds often obscure the coastline. Technologies such as topographic and bathymetric LiDAR provide new opportunities for rapid, timely, and extensive observation and quantification of many aspects of coastal systems. Innovative applications of existing remote sensing technology can also yield additional information; an example is the use of synthetic aperture radar imagery to detect bottomfast ice and incidentally glean data on water depth and bathymetry (e.g. Hirose et al., 2008; Solomon et al., 2008a, 2008b; Stevens et al., 2008).

3.2.2 Monitoring change in human communities and populations

The challenge of monitoring and change detection in the Arctic has traditionally rested with the biophysical sciences, building upon a long tradition of studies focusing on sea ice conditions, permafrost, atmospheric conditions, marine and terrestrial biology, toxicology, and hazard assessment.

While many early studies sought to provide information on changing conditions relevant to government, institutional, and community decision making, the majority of this work has been driven by a scientific agenda with the purpose of advancing scientific understanding. This research has significantly increased our knowledge of how the Arctic is changing and improved our understanding of susceptibility of biophysical systems to climate change, but its relevance to decision making has been challenged by both the scientific community and policy makers (Duerden, 2004; Ford et al., 2008a; Pearce et al., 2009; Smit et al., 2008; Gearheard and Shirley, 2007; NTI, 2001, 2005; Riewe and Oakes, 2006). In this context, biophysical change assessments and monitoring are increasingly focused on biophysical conditions and systems of relevance to community, government, and industrial stakeholders. Major research projects have actively worked with stakeholders to identify relevant biophysical conditions which need to be monitored. It is noteworthy that many such initiatives are still led and directed by scientists and scientific objectives, but aim to focus on concerns identified by Arctic inhabitants (e.g. Forbes et al., 2007b). This 'applied' research complements the 'pure science' research which remains a major feature of research programs and research publications.

Community-based monitoring

Residents of Arctic communities are the first to register the changes in their habitats due to environmental change (Figs. 34 and 36). Indeed, the alteration of the environment implies changes to the conditions in which traditional use of the surrounding environment have been performed for years. The behaviour and availability of wildlife, the seasonal activity and the subsistence strategies are all dramatically impacted by the changing environment. As climate change has emerged as a major issue affecting Arctic inhabitants there has been a corresponding increase in research initiatives and projects engaging community members to detect and monitor change. This trend is driven by scientific, ethical, and regulation trends (Pearce et al., 2009), and involves Arctic inhabitants in three main ways: Arctic inhabitants and stakeholders as research assistants; local people as sources of information; and community/stakeholder-led research.

Figure 36. School children in Ilulissat, Greenland
Source: Vincentvan Zeijst

The most common situation in which communities are engaged in monitoring and change detection is through measuring changes in the Arctic environment (e.g. measuring sea ice characteristics, seal monitoring, surveying etc.). In this context, community engagement often takes the form of hiring and training local people as field researchers. It may also include involving local people as informants, interpreters, guides, and research partners. Though a standard and essential practice in research for many years, the employment of locals as research assistants has often failed, however, to integrate local and traditional knowledge into project formulation and interpretation and analysis of the information collected (Laidler, 2006, Pearce et al., 2006; Gearheard and Shirley, 2007). It also does not guarantee that the conclusions drawn from the research will reflect local involvement.

Secondly, communities are increasingly being engaged to share traditional and local knowledge to identify and characterize changing biophysical conditions. These studies have used participatory research methods including community workshops, semi-structured interviews, focus groups, mapping, stakeholder meetings, and guided trips on the land/sea-ice, to enhance knowledge on how the Arctic is changing. In particular, this work has sought to improve the spatial and temporal resolution of change detection which is often constrained in studies of instrumental datasets, which are spatially and temporally coarse in resolution (Riedlinger and Berkes, 2001; Berkes and Jolly, 2002; Gearheard et al., 2006; Laidler, 2006; Laidler et al., 2008; Catto and Parewick, 2008).

Initial efforts to engage local and traditional knowledge in Arctic change detection took place in a North American context, where indigenous peoples have been engaged in co-management of resources and the settlement of land claims for decades, and have taken an active role in shaping the research agenda. Many of the early studies in this regard involved collaborations between indigenous peoples' organizations and scientists, including: "Voices from the Bay" (McDonald et al., 1997) which documented traditional knowledge of Hudson Bay Inuit and Cree on biophysical changes; the International Institute for Sustainable Development's "Inuit Observations on Climate Change" (IISD, 2001), one of the first projects to explicitly obtain traditional knowledge on a changing climate; and "Uikkaaqatigiit" (Nickels et al., 2006), a project documenting Inuit observations on climate change from 17 Inuit communities in Canada. With increasing acceptance of traditional and local knowledge as a valid and meaningful source of knowledge for climate change detection and characterization, recent years have seen a proliferation of scientific research with indigenous and non-indigenous communities across the Arctic (Krupnik and Jolly, 2002; Fox, 2004; George et al., 2004; Norton and Gaylord, 2004; Pearce, 2005; Ford, 2006a, 2006b; Laidler, 2006; Meier et al., 2006; Riewe and Oakes, 2006; Tyler et al., 2006; Berkes et al., 2007; Gearheard and Shirley, 2007; Huntington et al., 2007a, 2009a, 2009b; Woo et al., 2007; Carmack and Macdonald, 2008; Crate, 2008; Ford, 2008a; Ford et al., 2008b; Keskitalo, 2008a, 2008b; Laidler and Elee, 2007; Laidler and Ikummaq, 2008; Laidler et al., 2008, 2009; Lipovsky and Yoshikawa, 2008). Over the last decade indeed, Arctic residents and indigenous peoples have participated in community-based monitoring involving traditional knowledge throughout the Arctic coastal rim and made significant contributions to the understanding of recent environmental change (Huntington et al., 2007a, 2009b). During the International Polar Year, the main goals of community-based monitoring were formulated and launched in 2007 within the framework of the international project ELOKA (Exchange for Local Observations and Knowledge of the Arctic). ELOKA was started in the Canadian communities on Hudson Bay and Baffin Island and in Greenland, and expanded to include other Arctic areas (Huntington et al., 2008). In Russia, community-based monitoring using local and traditional knowledge is now starting in the Murmansk region, in the Yamal-Nenets Autonomous Okrug, and in the eastern coastal zone of the Chukotka peninsula. This work has significantly improved our understanding of how the Arctic is changing, has figured in the ACIA and IPCC AR4 (ACIA, 2005; IPCC, 2007b), is important in national / regional climate change assessments and projects (Lemmen et al., 2008; ArcticNet; HARC; BALANCE; Lange, 2008), and forms the basis of many projects being conducted as part of the International Polar Year.

Notwithstanding progress made in recent years in involving communities in detecting change, traditional and local knowledge in many instances is treated as one source of data contributing to western scientific research with minimal local involvement in other aspects of the research such as topic selection, interpretation and application (Pearce et al., 2009). In other cases, community engagement is limited to meetings in which scientific information is shared and feedback sought from local representatives. This has resulted in the emergence of a third way in which communities are being engaged in change detection and monitoring: community-led or -driven research, where communities identify research questions and hypotheses. In these projects, scientists may be involved but at the request of communities and on their terms. Examples of community led projects are limited, a notable exception being the book "Watching Weather Our Way" (Oozeva et al., 2004), a collaboration between Yupik communities in Alaska and northern scholars to document changing biophysical environments. There are, however, an increasing number of projects being led by communities, including IPY projects, and funding agencies and governments are increasingly viewing community-led research as an important component of future research endeavours (e.g. Kelman and van Dam, 2008). Initiatives are also underway to allow communities to communicate changing conditions to the global community through the internet (e.g. the "Many Strong Voices" initiative; Crump, 2008).

Health monitoring

Several studies have been conducted under the umbrella of the Arctic Human Health Initiative (AHHI), an IPY Fully Endorsed Program that focuses on human health concerns of Arctic peoples. AMAP (2009a) provided an overview of human health in the Arctic. However, the information base remains inadequate and Krümmel (2009) highlighted the vital need for Inuit-specific (and, by extension, other population-specific) health data as a foundation for the development of culturally relevant action plans.

People living and working in Arctic areas, including coastal communities, face a wide range of health issues (Hild, 1995). Work and survival at high latitudes present challenges to human physiology and all Arctic residents are impacted by long-term exposure to challenging climatic conditions (Furgal and Séguin, 2006; Furgal et al., 2008a, 2008b). Along with low temperatures, seasonal extremes of ultra-violet radiation, and variability of polarized electro-magnetic fields (Chernouss et al., 2001; Cherry, 2002), human-sourced contaminants are a major concern (Kraemer et al., 2005). Many originating outside the Arctic, these are concentrated in upper food-web marine and terrestrial species consumed by residents of Arctic coasts (e.g. Polder et al., 2003). Social, cultural, technological and economic changes imposed from outside over several centuries and particularly over the past 100 years have had severe consequences on the health of Arctic residents. Infectious diseases caused massive mortality in previously unexposed indigenous communities after first contact with Europeans, but no longer pose such a threat. Nevertheless, the incidence of infectious disease remains anomalously high in Arctic indigenous populations (Parkinson, 2008), while chronic diseases (e.g. diabetes, cardiovascular disease, tuberculosis) are on the rise, combined with high levels of accidents, violence, substance abuse, and suicides (Bjerregaard et al., 2004). Krümmel (2009) has summarized some of the "stark differences" in health indicators between Inuit and national averages in the circumpolar region, in terms of life expectancy, infant mortality, suicides, and disease.

Changes in climate and the biophysical environment may lead to physical and psychological stress (Young and Bjerregaard, 2008). Currently emerging climatic change is associated with a number of negative impacts on human health, including potential outbreaks of new insect-borne diseases during warmer summers, as well as enteric and other infections (Parkinson and Butler, 2005). Small communities on Arctic coasts also face problems related to food preservation and access to clean drinking water as a result of changing temperature regimes, thawing of permafrost and, in some places, the resultant exposure of dangerous buried wastes. Arctic areas that are likely to be potential hot spots for infection and disease may require greater access to medical services, including laboratory facilities for detecting any changes in environment related to health. Efforts to build social, cultural and economic resilience to climate change may have positive effects on social cohesion and support with resulting health benefits (e.g. Richmond et al., 2007; Richmond, 2009). Nevertheless severe challenges remain in the small remote communities of the Arctic. Documentation of health issues from local residents' perspective is an important recent development (e.g. Bird et al., 2008, 2009).

3.2.3 Integration of monitoring strategies in local to global scale frameworks

The importance of Arctic coastal observing was recognized early at national levels, albeit in very different fashions in the various countries along the Arctic coastal rim. In Russia, coastal investigations and monitoring essentially started with the inception of the Northern Sea Route Department (*Glavservmorput*) in 1932. This provided a structure for organized integration across all branches involved in the economic development of the Arctic coastal zone, resulting in a progressive and unique top-down and integrated coastal management system. This system was later abandoned to favor a more traditional organization around state departments focused on industrial needs (Andreeva, 1998). The current monitoring system on Russian coasts is a result of later fragmentation and involves state departments, federal agencies and research institutes. Recent efforts to develop effective integrated coastal area management are progressively being turned into laws which should help define a framework compatible with international management norms and standards and avoid conflicts between relevant stakeholders (Andreeva et al., 2003). Nevertheless, the early heavy utilization of the Russian coastal zone prompted considerable scientific investigation which provided the background and unique long-term datasets for today's monitoring of coastal biophysical processes (e.g. Vasiliev et al., 2005). However social and environmental issues were secondary to industry objectives during Soviet times and have only recently begun to be integrated into the Russian coastal framework (Andreeva, 1998; Andreeva et al., 2003). A pioneering program, Land-Ocean Interactions in the Russian Arctic (LOIRA), was initiated at the end of the 1990s to integrate and study these issues (IASC, 2000). More recently, in accordance with the national "Strategic Plan of Action in the Russian Arctic" elaborated in 2007, the task of establishing social-ecological monitoring networks in Arctic communities is planned to be completed by 2012.

In the USA, the Arctic coast is entirely located in Alaska. The state has been conferred with wide-ranging powers and duties that relate to the implementation of federal laws or the development, implementation and enforcement of coastal management strategies. Up until the second half of the twentieth century, the use of the coastal zone was focused on local and regional economic needs with little consideration for hazard planning (Mason, 1997). In 1977, however, the Alaska State Legislature created the Alaska Coastal Management Program (ACMP) in response to the federal Coastal Zone Management Act (CZMA). It prompted the elaboration of planning documents in 33 coastal districts in a participatory fashion, involving and greatly empowering local communities in the decision making process (Mason, 1997). Coastal monitoring efforts stem from these plans and today involve a series of actors from the state and federal administrations as well as universities and private industry, with the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) at the forefront of biophysical monitoring in the coastal zone (e.g. Jordan et al., 2008; Jones et al., 2008). The recent changes in the ability of coastal districts to enforce integrated strategies at the local level will most likely impact the way local communities are involved in the process, and may also transform coastal area management from a merely environment-protecting approach to one of natural resource management, involving a very large suite of stakeholders.

In Canada, several federal government departments have mandates that relate to coastal management with no one department being responsible for all aspects of managing the coastal zone. However, the Department of Fisheries and Oceans (DFO) is the lead agency (Muir, 2001). Environment Canada (EC) also has a role in the management of coastal areas in preserving water resources and ecosystems. Provincial and territorial authority for integrated management is limited to coastal features, such as the intertidal zone, dunes, salt marshes, mud flats and estuaries (Muir, 2001). However, there is no single provincial or territorial department that is solely responsible for managing these areas. Land claim agreements between the federal government and the Inuit, the Inuvialuit and other indigenous groups are superimposed on this constitutional division of powers. Consequently, these agreements have established separate regimes for the management of coastal wildlife, environment and resources. Despite this detrimental fragmentation of powers and mandates in the coastal zone, Canada has rapidly implemented pioneering programs in Arctic coastal monitoring and management. The Geological Survey of Canada (GSC) program is a prime example, despite being limited to biophysical and engineering issues (Prior and Pickrill, 1997). In this framework, survey work was undertaken at 282 Arctic coastal sites established at various times between 1912 and 2007, but the coastal monitoring program is not currently funded as a distinct activity. The Tuktoyaktuk Declaration (2006) called for the establishment of a northern coastal zone organization to strengthen the capacity for integrated management in the Canadian Arctic.

Scandinavia formalized coastal management and coastal monitoring early on, following on centuries of industrial and economic use of the coast. In Norway, the Integrated Management Plan for the Lofoten and Barents Sea areas calls for protection of the environment and regulation of fisheries and shipping in a zone starting one nautical mile off the coast (Olsen et al., 2007). The rest of the coastal zone is covered by the EU Water Framework Directive (2000) which focuses on coastal waters and coastal biodiversity. Several institutions are active in conducting monitoring in the coastal zone, notably the Institute of Marine Research and its Coastal Zone Ecosystem Programme, or the State Pollution Control Authority and its Norwegian Coastal Monitoring Programme, although the human aspects of the coastal zone are often subordinate to the physical system. In Greenland, integrated coastal zone management (ICZM) is virtually non-existent. However, the level of integration of the biophysical and human realms is probably greater than in other parts of the circum-Arctic, owing to the small size of the communities, the relatively homogeneous socio-economic framework, primarily organized around coastal resources, and the historical perception of the coastal zone as a holistic realm. A changing political and legal framework combined with greater interaction with aboriginal organizations from neighbouring countries could form the basis for future joint activities in the field of coastal monitoring, in particular in relation to its traditional knowledge dimension.

Coastal area management in the Arctic has historically not been embedded into regional frameworks, national borders often being hermetic to foreign insight, both for economic and sovereignty reasons. Integrated integrated coastal monitoring efforts at regional scale do not (yet) exist in the Arctic, but strong signs of cross-border environmental policy integration may lay the groundwork for future regional ICZM systems. The Norwegian and Russian co-operation for management of fish stocks in the Barents Sea and the North Atlantic Marine Mammal Commission, for example, have paved the way for what could be wider and more advanced co-management in the Arctic. The indigenous peoples' organizations of the North will likely play a prominent role in developing a regional understanding of coastal issues and in organizing coastal monitoring, making use and leading integration of traditional knowledge and western-type science. National borders are a reality, but the promising signs of integration of the Inuit nation across four different countries could show the lead for a greater level of integration.

At the international level, ICZM and coastal monitoring are directed and framed by a long series of UN agreements, by international organizations, as well as by a series of bottom-up research initiatives, the latter having recently been catalyzed in the Arctic during the IPY (2007-2008). Biophysical monitoring and coastal process studies are, for instance promoted and coordinated by the Arctic Coastal Dynamics (ACD project (Couture and Overduin, 2008), an international bottom-up initiative that initiated the Arctic Circumpolar Coastal Observatory Network (ACCOnet). ACCOnet is intended to encompass both the biophysical and socio-economical dimensions of changes in the coastal zone and to study those at 'observatory' sites spread along the Arctic coast. Although the ACCOnet network is not fully in place, many of the sites are based on ACD key sites where observations and monitoring have been ongoing for a number of years or decades. Some sites are actual physical observatories, but in many cases, they represent observation programs that are maintained by the dedication of individual researchers. These initiatives have gained international recognition through the sponsorship of international organizations, but remained largely unconnected to global coastal initiatives.

At the global scale, coastal monitoring and coastal studies are covered by three main entities: Land-Ocean Interactions in the Coastal Zone (LOICZ), a core project of the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Program on Global Environmental Change (IHDP); the Coastal Global Terrestrial Observing System (C-GTOS) (Fig. 37); and the upcoming coastal module of the Global Ocean Observing System (GOOS). Implementation strategies for the coastal modules of these programmes detail the most important data parameters needed by

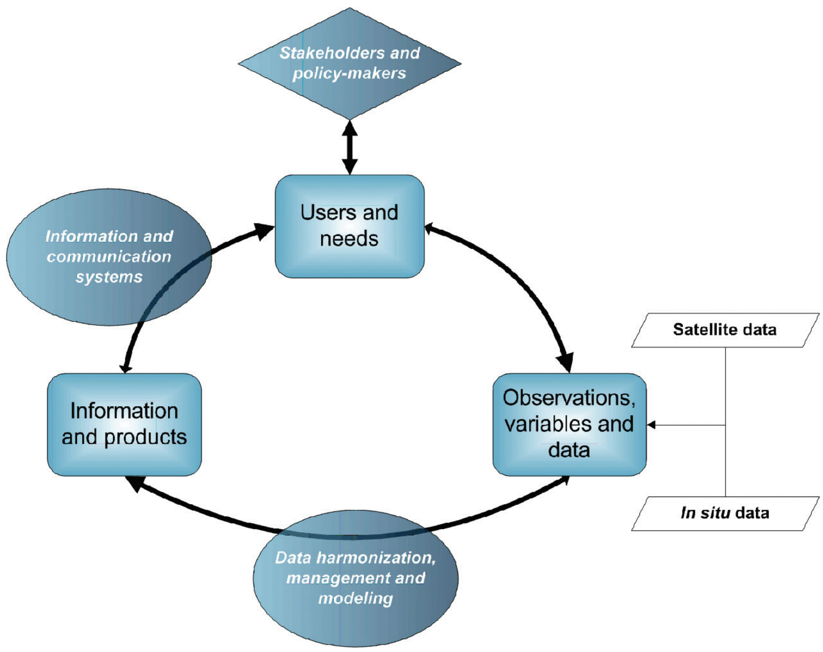

Figure 37. The structure of the Coastal Global Terrestrial Observing System (C-GTOS) includes observations, variables and data, which are transformed into information and products to provide for users and their needs. In turn, users and their needs provide feedback influencing the further development of observations, variables and data.
Source: Christian et al. (2005)

users, as well as recommendations on the desired temporal and spatial resolutions and measurement accuracies (UNESCO, 2005, 2006; Christian et al., 2005). Examples include geophysical data such as surface temperature, wind speed and direction, waves, and sea level, as well as biological or biochemical data such as particulate and dissolved matter, nutrients, and contaminants. An additional requirement is the mapping of physical parameters such as topography, bathymetry, or shoreline position, and ecological parameters such as habitat.

The coastal module of GOOS is a long-term, very large-scale initiative which aims at coordinating coastal observing efforts under the auspices of the Intergovernmental Oceanographic Commission (IOC), World Meteorological Organization (WMO), United Nations Environment Program (UNEP), International Council for Science (ICSU), Food and Agriculture Organization (FAO), and IGBP, feeding global observing efforts such as the Global Earth Observation System of Systems (GEOSS). In particular, it proposes to improve the capacity to detect and predict the effects of global climate change on coastal ecosystems, by providing a rationalized framework for the current cluster of national, regional and international observing efforts. By comparison, LOICZ focuses on specific research issues and brings researchers together to solve these issues, which may or may not deal specifically with ICZM and coastal monitoring. Both the coastal module of GOOS and LOICZ plan to rely heavily on regional coastal ocean observing systems (RCOOSs) that would be coordinated in a Global Coastal Network (GCN). Although LOICZ has acknowledged Arctic-focused bottom-up initiatives such as ACD as part of its effort, ties to the coastal module of GOOS and C-GTOS are weak and need to be strengthened. In parallel, the Arctic science community, under the auspices of the Arctic Council and with the impetus from IASC and AMAP has been working on a strategy to develop current observing efforts in the Arctic into an Arctic Observing Forum (AOF) (SAON, 2009). It is obvious that the confluence of these initiatives calls for the establishment of a strong Arctic coastal observing component, fitted into both the upcoming coastal module of GOOS and the AOF. The integrated approach that prevails in networks such as ACCOnet should form the basis for a regional integrated coastal observing system in the Arctic, one that is connected to global initiatives.

3.2.4 Modelling and projecting Arctic coastal change

The overarching goal of modelling efforts is to help understand the dynamics and complex interactions of natural, coupled air-land-sea systems, where possible including biophysical and social systems. Models allow for tracking of the uncertainties of projections or simulations within a geographical context. In this review, the focus is on coastal integrated biophysical and social systems. With appropriate validation in the field, models can be used to test our understanding of processes. In the event that models achieve a certain level of understood quantification, then they can be used to create prognoses of future system states under assumptions pertaining to given scenarios. These may include development scenarios leading to projections of climate or sea level, which in turn could be used to drive other coastal models of change, at various scales from regional studies to the community level.

Change projection

As modelling and prognosis are broad terms (with application in a number of research fields), it is appropriate to first define these terms.

A prognosis is a forecast of the likely outcome of a scenario or situation. The word prognosis has secondary meanings dealing with implications of projected outcomes. Often a prognosis is defined in qualitative terms. In dealing with the Arctic coastal zone, prognosis refers to projecting plausible futures. These futures may involve changes (inter alia) in:

- sea level
- sea-ice conditions
- coastal permafrost stability
- precipitation (magnitude and intensity)
- river discharge (timing and magnitude)
- coastal topography and landscape transformation
- biodiversity in coastal ecosystems
- coastal hazards
- constraints on subsistence activities
- impacts on cultural resources
- constraints on community, industrial, or other infrastructure.

A model is a simplified description (often mathematical) of a system to assist in quantitative calculations or predictions. Often models are used to quantify a prognosis or scenario. Because of their mathematical framework, models can be used to help understand the sensitivity of a process or system to changing boundary conditions. Advanced models are used to deal with non-linear behaviour of systems, including situational thresholds.

Prognosis and modelling applied to the Arctic coastal zone

Prognosis and modelling are important tools for working in data-poor regions as they can be used to test our understanding of processes through validation experiments and to help understand uncertainties in complex systems. The Arctic tends to be data-poor due to issues of accessibility, sampling density, limited long time series, and representation. In addition not all of the forcing functions that drive systems (human, physical, and biological drivers) are well constrained. Arctic processes often remain not fully understood – either we are missing information or we lack adequate understanding of the physical, ecological and socio-economic processes. Additionally we do not fully understand all the various nonlinearities in the system. Examples of coastal modelling in the Arctic range from process-specific analytical models (e.g. Hoque and Pollard, 2008, 2009) to community- or site-specific coastal erosion modelling (e.g. Peckham et al., 2002) to broader projections of climate implications for sediment supply or erosion rates (e.g. Syvitski, 2002, Syvitski et al., 2003, 2005). Examples of qualitative modelling for the development of adaptation policy include Brunner et al. (2004) and Lynch and Brunner (2007).

We recognize three types of models of importance to studies of the Arctic coastal zone based on the nature of the problem or process.

- **Physical system models:** These models are often targeted to specific components of the overall physical system such as ocean circulation, meteorology, climate dynamics and climate forecasting, hydrology, sediment transport, coastal morphodynamics, wave dynamics, tidal modelling, storm surge dynamics, permafrost dynamics, sea-ice and iceberg drift, and tidewater glacier dynamics.
- **Coastal ecosystems models:** These are largely driven by the physical and biological

environment and dynamics. They represent various levels of sophistication and dynamics; from simple box models to those that integrate more fully the dynamics that define the system. These models include those related to productivity, nutrient dynamics, light, water and temperature regime, snow cover, sea ice movement and trophic dynamics and interspecific competition.
- **Socio-economic models:** These may involve renewable or non-renewable resources, tourism, community development, coastal infrastructure and pollution, among a host other human issues.

Model scenarios for the Arctic coastal zone involve analysis of expected changes in the following components:
- climate,
- other aspects of the physical environment,
- social and economic conditions,
- ecosystems, and
- governance.

Risk assessment is predicated on the notion of humans being risk averse. Thus scientists must better understand the uncertainties associated with models (in data, forcing, physics, and representation). Model validation is imperative for proper risk assessment. Models can be validated with field data by using a hindcast methodology with re-analysis, but the short record lengths often associated with Arctic systems remain a systemic problem for validating Arctic models. Many Arctic coastal zone models are on the scale of human engineering, in other words on the time scale of years. These models differ from longer-term morphodynamic models that track changes in topography and bathymetry through decades and in some cases centuries. A worry in employing morphodynamic models is whether the science is in place to discern processes that operate with gradualism, versus those that employ different dynamics on either side of some well understood threshold condition. Four dimensional (4D) data assimilation schemes offer methods (inversion algorithms, conditional simulations) to improve our ability to incorporate large-scale observations with limited ground observations and model simulations.

It is unclear how the Arctic coastal research community should proceed with respect to prognosis and modelling at the village or hamlet scale? Often coastal zone models are used to understand the generic state of the Arctic environment; they do not necessarily address the needs of the indigenous peoples, nor are they able to easily incorporate oral-based indigenous knowledge (traditional knowledge). Coastal management models at the scale of individual communities can be applied on a case-by-case basis with good two-way communication, education and outreach. As noted earlier, Huntington et al. (2007a) described the application in the context of five community studies of dynamic simulation models in the context of five community studies. These models incorporated vegetation change, caribou migration and energetics, and household economies to feed various sub-models.

Constraints and future directions for modelling the Arctic coastal zone
An Arctic coastal zone model survey is required before we can effectively identify model gaps. A modelling framework system for the Arctic coastal zone is not yet implemented. Model integration is thus at a very early stage. More effort is required on

error propagation analysis and an understanding of model uncertainty.

Better understanding of the surface heat budget throughout the Arctic, a gap identified by Barry et al. (1993), remains a priority. This is important for most ocean-ice-climate modelling efforts as well as for many ecosystem dynamic models. Relative sea-level projections remain poor for the Arctic coastal zone, although some progress is being made.

No long-term coastal morphodynamic models have been identified that are applicable to the Arctic coastal zone, e.g. taking permafrost or other ice-sediment interactions into account, although some efforts have been made to incorporate thermal processes in physical dynamics models (e.g. Kobayashi et al., 1999) and longer-term modelling has been undertaken using hybrid models (e.g. Leont'yev, 2003, 2004)

Very limited long-term (and even medium-term) data are available for validating many of the existing physical models. Because the Arctic is entering a new state with limited summer sea ice, wave measurements of the past may be of limited use for the validation of wave forecast models. Furthermore, the present limited network of observation stations is inadequate for data assimilation schemes. This is a recognized need and formed part of the drive for a sustained Arctic observing network following on the International Polar Year (see Chapter 4).

Over the past few years, an international consortium led by the USA has developed a science plan for a 'community' integrated 'Arctic System Model', designed as a tool to synthesize models and observations for understanding the Arctic as a system. (Roberts et al., 2010a). Although clearly driven by the physical science community, this initiative aims to promote progressively more integrated approaches to modelling physical,

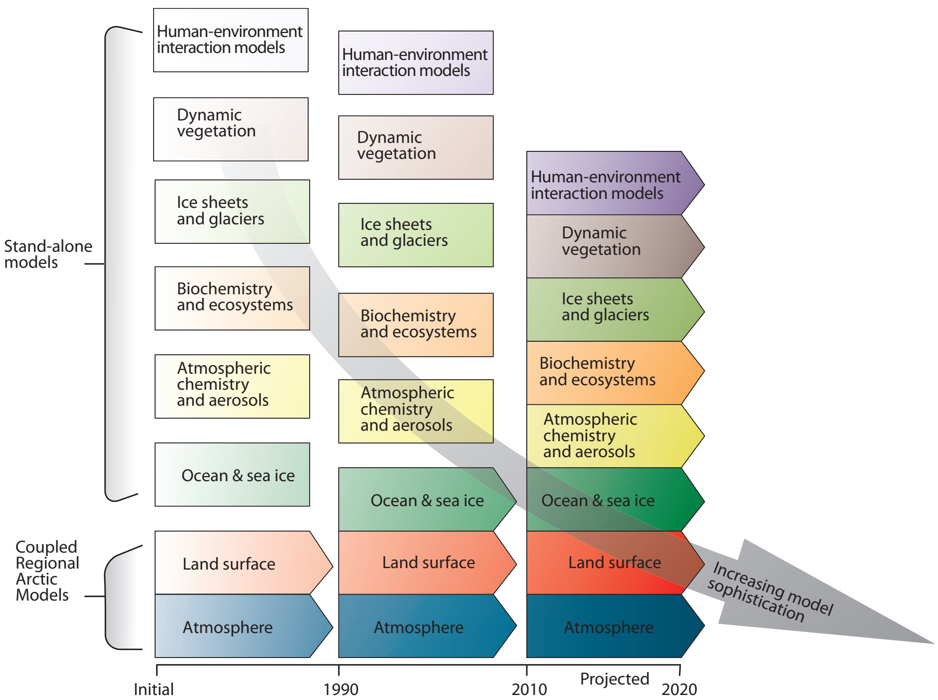

Figure 38. Model integration architecture for a community integrated Arctic System Model. (from Roberts et al., 2010a)

biological, and socio-economic aspects of climate-driven change and adaptation in the Arctic (Fig.38). Coastal erosion, coastal habitats and coastal communities are all seen as components of this system. While it is unclear to what extent this initiative will result in effective models of socio-ecological adjustments in the coastal zone, some progress has been made in the development of agent-based models of community response (Berman et al., 2004), which indicate a potential for integrated modelling.

Integrative Approaches to Change Projection

Both the Arctic Climate Impact Assessment (ACIA, 2005) and the Arctic Human Development Report (AHDR, 2004) focussed on an understanding of change based on existing data but with a more multidisciplinary than integrated perspective. Several more recent initiatives (e.g. the Millennium Ecosystem Assessment and the UNEP Global Environmental Outlook), aiming to provide integrated assessments of change combine several frameworks and tools (see Fig. B3 in Box, Section 3.1.2).

Recognizing the complex role humans play in coastal change, the LOICZ Science Plan and Implementation Strategy (Kremer et al., 2005) framing the second decade of the global LOICZ project, identified the need to expand research that contextualizes biogeochemical and physical processes with social, political and economic aspects. The goal is to elucidate human activity as an agent of change and reflect society's response to change, which influences resilience of coastal systems in a social-ecological context (Folke, 2007). Initial results from the EU project ELME (Langmead and McQuatters-Golop, 2007), linking lifestyles and the environmental state of marine and coastal ecosystems, underline the key role social choice plays in determining the quality, institutional aspects and robustness of political and management response to pressures and environmental change. Social choice prioritizes between value systems (e.g., consumerism vs. community values) and levels of governance (interdependence vs. autonomy). Resulting scenarios provide narratives for the anthropogenic footprint and likely consequences for coastal resources including 'winning' and 'losing' species

Figure 39. Hunter at the floe edge in the Canadian Arctic.
Source: James Ford, ArcticNet

in the coastal marine ecosystem. Such ecosystem shifts have implications for goods and services and feed back into human livelihood, health and cultural stability. The German research project "Coastal Futures" (Kannen and Burkhard, 2009) also explores scenarios, but the focus was to sketch the likely consequences of developing new forms of sea use in the German North Sea. Coastal Futures aims to apply integrative approaches to analyze coastal, offshore, and ocean changes. These approaches may also support spatial planning in coastal land and sea areas. They incorporate natural and social science expertise to ensure a unified systems description. Differing methods are applied to assess ecological risks (and opportunities) on the one hand and economic opportunities (and risks) on the other. Nevertheless, both types of analysis are needed when it comes to evaluating changes within resource and area use. While this project lies outside the Arctic, similar approaches could be adopted and adapted to Arctic settings.

Another integrative approach is the use of dynamic simulation models, which aim to offer integrated perspectives of future scenario outcomes based on a variety of ecological, economic and social indicators. User interactions and stochastically-driven processes in the model provide elements of contingency so that the alternative "futures" are not simply mechanically-determined forecasts. Huntington et al. (2007a) describe an approach for the application of a dynamic simulation model based on detailed statistical analysis of vegetation change, caribou energetics and migration, and northern household economies, which informed the various sub-models.

Approaches from the field of ecological economics aim to integrate different forms of information through a quantitative assessment of the value of coastal resources and ecosystems in monetary terms. Wilson et al., 2006 in reviewing earlier estimates (Costanza et al., 1997) indicate that total global coastal ecosystem goods and services of coastal wetlands may equal more than 40% of the whole global value, though deriving from only 8% of the world's surface. Similar assessments specifically for Arctic coasts are missing. However, many of the non-use values, which in reality have a substantial share, are neglected in such assessments. Given the high importance of non-use values (including religious and inspirational values) to indigenous communities in the Arctic, one may question whether such a highly rational quantitative approach is at all appropriate (Fig. 39). Nevertheless, recognising and mapping (in a qualitative way) the non-use value of Arctic coasts is a way to link traditional knowledge with scientific knowledge, thereby bridging both knowledge systems.

3.3 Vulnerability, Adaptation, Adaptive Capacity and Resilience

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Key Findings

- Increasingly governments, communities, and industry stakeholders are exploring ways to reduce the negative impacts of climate change and take advantage of new opportunities through adaptation.
- Many Arctic coastal communities are experiencing vulnerabilities to decreased or less reliable sea ice, greater wave energy, rising sea levels, changes in winds and storm patterns, storm-surge flooding or coastal erosion, with impacts on travel (on ice or water), subsistence hunting, cultural resources (e.g. archaeological remains, burial sites) and housing and infrastructure in communities.
- In some places, this has necessitated community relocation, which in some cases increased vulnerability.
- In places, coastal erosion is threatening critical infrastructure or contaminated sites, with potential for spreading of pollutants.
- There has been great progress in recent years in the understanding of exposures and identification of elements of adaptive capacity that may enhance resilience, but other challenges including social, technical, financial, and institutional barriers may be inhibiting successful adaptation.
- There is a wide range of adaptive capacity among coastal communities of the circumpolar Arctic. A community with a greater resource base, including physical resources, financial capacity, knowledge (of all kinds), and social cohesion, is in a better position to successfully adapt than one that lacks resources and options.
- Arctic indigenous peoples are traditionally resilient. This has allowed them to adapt to a harsh climate and changing environmental conditions over multi-century time-scales.
- With a faster pace of change and numerous compounding challenges, the indigenous peoples of the Arctic are generally less resilient today, although developments in regional governance and cultural initiatives, as well as growing familiarity with climate change, may be improving the situation to some extent.
- Quantitative scientific research concerning past, present, and future environmental changes and impacts is a key component informing policy and decision-making.
- Adaptation strategies perceived as imposed from outside will not be incorporated into the community's reservoir of mechanisms for coping with change, will not form a component of its adaptive capacity, and will thus not contribute to its resilience and ultimate sustainability.

Numerous changes in the northern coastal environment, combined with marked social, economic, and political change are already evident and challenging the validity of traditional knowledge, the viability of current economic activities (including traditional harvesting), and the social cohesion, capacity, and resilience of Arctic coastal communities. The range of choices, feasibility of responses, exposure and adaptive capacity of communities vary over a wide spectrum, but studies over the past decade have focused on a broad-based understanding of the physical and ecological changes occurring or likely to occur under projected climate changes and how these will affect communities and residents. Among the promising outcomes of increased awareness has been the development of community-based monitoring and adaptation initiatives, as discussed in the previous section. However the scale of potential impacts on Arctic communities and existing social, cultural, economic, demographic and governance constraints pose massive challenges.

3.3.1 Vulnerability and adaptation

Increasingly governments, communities, and industry stakeholders are exploring ways to reduce the negative impacts of climate change and take advantage of new opportunities through adaptation (Kelman and van Dam, 2008; ACIA, 2005; Séguin, 2008; Lemmen et al., 2008). Effective adaptation requires an understanding of vulnerability at present and in the future under various scenarios of climate-change and adaptive capacity to address potential exposure and sensitivity and thereby to limit or minimize negative impacts.

Vulnerability is the degree to which a person, community, or sector is adversely affected by change and/or to variability in climate and other drivers (see Smit et al., 1999; Kelly and Adger, 2000; Gunderson and Holling, 2002; Adger et al., 2007; Hyndman et al., 2008). Vulnerability is the combined function of exposure and sensitivity. The frequency of occurrence (exposure) is not the only factor influencing vulnerability. If the effects of the change are too great, any sector may be vulnerable. Communities or sectors that have fewer resources to cope are more vulnerable than those with greater resources, even if the degree of exposure is less. The necessary resources, collectively contributing to adaptive capacity, include money, expertise, trained emergency response personnel, medical facilities, previous experience, social networks (local people helping each other), and assistance from other communities, ranging from adjacent communities to national governments to world-wide appeals for aid.

Adaptive capacity refers to the ability to cope with or adapt to a change (see Smit et al, 1999; DesJarlais et al, 2004; Ford and Smit, 2004; Adger et al, 2005, 2007; Armitage, 2005; Kofinas, 2005; Anisimov et al, 2007; Vincent, 2007; Agrawal, 2008; Armitage et al, 2009; Armitage and Plummer, 2010; Ford et al, 2010). For natural terrestrial and marine ecosystems, adaptive capacity and vulnerability to change are directly related: an ecosystem which has a relatively greater capacity to evolve is also relatively less vulnerable. Most natural systems have moderate to high exposure to climate change impacts, in a multidecadal time frame. Ecosystems have evolved in response to the changing climate since deglaciation. In many cases a sudden shift in climate conditions will impact them adversely (e.g. Bean and Henry, 2001; Jacobs et al., 2006; Prowse et al., 2009; Tarnocai, 2009). Differences in lifespan and size of individual organisms influence the degree to which each species is exposed, as well as the immediacy of the reaction to changed conditions. Insect species respond more rapidly to climate variation

Community Adaptation and Vulnerability in Arctic Regions (CAVIAR)

J. West and G.K. Hovelsrud

The Arctic is experiencing rapid changes in environmental, societal and economic conditions. The particular conditions to which communities are sensitive are not well documented, nor have the conditions that might facilitate or constrain their adaptive capacity in the face of interacting climate and socioeconomic changes been substantiated. Insights into the particular vulnerabilities of Arctic communities have not been compared across the Arctic countries, nor are these studies well connected to policy development. CAVIAR (Community adaptation and vulnerability in Arctic Regions), a circum-Arctic research consortium and endorsed IPY cluster involving all eight Arctic nations, and 26 case sites, was designed to meet these research gaps, using a research strategy to develop a theoretical framework for community vulnerability assessment, refined a common methodology, established procedures for case studies, developed a process to compare and integrate results, and ensured direct application of research to policy (Smit et al., 2008; Hovelsrud et al., 2010). Research conducted under the CAVIAR Norway-Russia contribution identified past, current and future exposure-sensitivities and adaptation strategies in nine communities/regions, assessed community vulnerability and adaptation, determined the extent to which available meteorological data series could provide a meaningful description of local conditions that influence the sensitivity in selected communities, given downscaled climate projections with sufficient spatial resolution for vulnerability assessment.

One finding that emerged from CAVIAR research in Lebesby, Northern Norway was the existence of cross-scale adaptation challenges facing the coastal fisheries sector. While fisheries actors there are aware of, experience, and describe a number of connections between climate variability and coastal fishing activities, they do not characterize their livelihoods as being particularly vulnerable to climate change. Nonetheless, they identified a range of social factors that shape the flexibility of coastal fishing activities and livelihoods that constitute important aspects of adaptive capacity. Adaptation challenges identified through the fieldwork fell into a four "adaptation arenas": local perceptions of vulnerability and resilience to climate change; social and economic viability of the municipality; national fisheries management and regulations; and markets and the economy of coastal fishing. These arenas involve different geographic and temporal scales, creating specific barriers and opportunities for local adaptation (West and Hovelsrud, 2010).

A project of the International Polar Year 2007- 2010, the CAVIAR consortium was co-led by Grete K. Hovelsrud at the Center for International Climate and Environmental Research -Oslo (CICERO), Oslo, Norway, and Barry Smit, University of Guelph, Canada.

Coastal fishers hard at work in Lebesby, Finnmark County, Northern Norway. Photo: Jennifer West, ©CICERO

Nunavut Climate Change Partnership

Beate Bowron, Lee Ann Pugh, David Mate

This unique partnership included the Government of Nunavut (GN), the Earth Sciences Sector of Natural Resources Canada (NRCan), the Canadian Institute of Planners (CIP), and Indian and Northern Affairs Canada (INAC). The overarching goal of this multi-disciplinary climate-change adaptation program was to enable Nunavut communities (all but one of which are coastal) to incorporate climate-change adaptation measures into all aspects of their planning processes. All of the partners coordinated their respective areas of work (science, planning, community engagement, etc), so that the proverbial total was truly greater than the sum of its individual parts.

The project focused on three themes:

1. To create locally and regionally targeted scientific information for climate-change adaptation planning and to integrate this information into decision-making processes.
2. To build capacity for climate-change adaptation planning within the GN and Nunavut communities.
3. To develop tools to collect, publish, share and communicate climate-change adaptation knowledge across Nunavut and beyond.

Between 2006 and 2011, the following individual projects were completed:

- Prioritization of climate-change issues based on workshops held as part of the development of the Nunavut Climate Change Adaptation Plan (www.planningforclimatechange.ca);
- Climate change adaptation plans in the communities of Clyde River, Hall Beach, Kugluktuk, Cambridge Bay, Whale Cove and Arviat (www.planningforclimatechange.ca); volunteer CIP planning teams and scientists worked with these communities to produce adaptation plans. Aspects of these plans will feed into other planning processes such as community plans, emergency management plans, and infrastructure budgets, among others.
- Climate change adaptation work in the City of Iqaluit (Nunavut's capital) concurrent with the City's review of its Community Land Use Plan. Scientifically this included studies on permafrost and landscape hazards (Allard et al., 2010), coastal flooding and sea-level rise (Hatcher et al., 2010) and water resources (Brière, 2010). Planners from CIP worked with the city to establish a network among people from different levels of government and NGOs working on climate change issues.
- Supporting the establishment of the Ittaq Heritage and Research Centre in Clyde River (www.ittaq.ca).
- Conducting first order assessments of the impact of climate change on freshwater supply in a range of communities across Nunavut using geomatics and remotely sensed information (Brière, 2010). This process and technology was transferred to Nunavut Arctic College and the GN.
- First-order modeling of sea-level rise across Nunavut with an emphasis on the climate change adaptation action plan communities noted above (James et al., 2011).
- A methodology for landscape hazard assessments (combining permafrost and coastal science) in Nunavut with detailed studies conducted in Iqaluit (Allard et al., 2010), Pangnirtung (Leblanc et al., 2010) and Clyde River (Forbes et al., 2007b; Irvine et al., 2009).
- Reconnaissance landscape hazard assessments in collaboration with planners and the communities of Arviat, Whale Cove, Cambridge Bay and Kugluktuk.
- Establishment of a permafrost monitoring network across Nunavut (Ednie and Smith, 2011)
- A case study on how to visualize climate change impacts and adaptation options in Nunavut communities (using Clyde River as the example) by combining science and planning results.
- A Climate Change Adaptation Planning Tool Kit (www.planningforclimatechange.ca);
- A Nunavut Climate Change website (www.climatechangenunavut.ca).

The Nunavut Climate Change Partnership is committed to involving elders, hamlet councils, local stakeholders and the communities at large in all parts of its program. Some of the scientific research involves and trains community residents in data collection and monitoring. Partners are paying particular attention to the integration of old and new scientific knowledge with the traditional knowledge that exists in Nunavut communities. It is expected that this partnership will continue to evolve in the future.

and change, both in terms of survival and migration, than do many large mammals.

Marine ecosystems are also capable of evolving, but the interconnectedness of marine environments is a counterbalancing factor. Seasonal temperature variations in marine waters are less than the variations in air temperature, but many marine species are highly sensitive to temperature changes (e.g. Chabot and Dutil, 1999; Drinkwater, 2005; Dawe et al, 2007; Doniol-Valcroze et al, 2007; Lavers et al, 2008; Regular et al, 2009; Friedlaender et al, 2010). Marine waters are slower to respond to climate changes, and may also take longer to revert to previous conditions.

For human-related sectors considered in a climate-change context, adaptive capacity not only involves the potential (or latent) ability, but also the success at mobilization in response (see Scheffer et al., 2002; Etkin et al., 2004; Haque, 2005; Auld et al., 2006; Canadian Council of Professional Engineers, 2008; Hyndman et al., 2008; Reimer and Tachikawa, 2008; Füssel, 2009). In a community or sector, the evaluation of adaptive capacity involves comparison of available resources (financial, technical, and human) with the scope and magnitude of the issue to be addressed. A realistic assessment of adaptive capacity, however, must also consider the practicality, societal attitudes, and political willingness to proceed with the initiative. Climate change and variability will not occur in isolation of other human influences and adaption needs to be undertaken in the context of all other issues facing a community.

3.3.2 Resilience and adaptive capacity in Arctic coastal communities

The magnitudes and frequencies of the stresses imposed by changing and varying climates are important factors affecting Arctic coastal communities (Ford and Smit, 2004; Furgal and Seguin, 2006; Tremblay et al, 2006; Anisimov et al, 2007; DeSantis, 2008; Furgal and Prowse, 2008; Séguin, 2008; Ford et al, 2010). However, the ability of each particular community to respond and successfully adapt also depends upon the prevailing social, economic, and governmental conditions. A community with a greater resource base, including physical resources, financial capacity, knowledge (of all kinds), and social structures and relationships, is in a better position to successfully adapt than one that lacks resources and options. Adaptive capacity is a measure of both the physical stresses and the community resources and resilience.

Resilience is neither a finite nor a perpetually inherent quantity (Gunderson and Holling, 2002; Berkes et al, 2003; Resilience Alliance, 2011). In a community, the degree of resilience is constantly dynamic, in response to all manner of stresses and in a developing or diminishing capacity to cope. As communities are composites of numerous individuals, social and economic sectors, and physical landscapes, community resilience is a composite property.

From an adaptive system perspective, a community may encounter an actual decline in a physical resource dimension of the community (such as a decrease in the availability of a particular species for harvesting), or an apparent decline (such as a perception that changing weather conditions preclude successful application of traditional approaches), or an increase in stress (such as accelerated coastal erosion). Whether those physical stresses translate into increased community vulnerability depends upon the capacity of the community to adapt. A community with strong resilience can respond to the physical stresses through other socio-ecological system dimensions - people, organizations and the relationships that bind them to the land and sea, and to one another.

Adaptive capacity represents the extent to which compensation for changed physical conditions is theoretically possible. If capacity exists but is not utilized, however, the community's resilience will not be enhanced. A resilient community is one that not only has the capacity to respond, but proceeds in an attempt to adapt.

In a broader regional or national context, larger questions of governance, including jurisdiction and authority, characterize discussions of necessarily multi-scalar responses to coastal change (e.g. Kooiman, 1999, 2003). In this section, the focus is on the lived, local change and adaptive experiences of coastal peoples. Local governance and agency is a domain of particular interest in considering the accelerated morphological processes acting on Arctic coasts. In relation to both detailed local assessment of the practicability of any proposed or instituted adaptation measures, and supporting the individual and local agency needed to identify, assess and act on potential environmental stresses and hazards, the day-to-day realities of coastal community dynamics must be understood and respected.

In any assessment of appropriate adaptation measures for a community, quantitative scientific research concerning past, present, and future environmental changes and impacts is a key component informing policy and decision-making. Minimizing the adverse physical effects of changes requires a strong understanding of the physical environment. However, an approach that only considers the physical dynamics to the exclusion of the particular culture of the community, formerly practiced by many physical scientists (see Chester, 1993) will fail to generate adaptation measures that enjoy broad community support. A solution perceived as imposed from outside will not be incorporated into the community's reservoir of mechanisms for coping with change, will not form a component of its adaptive capacity, and will thus not contribute to its resiliency and ultimate sustainability.

Throughout the Arctic, there has been a fundamental change in the ethical stance of outside researchers in relation to the inhabitants in the last decade. A majority of researchers consider a community as a living group of people to be interacted with, rather than as an object of study or a group to be spoken to. The effort to see communities from the perspective of understanding the 'sense of place', cultural and physical, has allowed researchers and community to begin the process of true interaction, including all the key methods of engaging and listening: effective mutual communication, regular information-sharing, continuity of contact (old friendships, rather than passing summer acquaintances), and creative exploration and conceptual experimentation (c.f. Huntington, 1992; Hayward, 2005; Catto and Parewick, 2008).

The politics of knowledge collection, generation, and utilization bear the mark of decolonialization (cf. Sluyter, 2002). Researchers in many jurisdictions not only submit to both licensing and community stakeholder review processes, but strongly support these efforts to assure greater accountability and foster mutually beneficial partnerships.

Integrating coastal science with local decision-making presents 'cross-cultural' challenges in the conventional sense (between parties of different ethnicities or socio-economic backgrounds), and in the equally significant respect of the 'cultures of mind' which are characteristic of individual disciplines. Ongoing inter- or trans-disciplinary conversations entail new levels of effort. These can require researchers to discard habitual practices used for communication with disciplinary colleagues, which in a multi-cultural or multi-disciplinary context may present obstacles to true syntheses of knowledge. Communities contain vital information and energy for adaptation, which is best displayed by encouraging the exercise of community muscles, physical and mental.

Significant attention has been focused on the challenges facing traditional knowledge practitioners in relation to predicting weather, food harvesting, and traveling safely on the land, sea and ice (Berkes, 1999; Berkes et al., 2003; Jolly et al., 2002; Laidler, 2006; Nickels et al., 2006; Ford et al., 2010) as the Arctic environment changes. Issues related to contemporary physical infrastructure planning, design and location have also been examined in relation to communities (e.g. Allard et al, 2004; Catto and Parewick, 2008; Tremblay et al, 2006), industrial, and military developments (e.g. Reschny, 2007). The adoption of more collaborative practices by scientists working in the Arctic reflects the ongoing processes of legitimization of multiple 'ways of knowing' as a basis for arriving at the most comprehensive understanding of all the factors in play in a given community (see Section 3.1).

The impacts of ongoing environmental changes on knowledge and belief systems, language and the material culture of many Arctic populations have thus received substantial recent considerations by researchers. This includes the sociological components of culture, including the analysis of interpersonal relationships, community and societal organizations and practices, and responses to stresses. Adaptive cycling within cultural systems may be readily organized into those day-to-day adjustments made by individuals or communities encountering their environment, through the longer cycles of group and regional organization, to the uppermost levels of worldview binding the entire cultural community together. The explicit interest in the dynamic features of these enmeshed scales offers an organizing principle with which the multiplicity of other factors conditioning communities' experiences of change may be considered. Adaptation must occur throughout the system, with the potential for changes existing within cycles, working their way down or up through various levels (cf. Ostrom, 2008).

The 'local' is arguably the primary scale for considering human adaptation (Holling, 1986; Berkes et al, 2003; Johnson et al, 2003; Ford and Smit, 2004; Adger et al, 2007; Catto and Parewick, 2008; Armitage and Plummer, 2010; Ford et al, 2010). The consequences of coastal erosion, flooding, declining sea ice extent and duration, and permafrost terrain changes are visited upon the peoples preferentially settled there. The relatively recent built environment of many Arctic settlements in North America and Russia offers a starting point for exploring a variety of key adaptation themes. As tangible manifestations of intertwined form and function, they define a major transition and period of cultural adaptation. Traditional forms of indigenous Arctic shelters optimized mobility, minimized baggage, and used local materials to suit the season (snow, ice, skins, turf). The first generation of substitutes (e.g., canvas tarpaulins, tents) mirrored those forms and functions. However, the second generation of shelters, involving rigid construction anchored to terrain with exotic imported materials, represented a break with past experience. The experiential learning of older community members embodied in the traditional forms may not be lost, but neither is it preserved in anything but the most superficial of ways by contemporary Northern housing.

The rapid dissemination of imported forms and their accompanying infrastructure (streets, utilities, commercial and industrial uses) is such that within only a couple of generations, the appearance and nature of Inuit, Inuvialiut, and Aleut cultural landscapes have been radically altered (see e.g. Alunik et al, 2003). To what extent does the 'getting used to' by inhabitants of the appearance of their present community landscape, with its new sense of place, mirror other, less apparent adaptations? In particular, have other colonial institutions of similar vintage been 'adapted by' or 'adapted to' the original culture? What evidence is there of new forms and institutions emerging out of the meeting of any number of formerly distinct cultural traits?

Ongoing transitions on multiple levels in response to multiple stresses produce multiple strains of adaptive cause and effect, co-mingling to produce numerous complex adaptation scenarios. Strain rates vary as well, requiring adaptation efforts that vary in both time and space.

The dynamic interplay of local human dimensions (infrastructure, economy, organizations and governance) with a mutable environment is in evidence across the Arctic. In recent community case studies, documented physical change variables (sea level rise, isostatic movement, erosion rates) were assessed in terms of their relative degree of hazard and compared with community-based interpretive assessments of local economic, institutional and human resource circumstances. A bifurcation of interests into those of locational and relational sustainabilities was apparent. The best-practice 'engineering' of adaptations may then be seen as parallel system lifecycles of design, development, and maintenance interventions. While physical and social science evaluative methods (risk and hazard assessments, resilience assessments, cross-cultural knowledge-sharing and integration of science and decision-making) have moved in the direction of greater cross-over and integration, their outcomes with respect to policy have still tended to decouple. The duality of the physically and socially-constituted realities that condition human response to change are ever present in adaptive strategies: to adapt by changing the physical world at hand or to adapt by changing either the communities' spatial or functional relationship both to and within it.

In professional planning practice, there is another strategic posture that is always considered: the 'do nothing' scenario. Meant with the best of intentions to reinforce the rigorous consideration of every action scenario's merits relative to a baseline value, in the context of climate change, it could also be read as a maladaptive response to overwhelming and unfamiliar stimuli. Perhaps most pronounced in political arenas, the 'do nothing' scenario is regularly played out at the local level. The community-scale 'laboratory' is where the full array of informal adaptation experiments are played out. In concert with local physical hazard evaluations, community resilience assessments (e.g. Catto and Parewick, 2008) reveal significant community adaptation challenges stemming from human resource, organizational and relational factors. This approach leads to a working understanding of the many cross-scale interactions that ongoing physical changes are precipitating in tandem with globalizing economic and social influences on northern populations

Inquiries focusing on community-scale adaptation processes must examine a variety of community systems. In addition to numerous conventional forms of physical infrastructure, communities have 'non-structural' infrastructure – assets of a cultural, organizational or attitudinal nature - which can be more important to maintain. Although the non-structural assets are not physical, they are tangible to those engaged in the community. Absence of non-structural assets is quickly felt in a community, leading to erosion of community spirit, self-confidence, and adaptability, a sharp decline in both theoretical and real adaptive capacity, and a huge loss in resilience. Communities which superficially would appear equally able to cope with a given physical stress (such as a defined rate of coastal erosion) will exhibit very different responses, depending upon the strength of their non-structural institutions.

Restoring, preserving or enhancing these more relational capacities can take many forms. Locally-delivered employment-related training and certification, culturally-based activities or celebrations that aim to bring the community together, and health and wellness programs are critical examples.

In many northern communities, a key factor decreasing resilience is the replacement of the indigenous language with one from outside. Language loss is tied to the failure of inter-generational communication, leading to a collective failure to profit from community memory. Lack of communication between elders and youth occurs, as they literally do not speak the same language. Continuing negative feedback forms a classic 'trap', eventually resulting in reduced adaptive capacity and resilience in the face of physical stresses resulting from climate change. One key adaptation measure is thus to break the trap, by facilitating the transmission of critical community knowledge. Speakers are engaged to deliver a variety of indigenous language learning activities (interventions) in many community schools today. Relational interventions may also entail the development of physical infrastructure: for example, a community centre and gathering place if such a facility is otherwise lacking.

Until systematic training of Arctic residents progresses much further, communities will remain dependent on researchers, practitioners, and professionals and technical staff from outside. Non-resident engineers and planners tend to focus on specific pieces of infrastructure, both as a consequence of their short tenure in the Arctic and their previous disciplinary training. Public works design and management tends to react to rather than anticipate forthcoming changes, and inter-agency conflicts regularly stall responsive efforts.

The problem of attracting and retaining professional and technical staff in many Arctic communities also represents a 'trap'. Constant turnover not only limits the time available for new initiatives and research, but disconnects the revolving staff from the community. As the newly arrived staff members must integrate into a community of a different multi-dimensional culture (disciplinary as well as ethnically and socio-economically), time is required before effective work on adaptation and accentuating resilience can begin. The importance of institutional memory is greatly underappreciated: human resource turn-over interferes with the transmission of 'standard' and acquired operational procedures, leading to an erosion of preventative maintenance and even the loss of key infrastructure.

The Siku-Inuit-Hila Project

S. Gearheard and partners

The *Siku-Inuit-Hila* [Sea Ice-People-Weather] Project looks at the different ways in which the Inuit coastal communities of Barrow (Alaska), Kangiqtugaapik/Clyde River (Nunavut), and Qaanaaq (Greenland), live with and from sea ice. Indigenous experts from each of these areas have teamed up with scientists to examine sea ice and human-sea ice relationships. Despite being separated by vast distances, cultures, and languages, these groups all share knowledge and experience of sea ice. The *Siku-Inuit-Hila* project brings these perspectives together, and combines different community-based and innovative research methods in order to monitor sea ice, gather local and traditional knowledge about sea ice, and enable exchange between the partner communities and scientists (Huntington et al., 2010).

Siku-Inuit-Hila combines three main methods. The first and foremost is the knowledge exchange that happens between the different indigenous experts from participating communities, and between the indigenous experts and scientists. The team travels as a group to each of the communities, studying the sea ice together and learning about life with ice from the hosts in each community (Fig. B4) Travelling long distances together and living, camping, travelling the ice, hunting, talking, and eating together has created very strong bonds between the team members, who have become good friends as well as co-researchers. The sea ice acts as the common denominator for the group and each expert, no matter what their background, language, or particular expertise, is able to relate to the ice, share their unique perspective, and has something to contribute to the collective research. At various times, each team member thus has an opportunity to be a student or a teacher and everyone is able to broaden their understanding of ice in context.

The second method is the quantitative monitoring of sea ice that has been established in each community. Using stationary sea ice monitoring stations set up in the sea ice at freeze up each year (Mahoney and Gearheard, 2008), a local monitor has been trained in each location to measure various sea ice parameters such as ice thickness, snow thickness, and ice temperature, on a weekly basis. These measurements are graphed and combined with local qualitative observations of the sea ice environment and are shared with the local communities and with the project scientists who help further analyze the information for each community and comparatively across communities (e.g. Mahoney et al., 2009). The method has been successful as a community-based sea ice monitoring model and has been adopted in several other communities in Nunavut and Nunavik, Canada.

The last core method in *Siku-Inuit-Hila* is the establishment of sea ice expert working groups in each of the partner communities. These working groups meet on a regular basis (monthly), to discuss various topics such as past and recent sea ice conditions, sea ice travel, and hunting skills, and share stories and advice. The transcripts and minutes from these meetings provide detailed sea ice knowledge and insights into life with ice. The discussions are also a time for local experts to review project materials and analyze project data (e.g. interview material or data collected in the sea ice monitoring program).

Siku-Inuit-Hila reveals the true strengths of bringing together multiple perspectives on sea ice. The local-scale perspective of Inuit hunters and whalers, with their detailed knowledge of sea ice characteristics, dynamics, and changes, complements the larger-scale perspectives provided by some scientific methods such as remote sensing. As a team, the members of *Siku-Inuit-Hila* have also documented in detail what it means to live with sea ice and how sea ice changes are having an impact on local communities in different parts of the Arctic, as well as the broader environment and climate system.

The project ran through 2010 and the team is preparing to publish a book based on their research together. The project was funded by the National Science Foundation, with Dr. Shari Gearheard from the National Snow and Ice Data Center, University of Colorado, as the PI.

3.3.3 Summary discussion

The development of effective adaptation strategies requires an understanding of the vulnerability, sensitivity, and resilience of human-environment systems in a changing Arctic, in terms of who is vulnerable, to what stresses, what are the determinants of vulnerability and resilience, and what are the opportunities for adaptation policy (Ford, 2008b; Ford et al., 2008b, 2009; Furgal and Seguin, 2006; Turner et al., 2003a, 2003b).

Several frameworks and methodologies for vulnerability and resilience assessment have been proposed for application in Arctic contexts (Chapin, 2006, Chapin et al., 2004, Ford and Smit, 2004, Wolfe et al., 2007, Smit et al., 2008, Turner et al., 2003a, Alessa et al., 2008, Berkes et al., 2007, Ford, 2009; Keskitalo, 2008a, 2008b, Huntington et al., 2007a); common to the majority is the integration of insights from human and biophysical sciences with local and traditional knowledge. While there is an important role for expert assessment of hazard exposure and other sources of vulnerability, it is also important to recognize that communities and residents are often best placed to identify sources of vulnerability and to initiate coping strategies that form important components of adaptive capacity. A recent synthesis of case studies exemplifying these principles is the final report of the CAVIAR project (Hovelsrud and Smit, 2010).

Nowhere is the complexity of the climate change governance scenario more apparent than at the intersection of those communities ‘on the edge’ of land, sea, and cultural experience (Pearce et al., 2010; Loring et al., 2011). Ongoing assessment of adaptation in Arctic coastal community settings speaks to the gamut of traditional, theoretical and applied forms of knowledge in play, as well as the political and ethical dimensions of the transformative process. Adaptation must be understood as both an exercise of memory in relation to past hazards, and as an outcome of an ongoing community-scale ‘learning system’. Analyses based on this orientation have become more prevalent in the global climate change domain, but there remain few demonstrably-related initiatives to integrate Arctic-region investments in physical interventions with those of a social orientation. Future efforts need to focus on management in the face of change, building of community adaptive capacity and resilience, and recognition that change to both physical and human systems in the Arctic has become constant.

3.4 Governance and Adaptation

Lead author: Alf Håkon Hoel

Key Findings

- National agencies are the main actors in regional governance. In some areas such as northern Canada, regional (or in this case, territorial) agencies may play an equally important part. At national and international scales, almost all international land boundaries are settled, meaning that national jurisdiction at the coast is generally clear.
- There are enormous differences across the circumpolar Arctic in population size and distribution, economy, culture, institutional framework, and other factors.
- There are few Arctic-specific international regimes: the 1973 Polar Bear Treaty is the only legally binding regime.
- The Arctic Council, based on soft law (1996 Declaration), works primarily through assessment programs and projects to develop consensual knowledge and understanding on the status of the Arctic environment and related issues among the eight Arctic countries.
- Integrated coastal area management and integrated ecosystem-based oceans management are desirable strategies for coastal area governance and may embody a number of best practices which have emerged from recent reviews.
- Conclusions from consideration of integrated ecosystem-based management include the following:
  - Management needs to be flexible;
  - Decision-making must be integrated and science-based;
  - National commitment is required for effective management;
  - Area-based approaches and trans-boundary perspectives are necessary;
  - Stakeholder and Arctic resident participation is a key element;
  - Adaptive management is critical.
- It has been recommended that future research should focus on increasing support, opportunity, and capacity for local decision-making or effective resident input to decisions on broader institutional policies with local impacts.

Governance is a purposeful act to realize some objective of an organization, the efforts of some collective to confront problems or challenges they are facing through collective action. Collective action at all societal levels is complex and difficult (Olson, 1965), and constitutes a core area of study in the social sciences. The concept of 'institution', as social order governing the interaction of people, is central to this tradition (Scott, 2001).

In the realm of environmental studies, broadly speaking, two traditions have emerged in the study of collective action problems in relation to the environment: one considers how remedial *action* can be taken and what policy instruments are available for that (Young and Bjerregaard, 2008); the other takes a more resigned stand and asks how can we *adapt* to the deplorable state of affairs (rather than doing something about it) (Folke et al., 2005).

Either way, key questions in the study of environmental governance include the following:

- nature of the problem at hand (tragedy of the commons, etc)
- nature of institutions and flexibility to modify institutions
- drivers (causal factors) of institutions (knowledge, power, etc)
- institutional performance (effectiveness, justice, etc)
- interactions between institutions

Each of these questions is addressed by substantial and impressive literatures, and the state of knowledge with regard to these issues has been conspicuously improved during the last decade or so.

Figure 40. States, organizations, and strategic issues in the Arctic.
Source: People across Borders

3.4.1 Dimensions and scales of governance

The dimensions of governance involve:

- What is governed: what are the attributes of the governance problem? What is the societal sector in question –economic, social, military? Is it a local problem (e.g. pollution) or the ramifications of global change (climate)?
- Who is governing? Is the collective action confronted locally, at a regional or national level, or even at an international or global level? Or are we facing nested governance systems where international rules define national obligations and where implementation has local effects?
- How does governance occur? What are the rules of the game? Who can participate and how? What are the types of policy instruments that are in use: economic incentives, rules, information? At what level of governance does government occur? Are there interactions between the various levels of governance?

The question of institutional performance is particularly acute, as this addresses the issue of whether the collective action undertaken to confront challenges (that is, governance) actually works.

3.4.2 Arctic challenges and current institutions for governance

Many of the major challenges facing the Arctic today are of global origin (Fig. 40). Climate change, global overfishing, the drive to develop petroleum reserves in remote areas, the search for marine genetic resources – all of these are global phenomena with Arctic manifestations, also in the coastal zone where people live and work.

The institutional responses to these challenges are in many cases global, rather than Arctic. There is a global climate regime, a global Convention on the Law of the Sea, and these regimes set the standard that governments are expected to conform to when confronting these challenges. In particular when it comes to the oceans, the Law of the Sea Convention, which is a broad framework for the governance of all aspects of use of the world's ocean, settles questions of who can decide what where and who owns what.

There are few Arctic-specific international regimes: the 1973 Polar Bear Treaty is the only legally binding regime. The Arctic Council (see Section 2.3), based on soft law (1996 Declaration), fundamentally works through assessment programs and projects to develop consensual knowledge and understanding on the status of the Arctic environment and related issues issues. The Arctic Council consists of eight Arctic countries, six Permanent Participants (organizations representing indigenous peoples), and a number of observer countries and organizations.

The Arctic Council is a 'high level forum', under which the actual work is carried out in a number of working groups operating under the oversight of Senior Arctic Officials representing the foreign ministers of the eight Arctic countries:

- The Arctic Monitoring and Assessment Programme (AMAP)
- The Conservation of Arctic Flora and Fauna (CAFF)
- Emergency Preparedness, Prevention and Response (EPPR)
- Protection of the Arctic Marine Environment (PAME)
- The Sustainable Development Working Group (SDWG)
- The Arctic Contaminants Assessment Program (ACAP)

The Arctic Council has a central secretariat in Tromsø, Norway, and each of the working groups has a secretariat located in one of the Arctic countries. Altogether 15-20 people staff the Arctic Council secretariats. In addition, the chairmanship, which rotates among members on a bi-annual basis, has 2-3 persons working continuously on Arctic Council business.

The Arctic Council makes decisions by way of ministerial declarations which are adopted at ministerial meetings every second year. In between the ministerials, the Senior Arctic Officials (SAOs) of the Arctic countries run the business through two annual SAO meetings, providing the day-to-day directions for the working groups.

The Arctic Council has three functions: First, it examines the status of scientific knowledge in selected issue areas, and produces assessments of our current understanding of important issues like climate change in the Arctic, oil and gas development, shipping, pollution, quality of life and living conditions in the Arctic. This brings about a critical factor for political action: agreed knowledge. Second, in doing so, agency officials, scientists, and other actors from the Arctic countries and others establish a joint frame of reference for understanding various challenges facing the region and how they can be resolved. And thirdly, this in combination with the development of guidelines in various issue areas (for example offshore oil and gas development) enhances the capacity of countries to act in relation to management of the Arctic environment and other aspects.

Countries are the major actors in the governance of the region. All land boundaries and a majority of ocean boundaries are settled. In the coastal zone proper, the international dimension of governance manifests itself through the obligations that countries have to implement various principles and standards for environmental quality and performance. In Europe, this derives first of all from EU regulations, but also from global treaties, such as the Kyoto Protocol, the implementation of which has implications for economic activities in the coastal zone (e.g. shipping).

3.4.3 Best practices

In the Norwegian Chairmanship of the Arctic Council (2006-2009), a project was initiated to examine how the various Arctic countries have approached the need for ecosystem-based oceans management. The project was carried out by a project group working under the Sustainable Development Working Group (SDWG) and the Protection of the Arctic Marine Environment (PAME) Working Group of the Arctic Council. The project resulted in a report (Hoel, 2009) containing national case studies of Arctic ecosystem-based oceans management, as well as a set of "Best Practices" for ecosystem-based oceans management in the Arctic. The Best Practices were endorsed by the Arctic Council ministerial meeting in April 2009.

The report *Best Practices in Ecosystems Based Oceans Management in the Arctic* contains some *core elements*, as well as a set of *conclusions*. The Core Elements, which are aspects of ecosystem-based oceans management found in most countries, include the following:

- The geographical scope of ecosystems defined by ecological criteria.
- The development of scientific understanding of systems and of the relationship

between human actions and changes in other system components.
- The application of the best available scientific and other knowledge to understand ecosystem interactions and manage human activities accordingly.
- An integrated and multidisciplinary approach to management that takes into account the entire ecosystem, including humans.
- Area-based management and use of scientific and other information on ecosystem changes to continually adapt management of human activities.
- The assessment of cumulative impacts of different sectors on the ecosystem, instead of single species, sectoral approaches.
- A comprehensive framework with explicit conservation standards, targets and indicators in order to facilitate responses to changes in the ecosystem
- Trans-boundary arrangements for resolution and handling of trans-boundary ecosystems and issues.

The *Conclusions* were arrived at by reviewing the practices countries have established in developing and implementing ecosystem-based oceans management, and identifying elements that had been found useful in one or more contexts.

1. **Flexible application of effective ecosystem-based oceans management**
    - Differences in circumstances and contexts have to be taken into consideration as ecosystem-based oceans management is context sensitive. There is not one single method for ecosystem-based management. A number of different practices and understandings of the concept appear to work.
    - Ecosystem-based management is a work in progress and should be considered a process rather than an end-state.
    - Rule-based relationships between countries in oceans affairs, based on applicable international law and agreements, have to be promoted.
    - Recognition of humans as an ecosystem component, and increased consideration of social effects when food security and poverty alleviation are issues of concern.
    - Management must be based on best available science. Open lines of communication between managers, resource users, and the general public are necessary to foster mutual understanding and recognition of shared interests.
    - Biodiversity conservation strengthens the structure and functions of ecosystems, thus ensuring the long term delivery of ecosystem services.

2. **Decision-making must be integrated and science based**
    - Increased communication and exchanges among both states and sectors are also key components of successful ecosystem-based management. A great deal of scientific knowledge already exists. However, much of this information needs to be better synthesized and communicated to a variety of audiences. Cooperation in science and exchange of relevant information within and between countries is important for understanding the cumulative impacts to the coastal marine environment. Another challenge is to address what information exists and what information still needs to be gathered. Knowledge gaps can be closed through development/identification of key ecosystem indicators and comprehensive modelling, mapping, monitoring, and analysis.
    - Various forms of scientific, traditional, and management knowledge need to be integrated to improve ecosystem-based management. Potential advantages of

integrating various forms of knowledge include decision-making that is better informed, more flexible, and incorporates traditional ecological knowledge.
- A multi-sector approach lies at the core of the ecosystem approach as it contributes to a common understanding of challenges in oceans management and thereby an increased trust between authorities with different sector responsibilities/interests. Ecosystem-based management calls for coordination and shared responsibility between all levels of government and cooperation across sectors, with respect to monitoring, mapping and research. The challenge of monitoring, however, is both a scientific challenge and a policy issue. Monitoring programs can provide the ongoing basis for management, but require a long-term commitment of resources. Secondly, a multi-sector approach depends on providing opportunity for stakeholder comments on how a specific sector is to be managed or how to assess the impact of that sector in relation to the ecosystem. This is a difficult process, requiring care and time.

3. **National commitment is required for effective management**
    - National commitment to conservation and sustainable use of ocean resources is necessary. A 'road map', management plan or national action plan for addressing priorities in coastal and oceans management is developed in many of the Arctic countries.
    - An integrated organizational structure (framework) to support the coordination of a holistic approach to the implementation of ecosystem-based management (EBM) at the national level through inter-agency cooperation seems to be effective. In this respect, harmonization of domestic laws governing use of coastal and ocean resources with EBM principles, as well as with regional and international management efforts may be appropriate. This requires legislation and enforceable policy tools to provide government strategic directions and overall framework for EBM implementation.

4. **Area-based approaches and trans-boundary perspectives are necessary**
    - Area-based management approaches are central to ecosystem-based management. The identification of management units within ecosystems should be based on ecological criteria. Management measures should reflect the status of areas and take into account the human element.
    - Ecosystem-based management requires specific geographical units at various scales.
    - Issues of scale can be addressed viewing ecosystems as nested systems.
    - The identification and protection (including through protected areas and networks) of key areas, species, and features that play a significant role within the marine ecosystem help management set priorities and ensure ecosystem structure and function are maintained (see Box in Section 2.2.).
    - Increased international cooperation in shared ecosystems could be addressed through existing regional management bodies and, as necessary, new collaborative efforts focused on individual ecosystems.
    - Effective area-based approaches include mechanisms for addressing effects of land-based activities and atmospheric deposition on ocean ecosystems.

5. **Stakeholder and Arctic resident participation is a key element**
    - Stakeholder and Arctic resident consultation, co-management or decision-

making are important to build understanding and foster development of knowledge.

- Stakeholder participation can be encouraged by providing for public participation in a manner that enables stakeholders and members of the public who lack the capacity to prepare for/attend numerous meetings to make their voices heard in a meaningful fashion.
- Stakeholders can be engaged to develop and strengthen cooperative processes to sustain ecosystem structure and function.
- Effective stakeholder participation can encourage and achieve compliance with necessary conservation measures through education and enforcement.

6. Adaptive management is critical

- Effective management requires adaptive management strategies that reflect changing circumstances. This is especially important in view of the accelerating effects of climate change on marine and coastal ecosystems.
- Implementation of ecosystem-based management should be approached incrementally.
- Conservation objectives and targets, benchmarks and action thresholds should be set for the measurement of achievement of ecosystem health.
- Flexible mechanisms should be used for implementing ecosystem-based management
- While the best practices in Hoel (2009) were developed with oceans rather than coasts in mind, most nevertheless are applicable to and useful for coastal-zone management.

4 Synthesis and Future Directions

4.1 Introduction

The past decade has seen rapid growth in environmental and social research throughout the Arctic, combined with a growing number of assessments and reports. Various assessment reports noted in Chapter 1 included the Arctic Human Development Report, the Arctic Climate Impact Assessment, and a range of others pertaining to contaminants, oil and gas, shipping, and sustainable development, among others. The International Conference on Arctic Research Planning in 2005 (ICARP-II, 2007) spurred the development of a discussion paper on grand research challenges in the Arctic region (Corell et al., 2005) and a set of 11 science plans (SPs) covering a wide range of topics:

1. Arctic economies and sustainable development.
2. Indigenous peoples and change in the Arctic: adaptation, adjustment and empowerment.
3. Arctic coastal processes.
4. Deep central basin of the Arctic Ocean.
5. Arctic margins and gateways.
6. Arctic shelf seas.

7. Terrestrial cryosphere and hydrological processes and systems.
8. Terrestrial and freshwater biosphere and biodiversity.
9. Modelling and Predicting Arctic weather and climate.
10. Research plan for the study of rapid change, resilience and vulnerability in social-ecological systems in the Arctic.
11. Arctic science in the public interest.

The inclusion of a plan specifically addressing Arctic coastal processes was an important recognition of the importance of the coastal zone. At the same time, several of the other science plans bear directly on issues of importance in coastal regions and are considered in this report. Not the least of these was SP10, which proposed an integrated approach to the study of resilience and vulnerability of social-ecological systems in the face of rapid environmental and social change. Following on ICARP-II, the array of projects developed and pursued over the multi-year effort of the International Polar Year dramatically increased the research effort on a number of fronts (Krupnik et al., 2011). IPY in turn drove the series of SAON workshops on measures to promote sustained observation networks to monitor change in the Arctic region.

Pertinent recent reports include the following:

- Sustainable Development Working Group (Arctic Council), Workshop Report *Vulnerability and Adaptation to Climate Change in the Arctic*, February 2009
- Senior Arctic Officials Report to Ministers, Tromsø, April 2009
- *Tromsø Declaration* from Sixth Ministerial Meeting of the Arctic Council, April 2009
- WWF Report *Arctic Climate Feedbacks: Global Implications*, August 2009.
- Norwegian Polar Institute, *Melting Snow and Ice* (Koç et al., 2009), December 2009
- American Meteorological Society, *State of the Climate in 2009* (Arndt et al., 2010), July 2010.
- Circumpolar Biodiversity Monitoring Program (CBMP), Conservation of Flora and Fauna Working Group (Arctic Council), *Arctic Report Card: Update for 2010* (Richter-Menge and Overland, 2010), October 2010.

4.2 ICARP-II Science Plans

4.2.1 Monitoring coastal change in the circumpolar Arctic

Science Plan 3 (SP3) of ICARP-II (2007) addressed coastal issues explicitly. This plan noted the extreme vulnerability of the Arctic coastal zone to ongoing and anticipated environmental change and identified the need for coastal monitoring. As a primary objective, the plan proposed the establishment of “an internationally coordinated network of coastal observatories,” a vision that was carried forward in the SAON discussions but remains largely unrealized. Specific changes anticipated in SP3 included changes in sea-ice extent and thickness, sea level, storm frequency, coastal stability, biodiversity, and other changes induced by human activity. Changes resulting from ongoing processes were recognized to include rapid coastal retreat of permafrost coasts with large proportions of ground ice, with implications for coastal habitats and human settlements. Other important issues were recognized to include potential release of gas hydrates through permafrost degradation, particularly in the coastal zone, and the contribution of coastal erosion to fluxes of sediment, carbon, and nutrients, which play an important role in the material budget of the Arctic Ocean.

Four general outcomes were proposed:
- improved understanding of biophysical processes and possible impacts on ecosystems;
- ecoregion-based coastal-zone management;
- scientific support of sustainable development in the Arctic coastal zone; and
- improved web access to basic data for coastal-zone research and education.

SP3 also envisaged the preparation of this report to provide context and a snapshot of the state of the Arctic coastal zone five years on from the ACIA (2005). In other respects, this report constitutes a report card on the challenges of implementing SP3 and limited progress on some fronts, demonstrating the ongoing need to address the objectives highlighted in that plan.

4.2.2 Measures for assessing human community issues in the Arctic coastal zone

Science Plan 1 (SP1) of ICARP-II (2007) addressed issues of sustainable development in the Arctic. SP1 focused on Arctic peoples, particularly indigenous peoples with close ties to the land, as being among the most vulnerable to environmental, social, and economic change. While this plan did not explicitly address coastal issues, a large proportion of the Arctic population resides in large or small settlements located on or close to the coast (Fig. 2). SP1 identified eight determinants of sustainable development in the Arctic, including communities and demographics, large-scale resource extraction or other industrial development, infrastructure and technology, governance including policies and implementation, economic systems including subsistence and globalization, and environmental change including climate change. Climate change and other environmental changes in the coastal zone pose challenges to sustainable development in Arctic communities, but the impacts are dependent on resilience, which is affected by all the other determinants of sustainable development (see Section 3.3).

Considerations of trade-offs, equity, and cultural vitality are also important in this context. SP1 did not explicitly list knowledge gaps but identified a number of research and related priorities, relevant to both coastal and non-coastal communities, including:

- Identification of a suite of indicators of sustainable development applicable across the circumpolar Arctic, which would facilitate creation of a database (or initially regional databases) to enable development of long-term time series to support planning, policy development, decision-making.
- Synthetic and comparative studies drawing on the collective experiences of many researchers and projects.
- Development of appropriate education, outreach, and communication efforts reaching beyond the scientific community.

Science Plan 2 (SP2) of ICARP-II (2007) concerned indigenous peoples and change in the Arctic, including adaptation, adjustment and empowerment, and touched on many of the same issues identified in Science Plan 1. SP2 noted “the unique ability of Arctic cultures to exhibit resilience and thereby occupy new physical and social environments" (SP2, p.3). It referred to three issues considered critical to Arctic residents, as identified in the Arctic Human Development Report (AHDR, 2004): control of personal destiny, maintenance of cultural identity, and living close to nature, which in the Arctic often means close to living marine resources in the coastal zone.

Science Plan 10 (SP10) of ICARP-II (2007) was presented as a research plan for the study of rapid change, resilience and vulnerability in social-ecological systems of the Arctic and also provides useful guidance relevant to the present report.

Since 2005, parts of SP1, SP2, and SP10 have been addressed through the *Vulnerability and Adaptation to Climate Change in the Arctic* (VACCA) project (Kelman and van Dam, 2008), the *Survey of Living Conditions in the Arctic* (SLiCA) (Poppel and Kruse, 2009), the *Arctic Social Indicators* project (Larsen et al., 2010), and the IPY *Community Adaptation and Vulnerability in Arctic Regions* (CAVIAR) project (Hovelsrud and Smit, 2010).

4.3 Knowledge Gaps and Research Priorities

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4.3.1 Physical state of the circum-Arctic coast

- Predictions of sea-level change in the Arctic are poorly constrained compared to lower-latitude regions. Development of more robust projections of sea-level rise for residents and decision makers requires better knowledge of past sea-level change, improved vertical motion data, updated global projections, and better models for regional sea-level rise.
- We have limited understanding of the impacts of a changing sea-ice regime and wave climate on coastal stability, including issues such as sediment entrainment and export by sea ice and the incidence of ice ride-up and pile-up events onshore.
- Anticipating increased coastal erosion in the Arctic, the lack of a systematic circumpolar coastal observing network is a critical gap.
- There is a need for more detailed studies of Arctic storms and how they might change in the future.
- The effects of the changing character of carbon and other inputs on productivity are not known. The role of river-ocean interaction and the filtering/buffering role of deltas on carbon and nutrient delivery are not sufficiently understood.
- There is a need for comprehensive studies of coastal topography and landscape change. In particular, the fate of Arctic deltas and salt marshes faced with rising sea levels and wave energy in the context of growing human development pressure requires more attention.
- The distribution and stability of gas hydrates and other sources of methane venting in the Arctic coastal zone requires more attention.

4.3.2 Ecological state of the circum-Arctic coast

- There are still large gaps in understanding of the vulnerability of coastal ecosystems to changes in climate, rapid development, shipping and tourism in the Arctic. Ongoing research efforts and assessments are a priority.
- There is a need to identify prime ecosystem functions and their global, regional and local significance.

- Major stakeholders may, to some extent, self-identify but more effort is required to develop a comprehensive stakeholder inventory.
- There is a need to identify and list major biodiversity indicators for monitoring the sustainable use of Arctic coastal ecosystems

4.3.3 Social, economic, and institutional state of the circum-Arctic coast

- New and refined methods and tools are required to perform integrated assessments of socio-economic effects in Arctic regions and communities of environmental changes and societal changes inside and outside the Arctic.
- More work is needed to improve the understanding of societal risks of industrial activities in Arctic coastal regions and the socio-economic impacts of ecosystem changes.
- For many regions and groups of people, the subsistence economy is of great importance, but statistical data remain poor for this component of the economy in many regions. Better systems are needed to collect and compare data on the situation and development of subsistence and non-subsistence activities and employment and their importance for households, communities, and regions.
- More effort is needed on the collection of data pertaining to some indicators proposed in the Arctic Human Development Report and the subsequent Arctic Social Indicators project, including *fate control, cultural integrity* and *contact with nature*. Data need to be collected at regular intervals to detect changes and development patterns.
- Understanding the role and influence of external actors in the Arctic will be important, as the EU and China amongst others are increasingly directly involved in the region, and the policies of these major geopolitical actors have significant indirect effects (e.g. through trade, energy, shipping and fisheries).
- More attention is needed on strategies to develop businesses, industries and communities in the rural north that support social, cultural, economic and ecological sustainability

4.3.4 Integrated assessment

- There is a need for scenarios that integrate physical, ecological and social changes.
- A number of projects are moving towards integrated assessment of human-environment relationships, vulnerability, and resilience, but numerous challenges remain to developing frameworks within which different knowledge systems can be integrated (e.g. Lange, 2008).
- Documenting changes in indigenous languages and changes in some specific domains, such as orientation systems, would contribute to a better understanding of the global (climate, technological, or other) influences on human-biogeophysical interactions in the Arctic.

4.3.5 Monitoring, detecting and modelling coastal change

- The tools, methods, and research structures for coastal monitoring are currently in place and in use, however challenges still exist. At most sites, monitoring has only been going on for a few decades at most, and sustaining the long term *in situ* monitoring programs is important in order to capture decadal scale processes.

- The SAON process provided a stimulus to renewed efforts to expand circumpolar coastal monitoring. There is a pressing need for resources to support sustained coastal monitoring with innovative methods across a wider, international, circumpolar network, combined with new standards and protocols to enable better comparison of results from all sites.
- A stronger relationship with communities and the development of community-based monitoring can help increase on-the-ground monitoring capabilities.
- Some significant processes are still poorly understood and need to be investigated (e.g. shoreface evolution during winter).
- High resolution remote sensing imagery is now available to provide a good baseline for monitoring efforts and, if not already in place, needs to be secured for important sites.
- Despite important recent progress, the human health situation across the Arctic needs ongoing monitoring, especially for indigenous people outside urban centres. Use of traditional food is important for promoting a wholesome diet, but is at the same time a potential source of contaminants.
- There is a need for an inventory of models applicable to the Arctic coastal zone, as well as what pieces are missing. The inventory should include at least three classes of models: operational (using real-time data), predictive, and hindcast models;
- Significant, directed research effort is required to attain a level of sophistication and computational efficiency necessary to address complex human-biogeophysical interactions inherent in an integrated approach to issues in the Arctic coast zone.

4.3.6 Vulnerability, adaptation, and resilience

- The development of effective adaptation strategies requires an understanding of the vulnerability and resilience of human-environment systems in a changing Arctic, in terms of who is vulnerable, to what stresses, what are the determinants of vulnerability and resilience, and what are the opportunities for adaptation policy.
- There is a need for new, integrated monitoring approaches to document the nature of environmental change and human interaction with biophysical conditions in the Arctic coastal zone, assessing current adaptations and identifying constraints and opportunities for future adaptation.
- Future efforts need to focus on adaptive management in the face of change, building of community adaptive capacity and resilience, and recognition that change to both physical and human systems in the Arctic has become constant.
- More work is needed to understand the effects of scale, in particular global- to local-scale effects and their implications for adaptation policies.

4.3.7 Governance and adaptation

- Future research needs to focus on increasing support, opportunity, and capacity for local decision-making or effective resident input to decisions.
- More could be done to explore applications of integrated coastal area management strategies in Arctic regions.
- More effort is required to develop lines of communication between the science and policy communities concerned with Arctic coasts.

4.4 Building a Road Map to Integrated Coastal Systems Research in the Arctic

It is abundantly clear that the coast is a critical component of the Arctic system requiring explicit attention. Furthermore, as a locus of human activity with attendant hazards, the circumpolar Arctic coast may be seen as a priority for monitoring and change detection to support proactive adaptation.

A number of knowledge gaps and key findings of this report point to the need for an integrated approach to critical questions affecting ecosystems and human communities in the Arctic coastal zone. There is a clear need for intensified observing and monitoring efforts to provide the baseline information required to document rates of change, project the potential for future change, and assess current vulnerability to change. These are needed to support the development of adaptation mechanisms to increase resilience and minimize future impacts. Effective governance and management of coastal resources depends on a solid foundation of robust knowledge. A coordinated approach to monitoring and managing change in coastal landscapes and communities in the Arctic is likely to be more efficient and effective in the acquisition and dissemination of knowledge and in building connections between the science and stakeholder communities (Catto and Parewick, 2008).

The International Council of Scientific Unions (ICSU) recently completed an open consultation on grand challenges in global sustainability research using a systems approach to the identification of global research priorities (http://www.icsu-visioning.org/the-visioning-process/). Broad themes of this visioning blueprint include improving the usefulness and relevance of projections, developing observation systems, developing approaches to coping with environmental change, identifying institutional and behavioural changes to support sustainability, and technological and social innovation. Criteria for selection include scientific importance, relevance, broad support, global coordination and leverage. These criteria can be applied equally well to identifying priorities for coordinated circum-Arctic research in the coastal zone.

As the ICSU visioning process moves to the next stage, a key question is how to move from vision to action. Key questions include how to determine the balance between top-down and bottom-up approaches, how to interact with stakeholders, what sort of ongoing participatory prioritization process is appropriate, and how often it is needed (http://www.icsu-visioning.org/the-visioning-process/).

The SAON (Sustaining Arctic Observing Networks) process over the past 3 years has highlighted the need for enhanced and sustained Arctic observing systems, not only "sustaining … current levels of observing activities and information services" but "making every reasonable effort to increase the scope of those activities in the future" (SAON, 2009).

The challenge for coastal system monitoring and research is the cross-cutting nature of the coast and the absence of a clear model for integrated coastal monitoring in the Arctic. The Arctic Circumpolar Coastal Observing Network (ACCO-Net), an IPY initiative of the Arctic Coastal Dynamics Project, remains the primary model for international coordination of coastal monitoring and change detection (Krupnik et al., 2011). Although coastal issues received limited visibility in the final SAON report, ACCO-Net was recognized as one of a number of SAON building blocks. As the SAON process has progressed to formation of the SAON Steering Group and completion of a Plan for the Implementation Phase of SAON (SAON Steering Group, 2011), ACCO-Net is not currently included among the 17 SAON task proposals. It may be desirable to have the Arctic coastal community participate more actively in this process.

Several useful components of an action plan were identified by Couture et al. (2008), including the following:

- Building an inventory of existing stations, actors, and networks in the field is a clear step to be taken.
- Building awareness of the coast as a distinct and common entity can be supported by use of the term ‘coastal’ as a keyword in all relevant metadata.
- The existing ACD circum-Arctic coastal GIS provides a common mapping tool (see Lantuit et al., 2011).
- Government agency support will be critical to allocation of resources to support coastal monitoring.
- Increased communication of coastal issues in the Arctic is a prerequisite to recognition of the need for agency resources.
- Coastal communities represent an important source of demand and potential capacity to support monitoring efforts.

The ICARP-II Science Plan 3 on Arctic coastal processes advocated a network of focal areas and sites for detailed studies within a broader regional and circum-Arctic framework. Critical elements were identified as

- A network of coastal observatories (on- and off-shore), involving physical, ecological, and social observations;
- A broad-scale physical, environmental, and social circum-Arctic characterization to provide context [this report];
- Data management and information systems that include a particular emphasis on data synthesis;
- A cyber infrastructure and sensor technologies at multiple spatial and temporal scales.

A number of initiatives are underway to support governance and sustainability of Arctic communities and regions, including the Northern Research Forum (www.nrf.is), the Sustainable Development Working Group of the Arctic Council (http://arctic-council.org/working_group/sdwg), and the Arctic Governance Project (http://www.arcticgovernance.org/). None of these organizations has an explicit coastal focus, yet coastal issues will impinge in numerous ways on the issues they are attempting to address.

LOICZ is developing a set of major research themes to fit within the framework of the ICSU research vision. One of these themes is the Arctic coastal zone. A road map to integrated coastal systems research in the Arctic could follow this route, integrating physical, ecological, socio-cultural, and integrated monitoring through a revitalized ACCO-Net consortium. A pragmatic approach would see ACCO-Net developed in a modular fashion, with support from national agencies, research funding bodies, academic and community-based initiatives. To be successful, however, there is a need for a steering group and one or more sponsoring bodies or agencies with sufficient resources to ensure a framework of communications, coordinating infrastructure, and data management. Representation from northern residents, existing northern research consortia, appropriate Arctic Council working groups, LOICZ and IASC would be desirable. Possible models for raising the profile of coastal issues might include the establishment of an IASC coastal research committee (an evolution from the Arctic Coastal Dynamics network) or a Coastal Systems Working Group of the Arctic Council. Other approaches are possible, but to be truly effective, this would require some degree of formal organization and financial resources.

4.5 Summary Discussion

The Salekhard Declaration of the Fifth Arctic Council Ministerial Meeting in Salekhard, Russia, in October 2006 (Arctic Council, 2006a) endorsed efforts of the SAOs and Arctic Council working groups "to implement activities, as appropriate, to follow-up the Arctic Climate Impact Assessment" (ACIA, 2005) "and the ACIA Policy Document, adopted by the Fourth Ministerial Meeting. The Tromsø meeting on Arctic Coastal Zones at Risk (Flöser et al., 2007) took up this challenge, initiating the effort to develop this State of the Arctic Coast 2010 report. The intent of this report was to shed further light on the critical, multi-faceted interface zone represented by Arctic coasts and to highlight the challenges of environmental, social, and economic changes five years after the publication of the ACIA.

Arctic coasts cover a broad spectrum of geological and oceanographic settings, resulting in a wide variety of shore-zone geomorphology. Nevertheless, most parts of the circum-Arctic coast share common factors such as strong seasonality, cold temperatures, permafrost, and sea ice, resulting in distinctive high-latitude coastal processes found nowhere else except Antarctica. Arctic coastal biota exhibit distinctive characteristics of low biodiversity but locally high productivity, particularly in the marine and aquatic realm. The human population of the Arctic comprises "more than 40 distinct peoples, cultures and languages" (Arctic Council,, 2006b, p. 4) and a wide range of coastal communities, from European ports and fishing communities (Iceland, Faeroes, Norway and western Russia) to regional administrative centres (e.g. Nuuk, Greenland; Iqaluit, Canada) to small and remote indigenous settlements in Chukotka, Alaska, Canada, and Greenland, in some of which today's older residents were born on the land. Cultural challenges, including rapid introduction of a market economy, globalization, language, relationship to the land and living resources, cultural heritage resources, contaminants and health, education, and other issues create a complex human backdrop to climate change and the challenges it presents to traditional lifestyle, economy, health, and community infrastructure.

Evidence of a warming climate is widespread across the Arctic, with the potential for dramatic impacts on sea levels, sea ice, waves, permafrost, plant and animal species, and human use of the coastal zone. Dramatic reductions of multiyear ice in the Arctic basin have grabbed headlines in recent years, but more subtle changes involving later freeze-up, earlier breakup, altered conditions and safety of landfast ice, changes in storm patterns, increased wave action, accelerated coastal erosion, deeper seasonal thaw, shifts in species composition including the appearance of new "southern" species, and other observations are recognized impacts in Arctic coastal communities.

Managing change on Arctic coasts requires a range of responses at various scales. Many of the impacts of physical (climate) and cultural change are experienced at the human settlement scale and require community adaptation strategies, yet adaptive capacity may be limited. At regional and national scales, co-management systems, ecosystem-based management policies, and national assessments and policy reviews have pointed to new approaches and strategies to manage change. Nevertheless, severe challenges remain in the establishment of appropriate governance, not least because of cultural differences in perception.

Several recent initiatives, under the International Polar Year (IPY) and elsewhere, have addressed issues of vulnerability and the need to foster enhanced resilience at community and regional levels, as described earlier in this report. The Salekhard Declaration (Arctic Council, 2006a) reconfirmed previous commitments to continue efforts to implement ACIA (2005) recommendations on climate-change mitigation, adaptation, research, monitoring, and outreach. The Norwegian Chairmanship Programme (Arctic Council, 2006b) undertook to strengthen "climate change research and monitoring …[and] the adaptive capacities of Arctic residents, including indigenous peoples and local communities … identifying the most vulnerable sectors of society." The Senior Arctic Officials (SAO) Report to Ministers (Arctic Council, 2009) made a number of recommendations for action on these fronts. New international efforts in recent years include the Arctic Monitoring and Assessment Programme (AMAP) project on Snow, Water, Ice and Permafrost in the Arctic (SWIPA) and the *Update on Selected Climate Issues of Concern* (AMAP, 2009b), as well as the *Arctic Report Card: Update for 2010* (Richter-Menge and Overland, 2010), sponsored by the Arctic Council.

Useful as these are, they largely ignore the coastal zone. Yet, as noted in the Introduction, the coast is a key interface in the Arctic environment. It is a locus of human activity, a rich band of biodiversity, critical habitat, and high productivity, and among the most dynamic components of the circumpolar landscape. The Arctic coastal interface is a sensitive and important zone of interaction between land, ocean, and atmosphere, a region that provides essential ecosystem services and supports indigenous human lifestyles; a zone of expanding infrastructure investment and growing security concerns; and an area in which climate warming is expected to trigger landscape instability, rapid responses to change, and increased hazard exposure. A high proportion of Arctic residents live on the coast and many derive their livelihood from marine resources. The coast is a region exposed to natural hazards and is particularly sensitive to climate change; it is thus a high priority for change detection and awareness

A common theme throughout this report is the lack of adequate data and knowledge on which to base appropriate and effective adaptation strategies. It is hoped that this report will provide the stimulus for accelerated efforts to close these information gaps and to mobilize the resulting knowledge in an effective way for the betterment of Arctic coastal ecosystems, the peoples of the north, and the global community.

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