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

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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

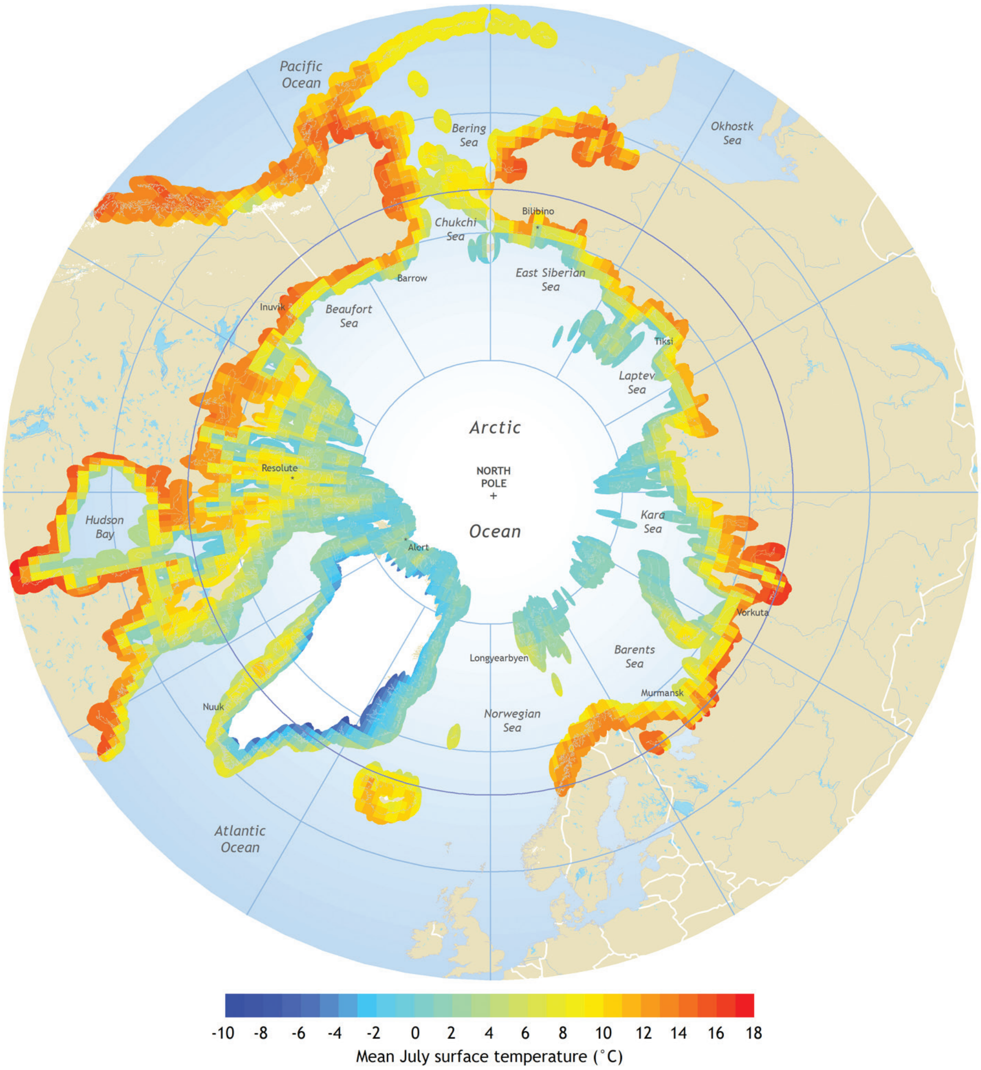


Figure 3. Mean July air temperatures in the circum-Arctic coastal zone (22-year mean: July 1983 to June 2005).
Source: US National Aeronautics and Space Administration, 2007 (http://swera.unep.net/index.php?id=metainfo&rowid=282&metaid=384).

(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

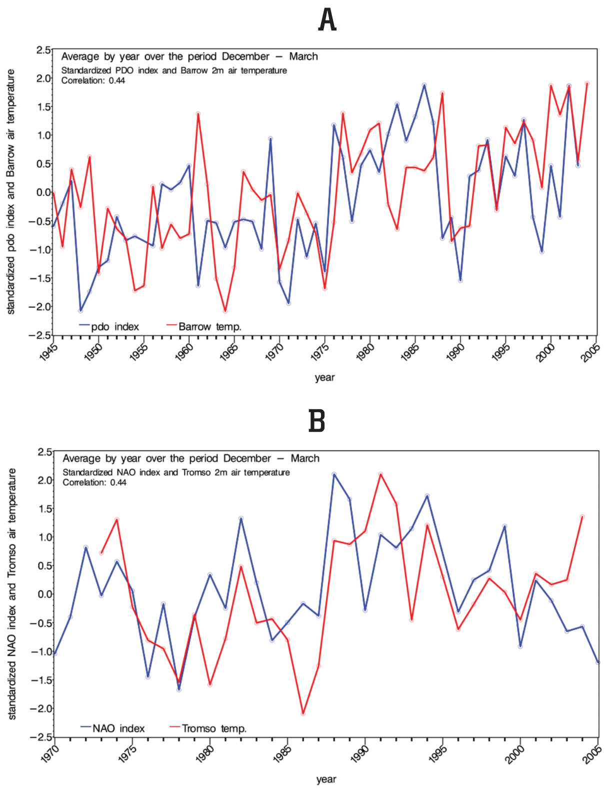


Figure 4. Influence of major regional modes of atmospheric circulation on locally observed 2 m surface air temperature in winter. Monthly temperatures were extracted and averaged over the December-March period to arrive at a single annual value. A single annual datum for the indices was similarly constructed. (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

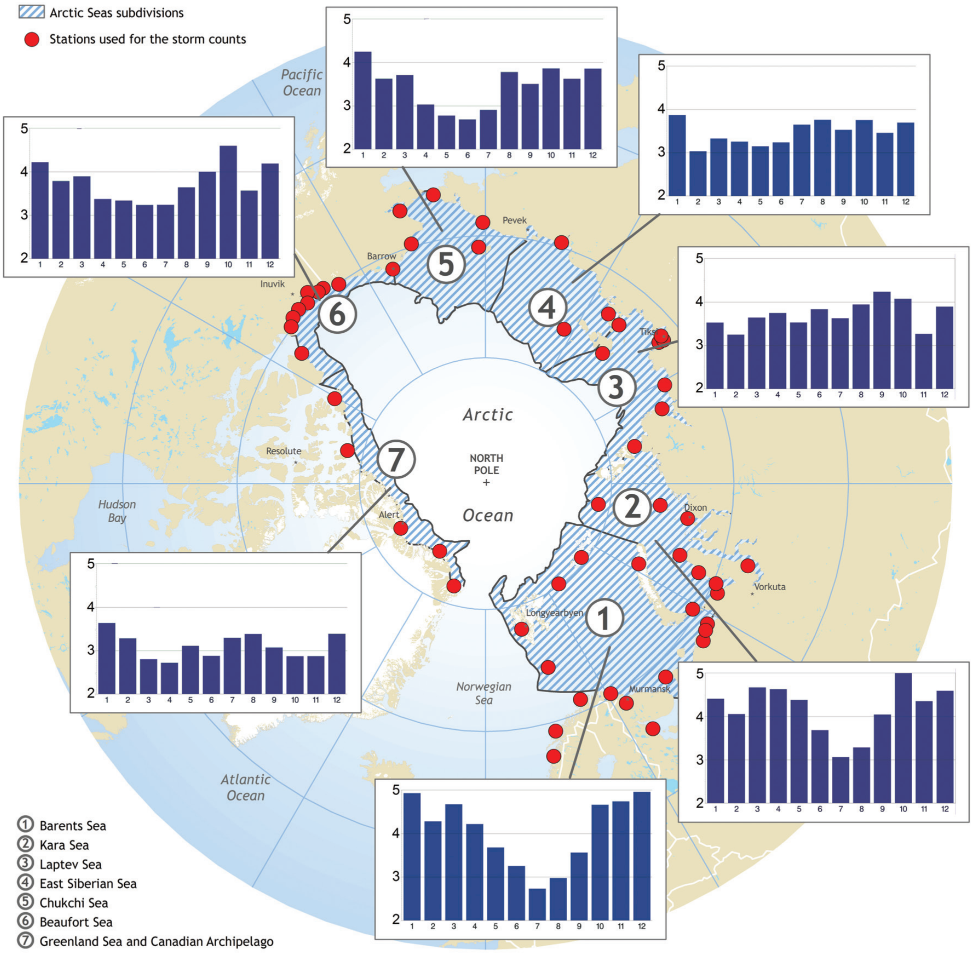


Figure 5. Annual patterns of coastal storm counts (1950-2000) for the circum-Arctic region, summarized for each of seven marginal seas. Histograms are equally scaled from 2 to 5 events and present mean annual storm event counts by month. A 'storm' is classified in this context to be an event in the locally-observed 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

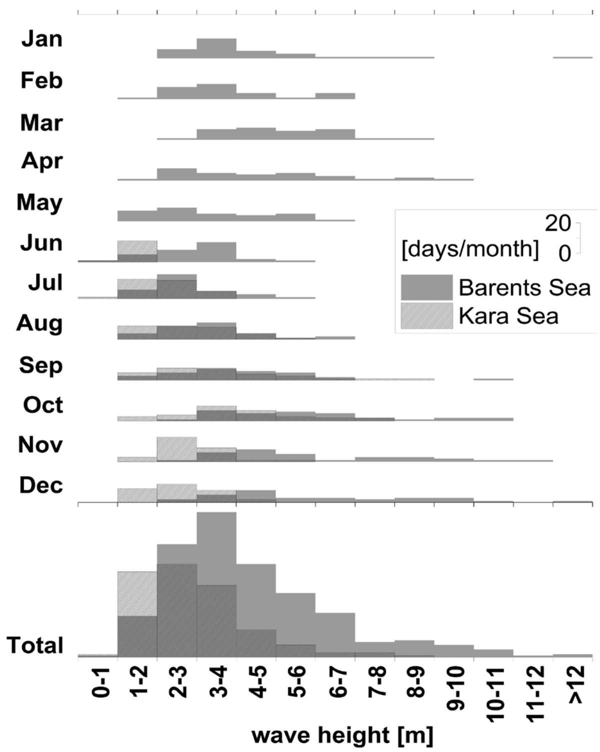


Figure 7. The distribution of wave heights (Hs) in the Barents and Kara Seas by month of the year (2007). Bar height shows the number of days in each month with the wave height indicated on the horizontal axis. Vertical scale is indicated in the legend.

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

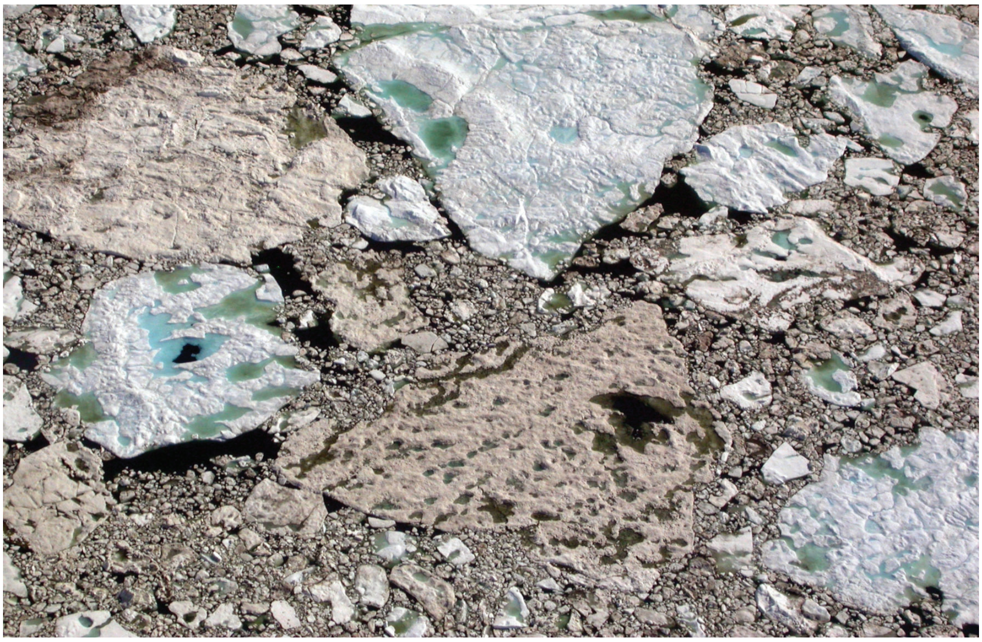


Figure 9. Clean and sediment-laden sea ice formed in the Beaufort Sea and exported to the Chukchi Sea, about 100 km north of Barrow, Alaska, 30 July 2006. Width of view is about 250 ± 50 m.

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.

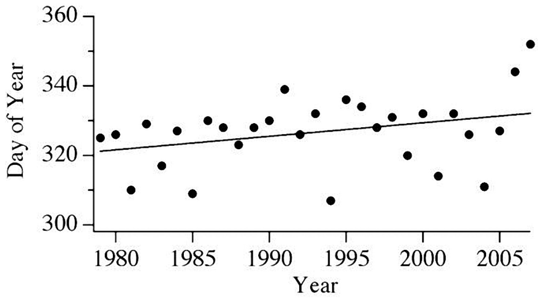
Source: Eicken (2003)

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.

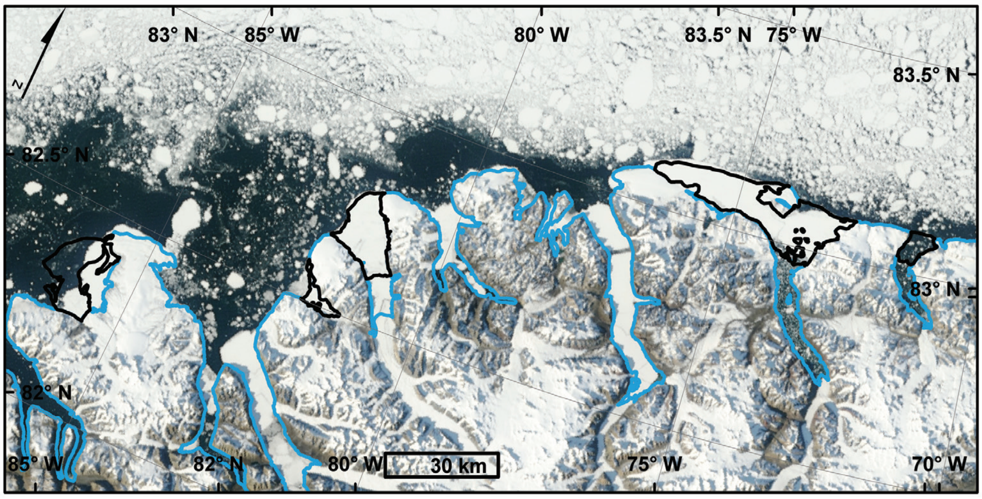


Figure 11. Ellesmere Island ice shelves at the end of August 2008. The 2007 ice shelf extent is outlined in black and coastline in blue. Left to Right: Serson, Petersen, Milne, and Ward Hunt. The unusually wide expanse of open water along the coast likely contributed to the 2008 break-up of three of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

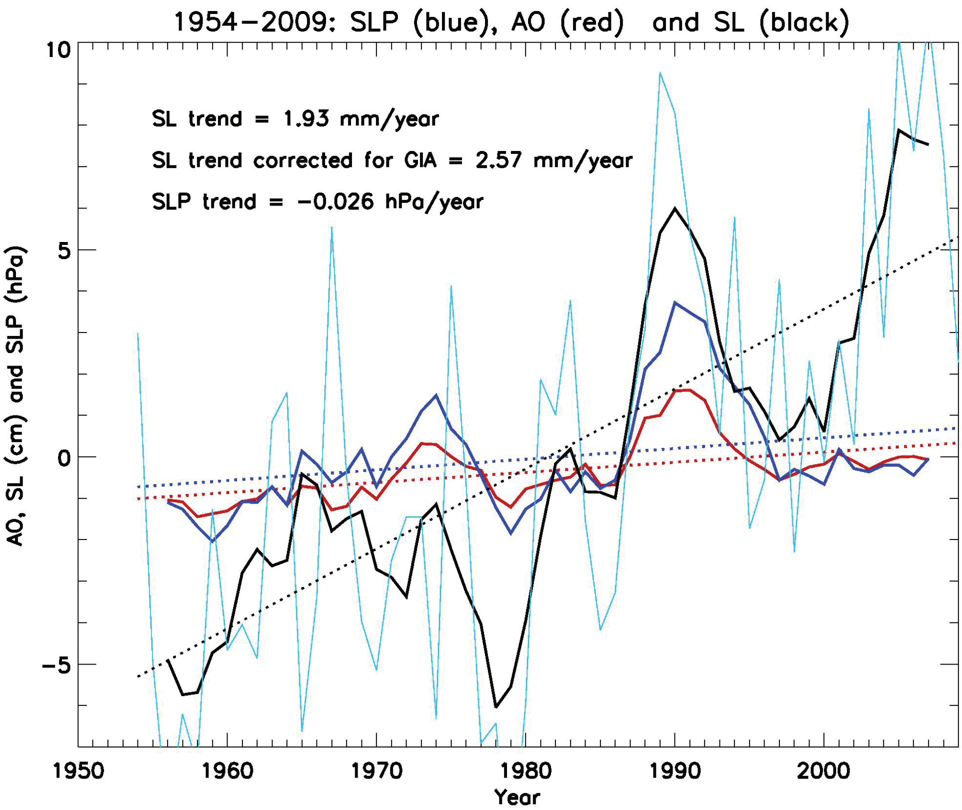


Figure 12. The 5-year running-mean time series of annual mean sea level (1954-2007) at nine tide gauge stations located along the Kara, Laptev, East Siberian, and Chukchi Sea coastlines (black line). The red line is the anomaly of the annual mean Arctic Oscillation Index multiplied by 3. The dark blue 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.

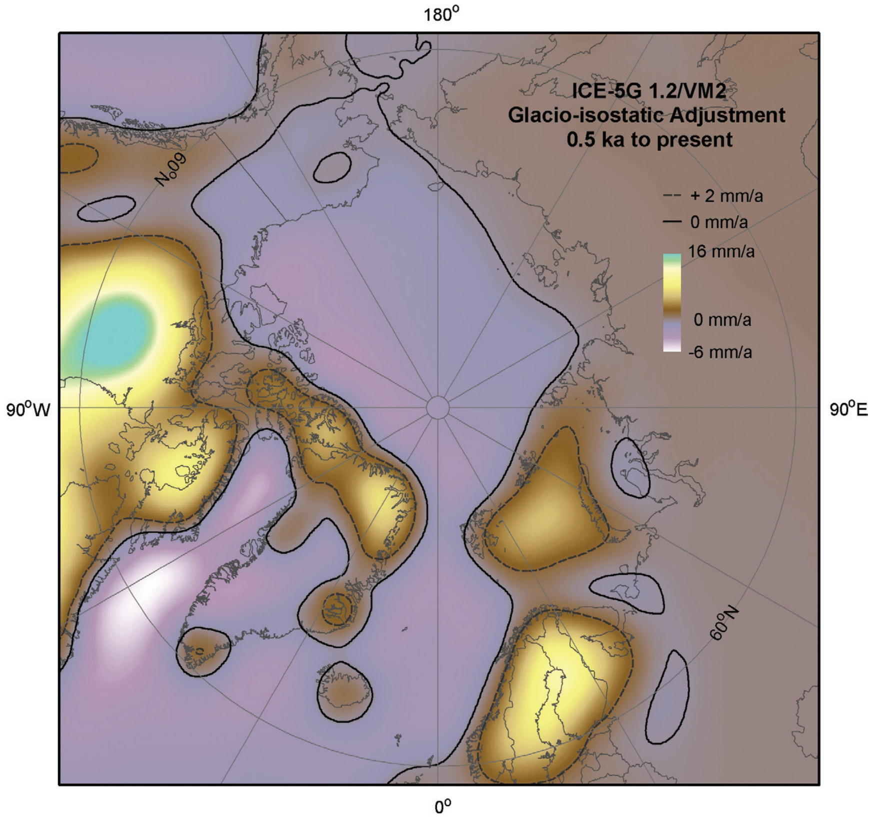
Figure 12 shows sea-level time series from nine coastal stations having representative records for the period of 1954–2007 in the Siberian seas (from the Arctic and Antarctic Research Institute data archives; Proshutinsky et al., 2007). There is a positive sea-level trend along Arctic coastlines of 1.94 ± 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.

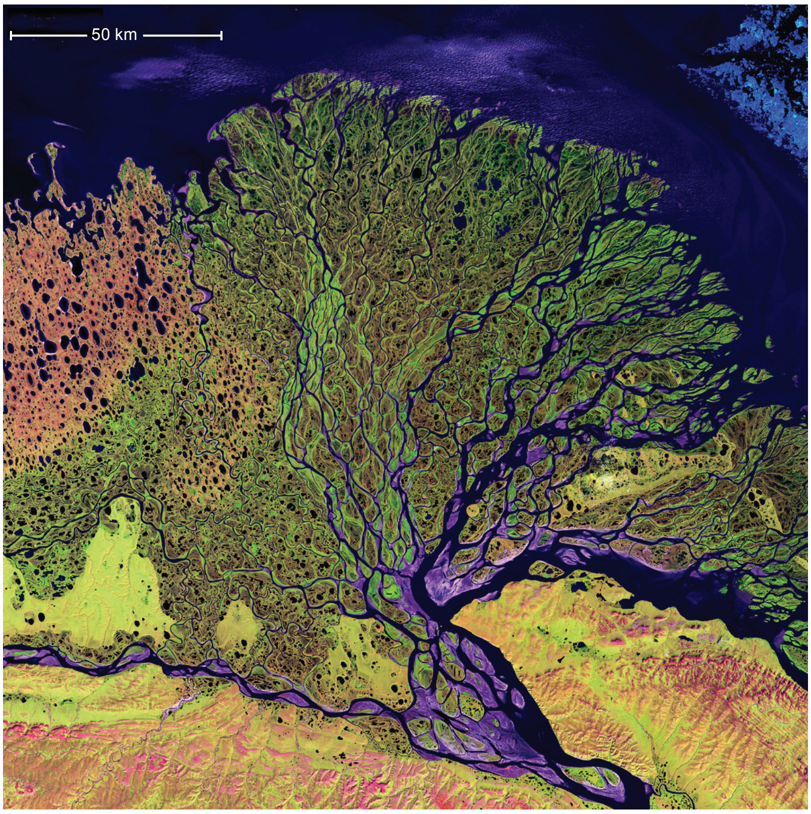


Figure 15. The Lena River delta in the Laptev Sea, northern Russia, is the second largest delta in the world and the largest in the Arctic.

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

Lead authors: Christoph Zöckler, Thomas Douglas
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,

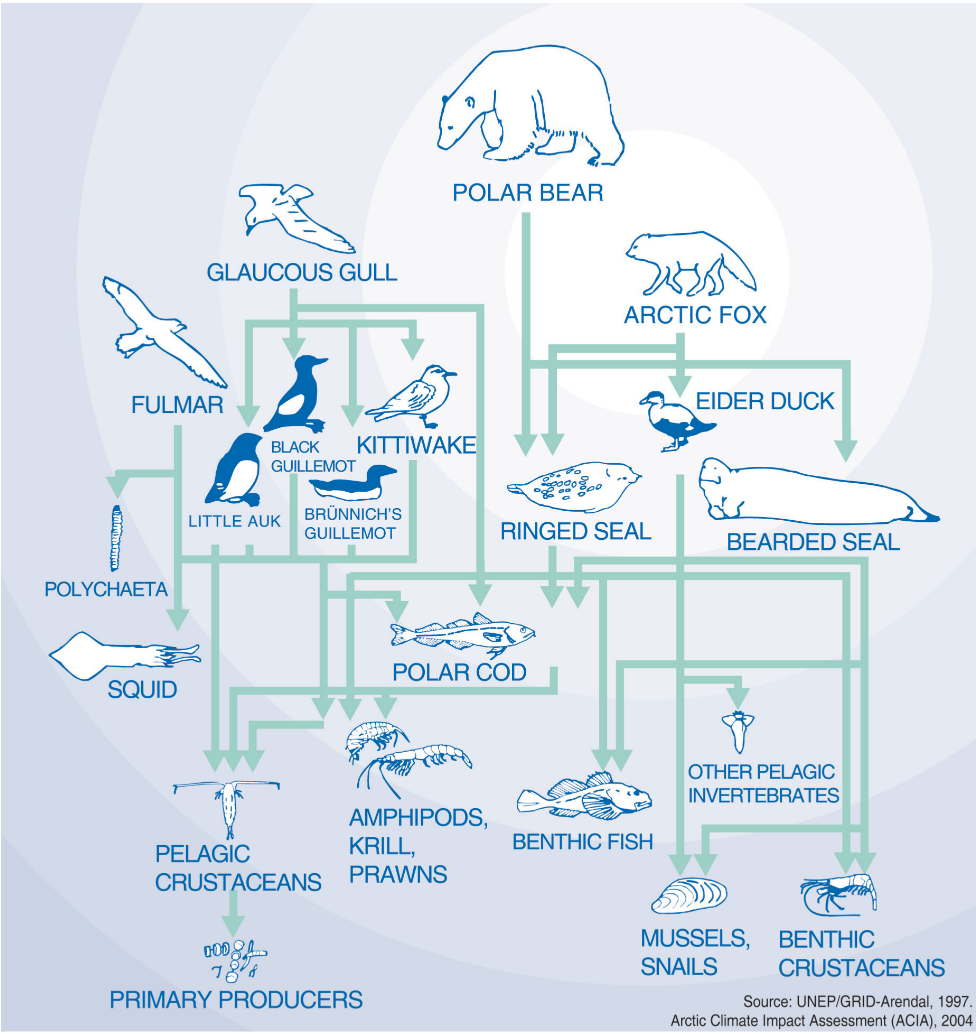


Figure 20. The coastal Arctic food web is closely related to drift ice conditions and seasonal use of shorelines by both terrestrial and marine mammals. Numerous species depend upon each other and on the transport of food between marine, coastal, and inland habitats.
Source: UNEP/GRID-Arendal.

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 km^2)	Total primary production (g C/m^2)	New primary production (g C/m^2)	Grazing rate of zooplankton (g C/m^2)
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.

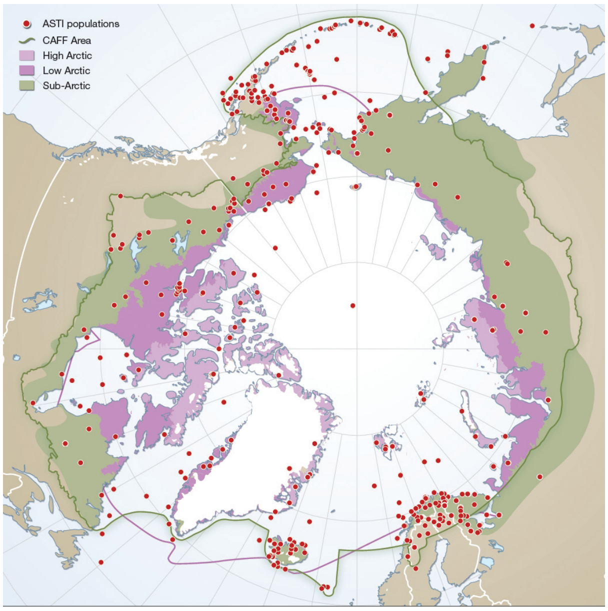
Arctic coastlines are subject to extensive disturbance through processes such as thermal abrasion, wave erosion, storm-surge flooding, and sea ice grounding in the shore zone, with implications for species distribution and abundance. Genetic, range, or other adaptations by plant and animal populations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

The Arctic Species Trend Index: A Barometer for Arctic Wildlife

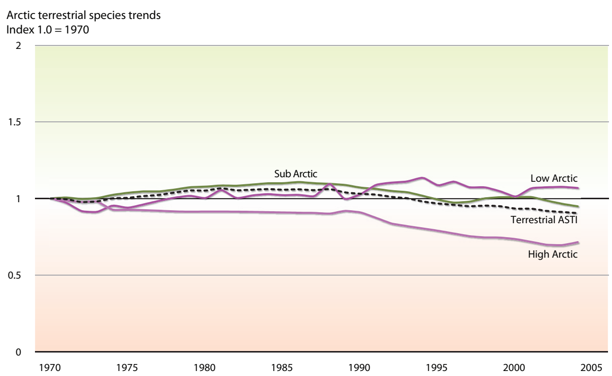
Michael J. Gill, Christoph Zöckler, Louise McRae, Jonathan Loh and Ben Collen

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)



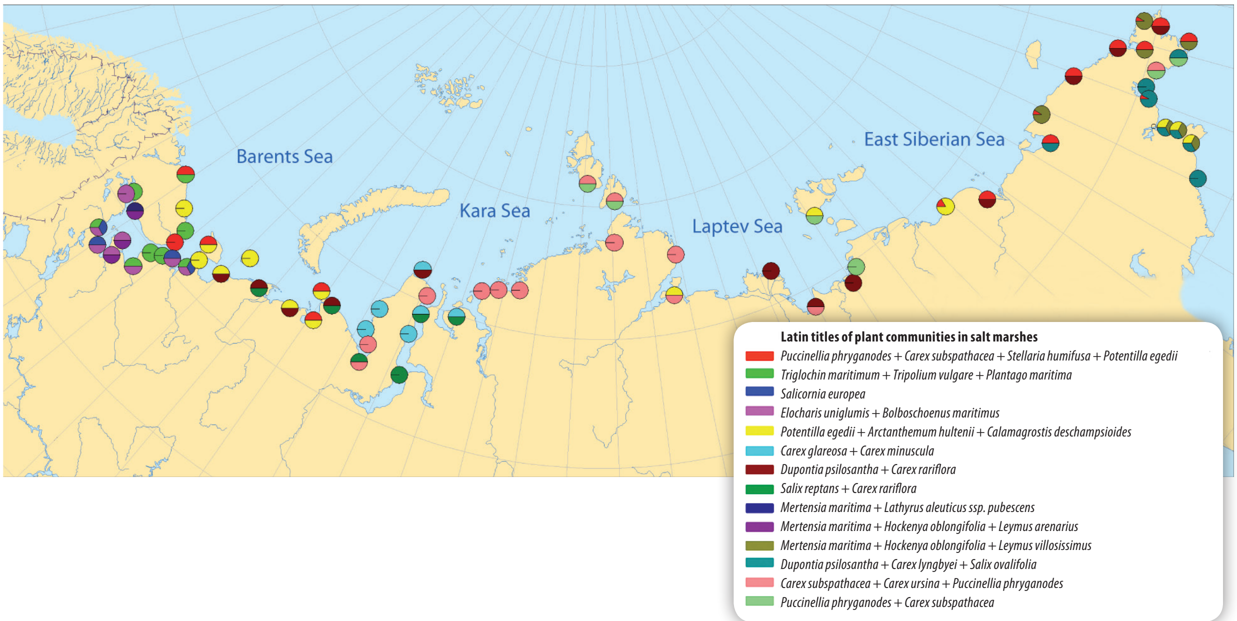


Figure 21. Distribution of salt marshes in the Russian Arctic. Colours represent variability in salt-marsh plant communities.
Source: L. Sergienko, unpublished data, 2009.

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

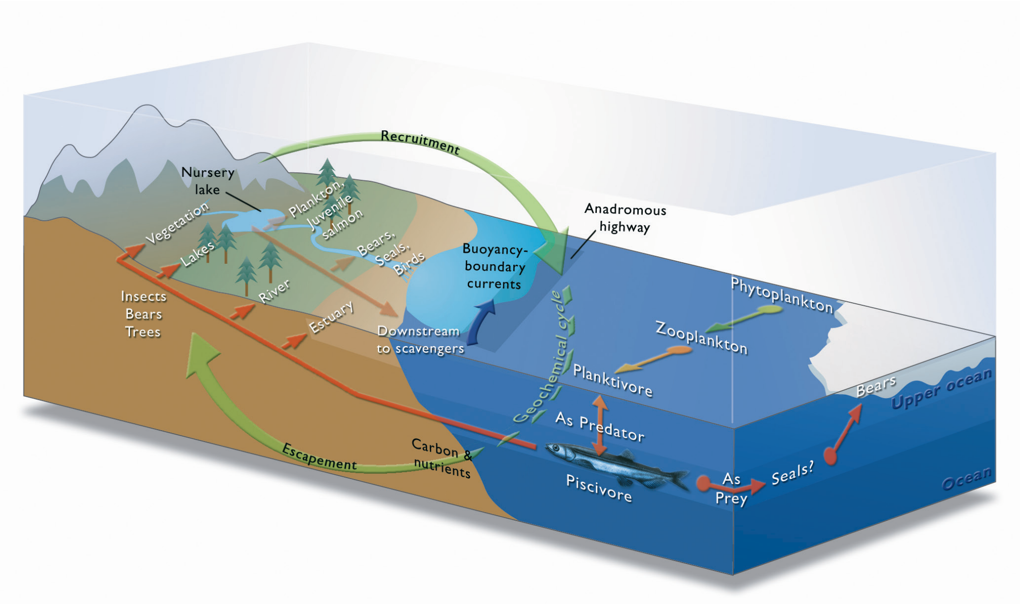


Figure 24. Schematic portrayal of the use of estuaries and the keystone role of anadromous fish in the trophic dynamics of Arctic nearshore estuarine and marine ecosystems.
Source: Wrona et al. (2005), © Arctic Climate Impact Assessment, 2005

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).

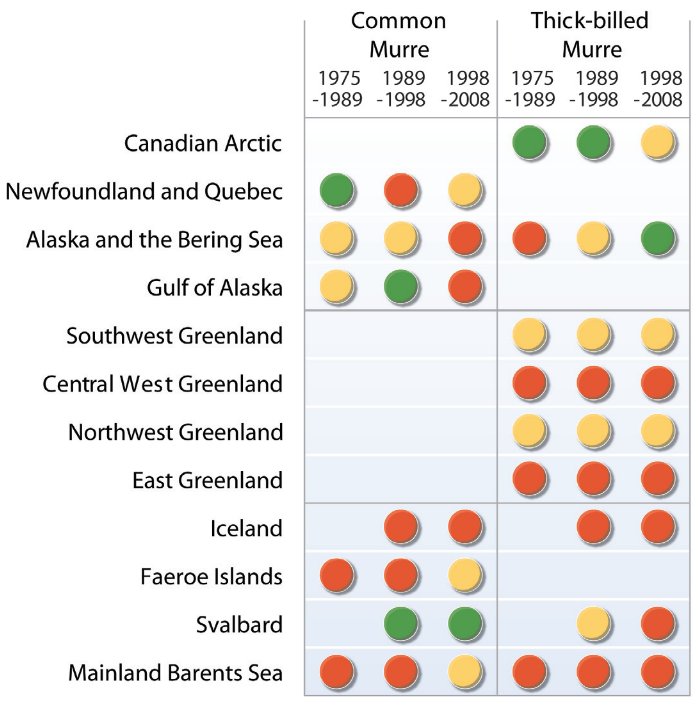


Figure 25. Changes in murre populations since 1975 by region and 'decade' (as defined by regime shifts in the Pacific Decadal Oscillation; see Irons et al., 2008). Green indicates positive population trends, yellow indicates stable populations, and red indicates negative population trends (http://web.arcticportal.org/en/caff/cbird).

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

	Estuaries and Marshes	Lagoon and salt ponds	Intertidal mudflats	Kelp	Rock and shell reefs	Seagrass	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).

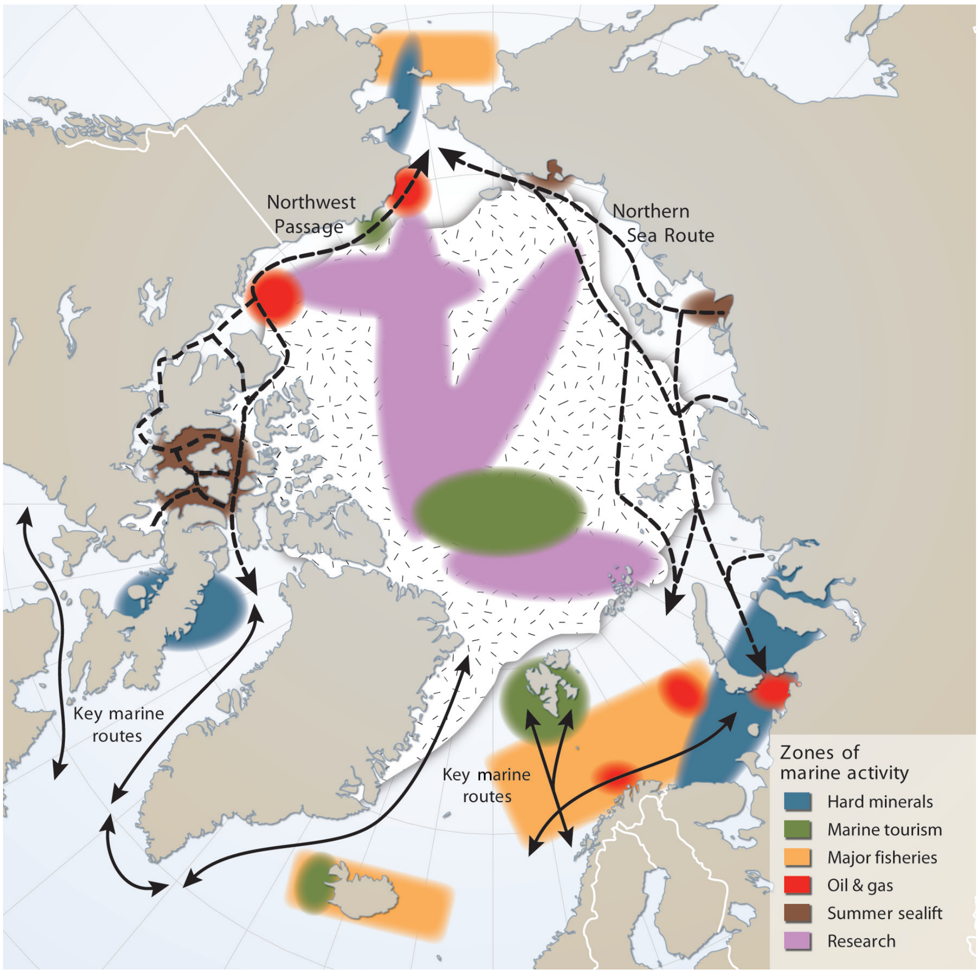
Oil spills present the greatest anthropogenic risk for the marine and coastal environment in the Arctic. Seasonality is a major driver for how pollutants can affect ecosystems. The impact of an oil spill on ice covered waters is of particular concern due to limited options in containing or responding 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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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

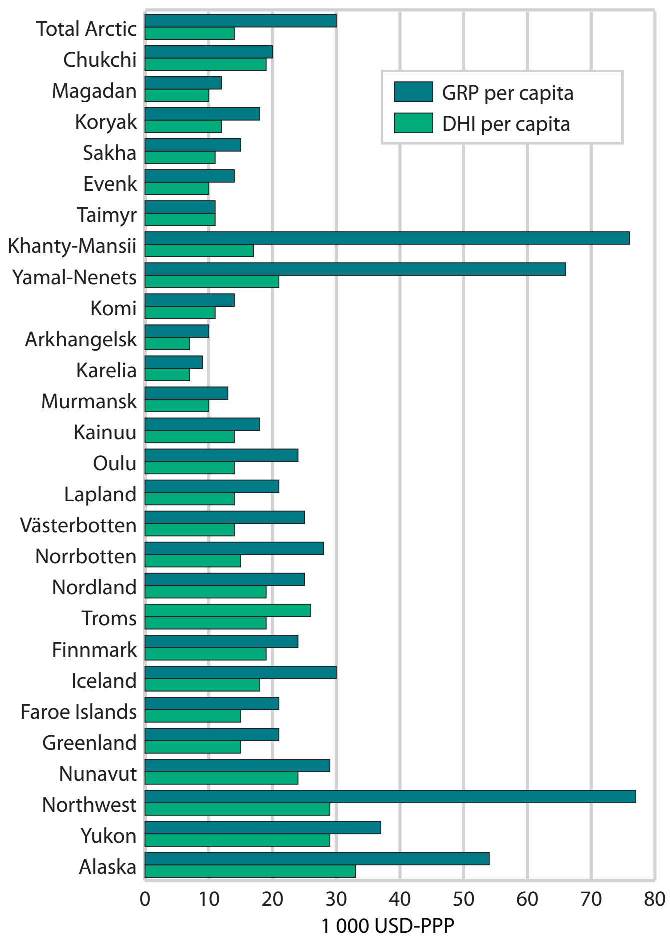

Figure 28. Gross regional product (GRP) per capita and disposable household income (DHI) per capita, by Arctic regions, 2005 (units US$1000-PPP).

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

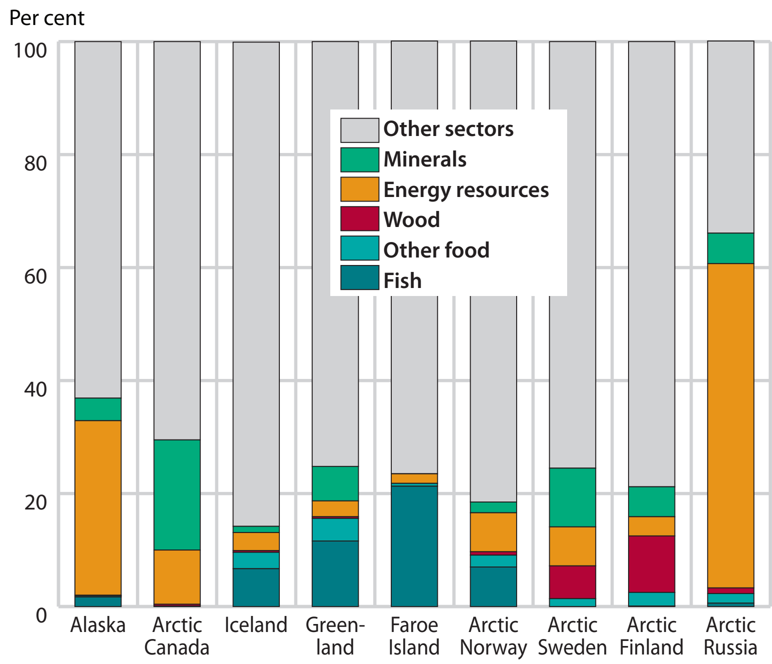

Figure 29. Value added in natural resource based industries in Arctic regions, 2005 (units US$1M).
Source: Glomsrød and Aslaksen (2009) and Marit Vågdal

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

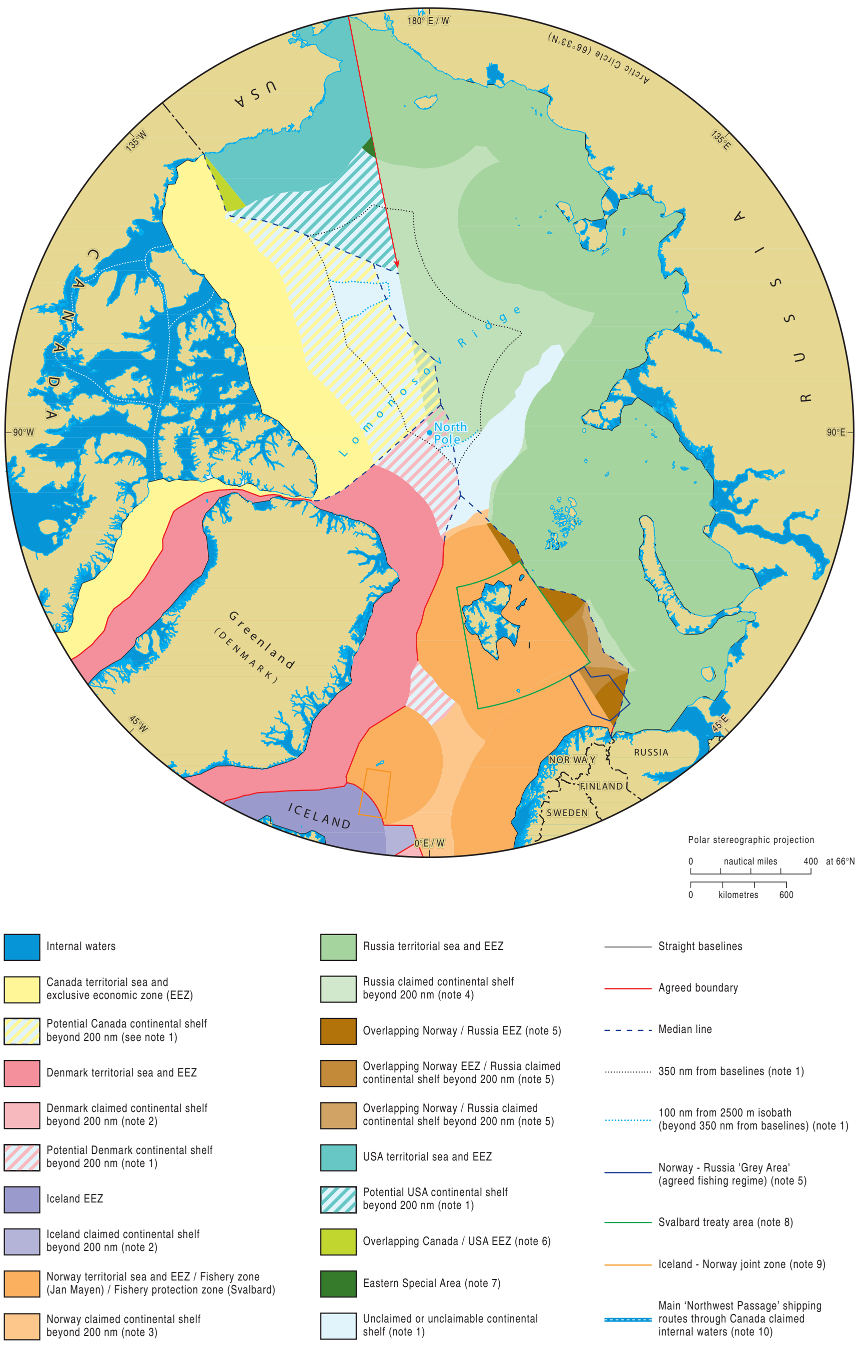

Figure 32. Maritime jurisdiction and boundaries in the Arctic region.
Source: International Boundaries Research Unit, Durham University, UK (www.dur.ac.uk/ibru/resources/arctic)

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).