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

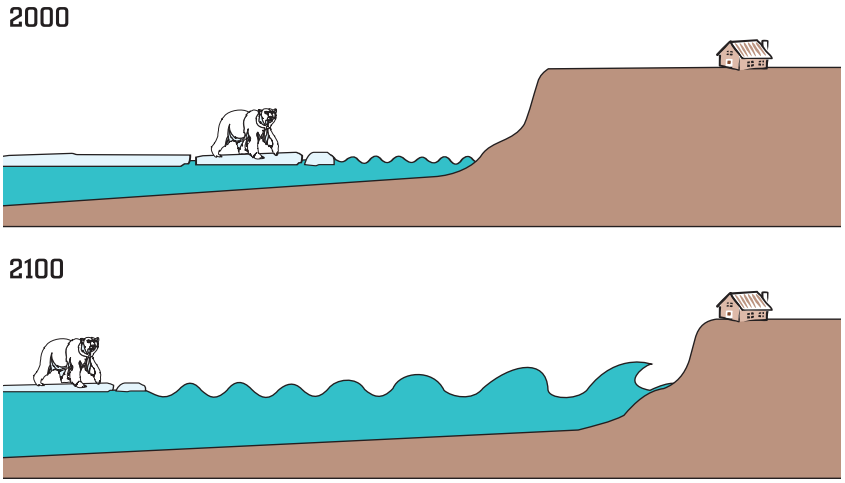

Figure 1. Trends of decreasing sea ice and increased open-water fetch, combined with warming air, sea and ground temperatures, are expected to result in higher wave energy, increased seasonal thaw, and accelerated coastal retreat along large parts of the circum-Arctic coast.

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 10ºC sea surface isotherm, the surface air 0ºC 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.