# Chapter 28. Polar Regions

**Coordinating Lead Authors**
Oleg A. Anisimov (Russian Federation), Joan Nymand Larsen (Iceland)

**Lead Authors**
Anne Hollowed (USA), Nancy Maynard (USA), Pål Prestrud (Norway), Terry Prowse (Canada), John Stone (Canada)

**Contributing Authors**
Terry Callaghan (UK), Andrew Constable (Australia), Peter Convey (UK), Andrew Derocher (Canada), Bruce C. Forbes (Finland), Solveig Glomsrød (Norway), Dominic Hodgson (UK), Eileen Hofmann (USA), Grete K. Hovelsrud (Norway), Gita L Ljubicic (Canada), Harald Loeng (Norway), Eugene Murphy (UK), Steve Nicol (Australia), Alexander Sergunin (Russian Federation), Phil Trathan (UK), Barbara Weinecke (Australia), Fred Wrona (Canada)

**Review Editors**
Maria Ananicheva (Russian Federation), Terry Chapin (USA)

**Volunteer Chapter Scientist**
Vasiliy Kokorev (Russian Federation)

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## Executive Summary

The impacts of climate change on the Arctic must be seen in the context of other interconnected factors such as demography and culture, economic developments, environmental changes caused by factors other than climate, land use changes and health. [28.4.1, 28.2.5.1] There is evidence that climate change has exacerbated existing vulnerabilities (*medium confidence*). Strategies to adapt to climate change also have the potential to effectively address sustainable development. [IPCC AR4 WGII]

The decline of Arctic sea-ice in summer is occurring at a rate that exceeds previous projections (*high confidence*). Evidence of similar accelerated rates of change in the cryosphere is emerging in Antarctica. There is some evidence, for example in the reduction of sea-ice extent in the Arctic and in the west Antarctic Peninsula, that the changes are non-linear, and may be accelerating. [IPCC AR5 WGI] The rate rather than the magnitude of changes in the Arctic may become a key factor leading to dramatic impacts on natural and social systems if it exceeds the rate at which systems can adapt (*low to medium confidence*). [28.4.2] While at the time of ACIA (2005) these were largely based on modeling, we now have some examples of such processes taking place.

The breeding cycle of some copepods, shellfish and fish in the Arctic coincides with the spring bloom that enhances the survival. Shifts in the timing and spatial distribution of seasonal production could disrupt the matched phenology leading to decreased survival. In addition, the loss of sea ice in summer is expected to enhance secondary pelagic production with associated changes in the energy pathways within the marine ecosystem. These changes are expected to alter the species composition and carrying capacity of pelagic and benthic marine habitats with associated impacts on the ability of the region to support marine fish and shellfish populations (*medium confidence*). [28. 2.2.1]

The abundance and biomass of deciduous shrubs and grasses has increased substantially over large – but not all – parts of the Arctic tundra in recent years. It is very likely that most of this increase in biomass can be attributed to longer growing seasons and higher summer temperatures. The tree line has moved northwards and upwards in many Arctic and alpine areas, respectively. Although there is *high confidence* that the tree line has not shown a general circumpolar expansion in recent decades, *in situ* increases in tall shrubs are significant in certain sectors. Other factors like changes in herbivore grazing, anthropogenic disturbances, and changes in precipitation and the snow/water regime also influence the tree line and structural vegetation changes in the tundra. [28.2.3.2, 28.2.3.3]

Climate change is impacting terrestrial and freshwater ecosystems in some areas of the Arctic and Antarctica due to the direct effects of increased temperatures on the duration and extent of ice free periods and thaw in summer (*very high confidence*), and through the indirect effects of temperature on climate which have caused changes in the precipitation-evaporation balance (*medium confidence*). [28.2]

Many maritime Antarctic lakes have experienced extended open-water periods allowing the water and sediments to absorb more solar energy which has further warmed the lakes during winter. Summer phytoplankton levels have increased significantly together with higher nutrient inputs from exposed fellfield soils and thawed ground (*very high confidence*). [28.2.1.2] In continental Antarctica non-dilute lakes with a low lake depth to surface area ratio have been susceptible to inter-annual and inter-decadal variability in the water balance (*high confidence*).

Where change leads to increased energy availability (warming) in combination with increased water availability, native terrestrial biota respond with increased productivity, biomass and development of community complexity (*high confidence*). However, these responses are potentially confounded by multiple stressors, including human activities in the same ice-free areas as the biota (stations, tourism) and, on subantarctic islands and the Antarctic Peninsula, recovery of Antarctic fur seal populations from near extirpation due to sealing in the 18th to 20th centuries (*very high confidence*). [28.2.3.2]

Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous taxa, the majority likely to arrive through direct human assistance, which poses the greatest threat to terrestrial plant and animal communities in the future (*high confidence*). [28.3.3.2]

Environmental changes and ecosystem responses in the marine environment differ between ecological regions within both the Antarctic and Arctic, largely as a result of differences in the changes to sea ice dynamics and surface temperature. Off the Western Antarctic Peninsula, ecological communities have responded to changes in temperature and declines in sea ice. In the Ross Sea increases in sea ice have also had direct but different ecological effects. Ecological responses to future physical and chemical changes will also differ between regions (*high confidence*). [28.3.2]

The changing sea ice environments off the Western Antarctic Peninsula and in the Arctic have resulted in measurable changes in phytoplankton communities. [28.2.2] In the Western Antarctic Peninsula region, krill production has been linked to sea ice extent and duration. Further sea ice changes are likely to have a negative effect on krill populations and on the species that depend on them (*high confidence*). [28.2.2.2]

Changes in populations of many Antarctic predators are well documented. [28.2.2.2] Some species, such as Antarctic fur seals and humpback whales, are increasing as they recover from past exploitation (*very high confidence*). Decreases in populations of other species (chinstrap and Adelie penguins on the Western Antarctic Peninsula) have been associated with long-term changes in physical properties such as sea ice (*medium confidence*). [28.2.2.2] Future trends in populations of vertebrate species will be a complex response to multiple stressors. [28.3.2.2]

Impacts on the health and well-being of Arctic residents from climate change are projected to be significant and increase – especially for indigenous peoples (*high confidence*). [28.2.4] Impacts include injury and risk from extreme and unpredictable weather; changing ice and snow conditions compromising safe and predictable hunting, herding, and fishing; food insecurity and malnutrition due to decreased access to local foods; increased social and economic problems due to loss of traditional livelihood and culture; contamination of water and food; increases in infectious diseases; permafrost and erosion damage to homes and infrastructure, loss of homelands and forced relocation of communities. These impacts are expected to vary among the highly diverse settlements which range from small, remote predominantly indigenous to large industrial settlements (*high confidence*). With rising temperatures, comprehensive adaptation strategies based upon combined traditional and scientific knowledge as well as local community involvement is needed to address projected health impacts of the changing Arctic climate. [IPCC AR4 WGII, 28.2.4]

Traditional livelihoods and food security of Indigenous Peoples in the Arctic are being impacted by the current rate of climate change and when seen in combination with the effects of globalization and resource development these impacts are projected to increase significantly in the future (*high confidence*). [28.2.7, 28.2.4] These impacts are directly affecting indigenous peoples' ways of life and access to traditional foods, such as marine mammals, reindeer, fish and shellfish which have provided sustenance, cultural, religious, economic, medicinal, and community health for many generations. However, Arctic Indigenous Peoples have a high adaptive capacity to highly variable conditions and have begun to develop novel solutions to adapt to climate change through developing systems to monitor and predict weather, snow and ice changes; creating Indigenous Arctic observing networks; integrating data into decision and policy-making processes; and co-producing climate studies with scientific partners. [28.2.7]

Climatic and other large-scale changes can have potentially large effects on Arctic communities where relatively small and narrowly based economies leave a narrower range of adaptive choices. [28.2.6.1.5] It is projected that there will be significant impacts on the availability of key subsistence foods as climate continues to affect marine and terrestrial species. Increased economic opportunities and challenges for culture, security and environment, are expected with the increased navigability of Arctic marine waters and the expansion of land- and fresh water-based transportation networks (*high confidence*). [28.2.6.1.4]

## 28.1. Introduction

The conventional definition of the Polar regions is based on geographic features. Previous IPCC reports define the Arctic as the area within the Arctic Circle, and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58ºS (IPCC, 2001). There are many other definitions of the polar regions based for instance on the northern treeline, +10º C July temperature isotherms, zones of continuous permafrost on land, sea ice extents on the Ocean, and most recently in the South an 'environmental domains analyis' of physical environmental properties (Barcits, 2000; Morgan et al. 2007; Selkirk 2007; Terauds et al. 2012). Within the territories of each of the eight Arctic countries the boundary is defined individually, while the marine boundary has been established by international agreements. For the purpose of this report we follow the approaches adopted in the Arctic Climate Impact Assessment (ACIA) and Antarctic Climate Change and the Environment (ACCE) report (ACIA 2005; Turner et al. 2009; Convey et al. 2009). These both incorporate a degree of flexibility when describing the regions in relation to particular subjects. In this report we take this approach over both, while using the conventional IPCC definition of the Polar regions as a basis.

The Arctic Ocean is bordered by the northern regions of the North American, Greenland and Eurasian land masses (Figure 28-1). The deep basins of the Arctic Ocean are surrounded by shallow shelf marine ecosystems (Figure 28-1). The physical oceanography of the Arctic Ocean is primarily influenced by sea ice, advection of Atlantic and Pacific water, freshwater runoff from land, and winds forced by the Arctic oscillation. The declination of the earth insures that during winter months the Arctic Ocean and its neighbouring seas will remain cold, dark and ice covered and summer growing seasons will continue to be shorter than at lower latitudes (Wang, 2009). Topographic features, sea ice, the confluence of water masses and currents create salinity and temperature fronts that define the major marine ecosystems of the Arctic (Carmack, 2006)( Stabeno et al. 2011, Stabeno 2010). Strong advection of warm saline Atlantic water enters the Arctic Ocean through Fram Strait Strait (Drinkwater, 2011). South of Spitsbergen, the northward flow bifurcates along the Polar Front and flows into the Barents Sea. In the Pacific, weak flow of lower salinity high nutrient waters enters the Arctic Ocean from the eastern Bering Sea across the Bering Strait (Figure 28-1;(Danielson *et al.*, 2011)). In the Arctic Ocean, water stratifies in response to temperature and salinity with cool low salinity deepwater along the bottom overlain by warm saline Atlantic water, overlain by lower salinity cooler Pacific water topped with low salinity surface water (Carmack, 2006). Water exits the region along the eastern coast of Greenland and through Baffin Bay. It is unclear how Climate Change will impact the strength of flow into the Arctic Ocean and how these changes would impact the water mass structure of the Arctic Ocean (IPCC WG 1).

[INSERT FIGURE 28-1 HERE
Figure 28-1: Location maps of the North and South polar regions. Source: IPCC, 2007. [Note: WGII AR4 Figure 15.1 to be updated, including the addition of major currents. Credit: P. Fretwell, British Antarctic Survey.]]

In recent decades, reductions in sea ice thickness and extent have been observed in the Arctic (Grebmeier *et al.*, 2010)(Wang, 2009) (SWIPA 2011, IPCC WG 1). These changes lengthened the summer open-water season and reduced the formation of thick multiyear sea ice. Observations since AR4 show the pace of the loss of sea ice in the Arctic exceeded that previously predicted. Model inspection revealed that models that incorporated seasonality in atmospheric forcing tracked the observed pattern of sea ice loss. Revised forecasts based on seasonally adjusted models indicate that the Arctic is likely to be ice-free in summer by mid century (Wang, 2009) (SWIPA 2011).

In the south, the Antarctic land mass is surrounded by the waters of the Southern Ocean. Habitats in the Southern Ocean are differentiated, zonally, by the continental shelf, the sea ice extent in summer and winter and the different oceanic fronts and, meridionally, by the Ross and Weddell Gyres, the Scotia Arc in the southwest Atlantic, the Kerguelen Plateau in the Indian sector, and the Macquarie Ridge and seamounts to the north of the Ross Sea in the western Pacific sector (Experts Workshop on Bioregionalisation of the Southern Ocean (September 2006 : Hobart) *et al.*, 2006). The complexity of interactions between seasonality in light and sea ice, the Antarctic Circumpolar Current, the continental system, atmospheric dynamics and the latitudinal variation in these interactions results in substantial differences in climate change impacts on ecosystems in different regions of the Southern Ocean (Nicol *et al.*, 2008; Smetacek and Nicol, 2005) (Constable and Doust, 2009) (Montes-Hugo *et al.*, 2009) (Trathan *et al.*, 2011) (Trivelpiece *et al.*, 2011).

In the terrestrial and freshwater (and to some extent the nearshore marine) realms, Antarctica is conventionally considered, based on consistent biological and climatic characteristics, in three broad-scale biogeographic regions, the sub-Antarctic (oceanic islands near the Polar Frontal Zone), maritime Antarctic (western Antarctic Peninsula and Scotia arc archipelagos), and continental Antarctic (bulk of the continental landmass plus the eastern Antarctic Peninsula), although this formulation is now recognised to be incomplete (most recently reviewed by Chown & Convey 2007; Terauds et al. 2012). As with the Southern Ocean, there are considerable differences in climate change processes and their ecosystem impacts on land in different parts of Antarctica (Chapin et al. 2005; Mayewski et al. 2009; Turner et al. 2009; Convey et al. 2009).

Rapid alterations in Arctic and Antarctic climates are triggering rapid and unexpected changes, including "tipping points" (*a point at which a relatively small perturbation causes a large change in the future state of a system*), in polar ecological and socio-economic systems. As such, the Polar regions provide a forewarning of the kind of complex, non-linear changes that are expected to unfold elsewhere on the planet later this century and, as such, can provide valuable lessons for societies elsewhere (Wassman and Lenton, 2012).

#### *Summary of Knowledge Assessed in other Reports (including IPCC, ACIA, SWIPA, etc.)*

Several international climate assessments, including the IPCC (2001, 2007), ACIA (2005), Snow, Water, Ice and Permafrost in the Arctic (SWIPA, 2011), and the State of the Arctic Coast 2010 (2011) reports and the Antarctic Climate and the Environment (Turner *et al.*, 2009a), draw a consistent pattern of climatic and environmental changes in the Polar regions, as well as climate-driven societal and economical changes in the Arctic in the beginning of the 21st century.

Here we summarize the key findings of these assessments.

*Arctic*

Since 1980 the annual average temperature in the Arctic has been warming at approximately twice the global rate (SWIPA 2011). Sea ice declined at an unprecedented rate reaching the absolute minimum of 4.7 million km$^2$ in 2007 with 2008, 2010 and 2009 having the second, third and fourth rank since the beginning of satellite observations in 1979. Sea ice is getting thinner and younger, about 70% of it is 1-2 years old, and 95% is younger than 5 years. With less ice the Arctic seas absorb more heat which leads to the further reduction in sea-ice and the more pronounced atmospheric warming in autumn close to the edge of the sea ice. The feedback is known as the albedo effect. The Arctic Ocean is projected to become nearly ice-free in summer within this century and likely within the next thirty to forty years.

The observed and expected future changes to the Arctic cryosphere impact Arctic society on many levels. There are challenges, particularly for local communities and traditional ways of life. There will also be new opportunities. Coastal settlements in the Arctic will become more vulnerable due to loss of the sea ice (SOAC 2011; SWIPA 2011). Transport options and access to resources are radically changed by differences in the distribution and seasonal occurrence of snow, water, ice and permafrost in the Arctic. Infrastructure in the Arctic faces increased risks of damage due to changes in the cryosphere, particularly the loss of permafrost and land-fast sea ice (SWIPA 2011).

Changes in the cryosphere will cause fundamental changes to the characteristics of Arctic ecosystems and in some cases loss of entire habitats. However, projections of these impacts on the structure and function of Arctic ecosystems involve uncertain and complex non-linear feedbacks, and “tipping points” may occur if tolerance thresholds are exceeded or species are unable to adapt adjust (Duarte et al. 2012; Wassman and Lenton 2012). The observed and projected changes to the cryosphere are expected to have consequences for people who receive benefits from these resources (SWIPA 2011).

The Arctic Climate Impacts Assessment report ACIA (2005) and the synthesis report SWIPA (2011) both concluded that the duration of snow cover and snow depth are decreasing in North-America while increasing in Eurasia. These changes in snow cover are, according to SWIPA (2011), already generating widespread human, ecological, and economic impacts which will probably intensify in the future.

The dominant response of Arctic terrestrial species to climate change, as in the past, is very likely to be relocation rather than adaptation (ACIA 2005). It is expected over time that forest will replace significant proportions of the tundra and that this again will have great effects on biodiversity which very likely will increase. The current rate of change, together with other stresses, will challenge the adaptive capacity of northern peoples (e.g. SWIPA 2011; AHDR 2004).

As argued in the AR4, the most effective adaptation options will be those that recognize the nexus between adaptation and sustainable development (Yohe et.al., 2007(IPCC WG2)). One consequence of this observation is the potential of “mainstreaming” adaptation into existing policy processes and priorities (such as those for poverty alleviation, health standards, emergency planning and insurance) leading to “win-win” options.

Although climate change and other processes affecting natural resources 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 (SOAC 2011).

The holistic perspective of indigenous culture suggests that efforts to understand, manage, and respond to change in Arctic local communities and coastal systems may benefit from the integration of this knowledge with Western science. Recognizing the value of traditional ecological knowledge may contribute to enhanced resilience and adaptive capacity in local and coastal communities (E.g. SOAC 2011; SWIPA 2010).

Arctic societies have a well-deserved reputation for resilience in the face of change. But today they are facing an unprecedented combination of rapid and stressful changes involving environmental processes, cultural developments, economic changes, industrial developments, and political changes. That may limit this resilience. To respond to the combination of multiple stressors Arctic societies will need to find the right mix of continuity and change (AHDR 2004).

*Antarctic*

The strongest rates of atmospheric warming seen in the Southern Hemisphere are occurring in the western Antarctic Pensinsula region of West Antarctica, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent. Temperatures over the bulk of the Antarctic continent have not changed markedly in recent decades, but this is thought to be a result of protection contributed to by the separate anthropogenic process of ozone hole formation, which has also contributed to a strengthening of the atmospheric polar vortex, increased average wind speeds over the Southern Ocean, and currently increasing trend of sea ice extent off East Antarctica. As the ozone hole repairs over the next century, this protection will decrease, and strongly increasing temperature and decreasing sea ice trends are expected to become apparent in these regions (ACCE, SASOCS (2009)).

On land and in freshwater environments across Antarctica, a complex range of responses to different specific climate changes have been identified. Strongly warming regions experience considerable glacial recession and snow loss, with resulting ground rapidly colonised by native communities, and greater productivity and biomass in these communities, whose members' existing physiological flexibility means that they are generally less rather than more stressed by the changed environmental conditions. Increased productivity and nutrient flows are also characteristic of freshwater environments. However, confounding threats to native ecosystems are provided by the increased likelihood of non-native species colonisation, and the strong direct relationship between this and human presence and activity, as well as synergy with climate change reducing the natural barriers to such colonisation and establishment (ACCE, SASOCS (2009)).

The thermal stability of the Antarctic marine environment provides a large contrast with that on land, as does the large native diversity and biomass present in shelf benthic ecosystems. The highly stenothermic adaptations and long life cycles characteristic of much of this fauna means they are thought to be unable or poorly able to cope with temperature increases of as little as 1-3°C, changes well within current predictions and trends for parts of this region over the next century. Future changes in sea ice are expected to result in major changes to ice disturbance patterns and diversity in benthic communities, mediated by increased impacts of scour from icebergs (Barnes & Souster 2011).

## 28.2. Observed Changes and Vulnerability under Multiple Stressors

### *28.2.1. Hydrology and Freshwater Ecosystems*

#### *28.2.1.1. Arctic*

Rivers and lakes within the Arctic high latitudes continue to show pronounced changes to their hydrology, which can have cascading effects on their aquatic ecology. One of the most conspicuous hydrologic changes has been to river flow. Previously noted increases in Eurasian river flow (1936-199) (Peterson *et al*., 2002) could not, for a similar period (1952-2000), be attributable with certainty to precipitation changes (Milliman *et al*., 2008), although decreases observed in the flow of major high-latitude Canadian rivers (1964-2000; average -10%) does match that for precipitation (Dery and Wood, 2005).

More recent discharge data (1977-2007) for 19 large circumpolar rivers indicates an average increase of +9.8%, with the flow of some (e.g., Lena and Yenisei) accelerating in more recent years (OVEREEM and SYVITSKI, 2010).

This has been accompanied by shifts in flow timing with the main month of snowmelt (May) increasing by an average 66% but flow in the subsequent month of peak discharge decreasing by ~7%. Earlier timing of the maximum spring flood has also found for a suite of Russian Rivers (~5d/[1960-2001]) and being most pronounced in eastern, colder continental climates that have experienced rises in air temperature (Shiklomanov *et al.*, 2007). Upward trends in air temperature, particularly in the coldest of the major Eurasian Arctic river basins rather than flow regulation, has been identified as the dominant control of such timing shifts (Tan *et al.*, 2011).

Although the magnitude of such earlier spring flow peaks on Eurasian rivers have not increased ((Shiklomanov *et al.*, 2007), the winter minimum flows have risen on many Eurasian and North American rivers (Smith *et al.*, 2007; St. Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007; Ye *et al.*, 2009); the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm *et al.*, 2010). Most such studies suggest that winter flows increases because of enhanced groundwater inputs from permafrost thawing (see WGI, Chapter 4), the concept supported in part by some satellite-gravity measurements (Muskett and Romanovsky, 2009). Others argue that the primary control is an increase in net winter precipitation minus evapotranspiration (Landerer *et al.*, 2010; Rawlins *et al.*, 2009a; Rawlins *et al.*, 2009b). Insufficient spatial coverage of Arctic precipitation stations precludes deciphering the relative importance of these two controlling factors.

Information about the changes to the hydrology and water budget of lakes is scarcer than that for rivers. Information from satellite thermal imagery, however, indicates that lake, surface water temperatures of large water bodies have been warming for the period 1985-2009 (Schneider and Hook, 2010). Greatest warming was observed for mid- and high latitudes of the northern hemisphere with the spatial patterns generally matching those for surface air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming.

Changes to terrestrial hydrologic and freshwater ice regimes have also produced a number of physical, geochemical and ecological effects on some arctic lake, wetland and river systems. Reduced ice cover accompanied by higher air temperatures and evaporation, have been identified as being responsible for the recent summer drying out of some Canadian High Arctic ponds, which had been permanent water bodies for millennia (Smol and Douglas, 2007). Where water has persisted and lake-water temperatures increased, organ carbon burial has likely been reduced because of a strong positive relationship with the mineralization of organic carbon in lake sediments (Gudasz *et al.*, 2010).

In the case of permafrost thermokarst lakes, new studies have documented changes in their size and number in various parts of the Arctic (Hinkel *et al.*, 2007; Marsh *et al.*, 2009; Riordan *et al.*, 2006). Their spatial patterns and rates of change, however, are not consistent and may be related to differing states/condition of the permafrost as well as spatial variations in warming (D. and Kirsten, 2010). Thawing permafrost has also been identified as causing major changes to the biogeochemistry of water entering high-latitude lakes and rivers (Frey and McClelland, 2009), and to have implications for their ecological structure and function (Lantz and Kokelj, 2008; MESQUITA *et al.*, 2010) (Thompson *et al.*, 2008), with some documented cases resulting in enhanced lake eutrophication through an ecological shift from pelagic-dominated to benthic-dominated production (Thompson *et al.*, in Submission).

The ecology of rivers has also been demonstrated to be dependent on changes to their freshwater ice regimes. Reductions in the dynamics of spring river-ice break-up (see WGI, Chapter 4) in the vast riparian zones of the Mackenzie River Delta has been observed to decrease the supply of ice-jam floodwaters and related nutrients and sediments to the delta's riparian zone, and hence, its ecological health (Lesack and Marsh, 2007). Such reductions in spring flood levels, combined with rising arctic sea level and sea ice recession, have also been proposed as the proximal drivers of biodiversity loss in this system. This is primarily related to the decline of lakes with short and variable hydrologic connection times, plus low and variable river water renewal (Lesack and Marsh, 2010). Because circumpolar river deltas act as biogeochemical processors of river water before its discharge to the Arctic Ocean (Emmerton *et al.*, 2008), changes in delta flooding are also likely to affect primary production and food web processes in the coastal marine ecosystem, although these remain to be assessed. Changes to some near-coastal freshwater environments have been documented for the case of epishelf lakes (Veillette *et al.*, 2008). Such ice-dependent freshwater lakes have become increasingly inundated with seawater as a result of the loss of integrity in their retaining ice dams (Vincent *et al.*, 2009), and as a result, the microbiologically rich ice-shelve lakes are disappearing (Mueller *et al.*, 2008).

### *28.2.1.2. Antarctic*

The majority of the Antarctic continent's hydrology and freshwater ecosystems occur as a vast network of lakes and rivers underneath the ice sheet. Nevertheless in supraglacial habitats, ice free coastlines, glacial forelands, sub-Antarctic islands, on exposed mountains and other ice free areas, the presence of liquid water in lakes, ponds, streams and in terrestrial habitats is essential to all forms of life. Antarctica also differs from the Arctic in not having any major river systems; those that do exist are mostly fed by seasonal glacial meltwater and restricted to the coastal oases. The largest river, the Onyx River in the McMurdo Dry Valleys, is just 32 km long with recorded flows of 0.01 $m^3S^{-1}$ to a single flood event of 30 $m^3S^{-1}$ (McKnight *et al.*, 2008). The rivers often flow for just a few weeks each year, but in this time supply lakes with freshwater and provide seasonal wetted areas that support a diversity of microbial communities. However, in comparison with the Arctic, the rivers provide only very minor discharges of freshwater to the global ocean, the main contribution being from calving glaciers and subglacial meltwater.

The instrumental record of changes in Antarctic hydrology and freshwater ecosystems is relatively short. The longest monitoring programs span 15-18 years (Lyons *et al.*, 2001; Quayle *et al.*, 2002) but data mining of single year datasets has allowed other parameters to be compared over similar timescales (Verleyen et al., 2012).

As in the Arctic systems, the response in aquatic systems partly depends on their thermal proximity to freezing, which applies critical limits to environmental responses including ice extent, snow cover, light availability, and albedo. Monitoring of Signy Island lakes (maritime Antarctic) from 1980 to 1995 indicates that the local climate increase of 2°C over the past 40 to 50 years has reduced both permanent terrestrial ice cover and albedo and extended open-water periods by up to 63 days allowing the water and sediments to absorb more solar energy which has further warmed the lakes during winter (Quayle *et al.*, 2002). As a result chlorophyll a concentrations show summer phytoplankton levels significantly increased in seven of nine oligotrophic lakes measured, and means rose from 1.4 mg/litre in 1981 to 3.5 mg/litre in the mid-1990s (maximum 6.8 mg/litre in 1995). More recently, streams have accumulated higher nutrient concentrations (especially dissolved reactive phosphorus (DRP) which increased 5 times and ammonium which increased 2.5 times) by draining exposed fell-field soils and thawed ground. Increased plant and microbial activity has also resulted in elevated autochthonous carbon production in lakes, much of which accumulates in the sediments. Thawing of permafrost in lake catchments has also been recorded elsewhere in Antarctica, increasing nutrient loads in subsurface waters and lake inflows (Burgess *et al.*, 1994) and altering lake trophic status (Laybourn-Parry, 2003).

Whilst warming has increased biological production in lakes changes in the balance between precipitation and evaporation can also have detectable effects on lake ecosystems through changes in water body volume and lake chemistry (Lyons, 2006; Quesada *et al.*, 2006). Verleyen et al (2012) compared repeat specific conductance measurements from lakes in the Larsemann Hills and Skarvsnes (East Antarctica) covering the periods 1987 to 2009 and 1997 to 2008, respectively and identified that non-dilute lakes with a low lake depth to surface area ratio were most susceptible to inter-annual and inter-decadal variability in the water balance, as measured by changes in specific conductance.

In the absence of long-term datasets lake sediments provide valuable records of responses to climate (Hodgson *et al.*, 2004). Studies on Signy Island have shown an increase in lake sediment accumulation rates since the 1950s that corresponds with the measured increase in atmospheric temperature (Appleby *et al.*, 1995). Similar increases in sediment accumulation rates have also been recorded in some marine cores (Domack *et al.*, 2003). In the Windmill Islands (East Antarctica) sediment records show that some lakes have recently become more saline (Hodgson *et al.*, 2006), and a number of ancient moss banks have become desiccated (Wasley *et al.*, 2006) due to increased evaporation and sublimation rates; possibly in response to the increased wind speeds. Other studies have tracked changes in the precipitation evaporation balance through the Holocene (Hodgson *et al.*, 2005; Roberts and McMinn, 1999; Roberts *et al.*, 2004; Verleyen *et al.*, 2004). Whilst the recent rapid warming has been recorded in some palaeolimnological proxies, few studies have focused on this period in the proxy records at sufficiently high resolution to determine if the changes are outside of the natural variability of the Holocene.

## *28.2.2. Oceanography and Marine Ecosystems*

### *28.2.2.1. Arctic*

Global warming is expected to affect Arctic marine ecosystems by: (1) altering the timing and extent of sea ice retreat, (2) changing sea water density through increased freshwater supply, (3) reducing sea ice thickness and multi-year ice formation which in turn changes the timing and duration of irradiance in the water column (Maslowski et al. 2012; Wassmann 2011)(Stabeno *et al.*, 2010). The expected rate and magnitude of these changes is documented by the IPCC Working Group 1. There is evidence based on observations and models that the Arctic Ocean is warming and this warming is leading to and reductions in the spatial extent of sea ice in summer and thickness of sea ice (Maslowski et al. 2012)(Stroeve *et al.*, 2007). Retrospective studies show the Arctic and its neighboring seas are influenced by interannual, decadal, and multi-decadal climate variations including the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008), the North Atlantic Oscillation (Kushnir, 1994), the North Atlantic Multidecadal Oscillation (Keenlyside *et al.*, 2008), the Pacific Decadal Oscillation (Mantua *et al.*, 1997), and the Arctic Oscillation (Thompson and Wallace, 1998). These variations in climate forcing are expected to continue in the future (OVERLAND and WANG, 2010) and will likely influence the ocean conditions in the Arctic (Ogi et al. 2010; Rigor et al. 2002). For example, recent (2007-2012) ocean conditions in the Bering Sea have been cold (Stabeno *et al.*, ).

Observations and model predictions indicate that the Arctic Ocean is vulnerable to ocean acidification. Cold temperatures and ocean mixing patterns that are found in Arctic Ocean increase the solubility of $CO_2$ creating an environment with naturally low carbonate ion concentrations (Fabry *et al.*, 2009). Elevated $CO_2$ concentrations, enhanced air-sea exchange due to reduced summer ice cover, and freshening of the waters due to glacial runoff and thawing permafrost are expected to decrease the pH in the Arctic (Denman *et al.*, 2011; Steinacher *et al.*, 2008a). The acidification of the Arctic means that some regions of the Arctic will be understaturated with respect to aragonite, the primary structural component of the shells of marine califiers such as pteropods (small planktonic shelled mollusks), urchins, clams and crabs (Chierci, 2009; Fabry *et al.*, 2009; Yamamoto-Kawai *et al.*, 2009). Surface waters in the Canada Basin have been observed to be understaturated with respect to aragonite (Yamamoto-Kawai *et al.*, 2011). Laboratory experiments showed a decline in the calcification of a pteropod (*Lamacina helicina*) in the Arctic under projected acidification (Comeau *et al.*, 2010). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on this species (Orr et al. 2009). The lack of systematic sampling over large areas of the arctic and the paucity of experimental studies examining the response of marine organisms to multiple stressors impede the ability to project when and where waters will become understaturated in aragonite in the Arctic and the vulnerability of calcifying marine organisms to understaturated waters.

Climate change impacts the timing and magnitude of primary production. Two sources of primary production include spring and fall ice algal blooms and pelagic blooms in response to the solar cycle and stratification (Wassmann 2011). Considerable geographic variation in primary production has been observed (Grebmeier, 2012a; Lee *et al.*, 2010). With the onset of the Arctic summer sea ice begins to melt and the water column stratifies. The upper mixed layer of the Arctic Ocean is nutrient-rich and the combination of increased light and nutrients triggers spring bloom (Zhang *et al.*, 2010). Changes in temperature and wind-driven upwelling of deep nutrient-rich waters will alter sea ice thickness, the date of ice breakup and stratification will alter the timing, duration and magnitude of summer production (Zhang *et al.*, 2010). Simulation models show gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad *et al.*, 2011). Satellite derived estimates of primary production provide evidence of increased primary production in response to extended ice free periods during summer have been documented (Arrigo *et al.*, 2008b). Studies based on a short (5 year) time series in the Canadian Basin suggests that warmer ocean conditions will favor small phytoplankton over large phytoplankton (Li *et al.*, 2009)(MORÁN *et al.*, 2010) but additional observations over a broader spatial scale are needed to confirm this relationship.

Copepods (pelagic crusteceans that are a major prey of fish) tend to dominate the Arctic with regional differences in species composition. These copepods occupy different regions of the Arctic and they exhibit different strategies for survival. *Calanus finmarchicus* are common in the Barents Sea, *C. glacialis* dominates the western shelf along the Canadian basin and the White Sea, and has been observed in the Chukchi Sea. *C. hyperboreus* is a deep water species found in the Greenland Sea, Fram Strait, the Labrador Sea, the Baffin Sea and the Arctic Ocean Basin (Falk-Petersen *et al*., 2009). *Neocalanus cristatus* and *N. flemingeri*, *C. marshallae* has been reported in the southeastern Bering Sea middle domain (Baier and Napp, 2003; Grebmeier, 2012b). *Metridia longa* has been observed in the Beaufort Sea. These large copepods use different strategies to overwinter. *M. longa* continues feeding and remains active through the winter (Seuthe *et al*., 2007). It is hypothesized that *C. marshallae* are able to overwinter on the shelf of the southern Bering Sea and it is known that *C. finmarchicus* overwinter in deeper waters over the slope of the northeast Norwegian Sea (Gaardsted *et al*., 2011). *C. hyperboreus* is the dominant mesozooplankton in the Greenland Sea (Hirche and Niehoff, 1996), and also found in the Arctic Ocean (Kosobokova and Hirche, 2009). *C. hyperboreus* undergoes diapause to save energy during winter (Seuthe *et al*., 2007).

In the north, the initiation of spring primary production is delayed due to the persistence of sea ice and the light cycle. Zooplankton blooms are also delayed until July and August (Falk-Petersen *et al*., 2009) (Wassmann 2011). In the Barents Sea, a large fraction of the phytoplankton biomass is retained in the pelagic system by zooplankton grazing (Wexels Riser *et al*., 2008), while farther north in the Chukchi Sea low grazing pressure results in underutilization of early spring production which in turn leads to export of carbon on the seafloor where it feeds a productive benthic ecosystem (Grebmeier *et al*., 2006; Wexels Riser *et al*., 2008). Factors that alter the timing and duration of phytoplankton production could disrupt the match between copepod hatch dates and spring production which in-turn would impact the survival of zooplankton and timing of spring prey availability for their predators (Søreide *et al*., 2010). In a future more productive Arctic Ocean *C. hyperboreus,* with its extended life cycle, may be able to exploit the conditions in the Arctic Ocean (Slagstad *et al*., 2011). Shifts in ocean temperature may also change the species composition of zooplankton. Observations over a short time period in the southeast Bering Sea showed *Calanus marshallae* were more abundant in cold years than warm years (COYLE *et al*., 2011).

Krill (*Thysanoessa sp*.) are an important component of marine ecosystems representing an important prey item of several dominant pelagic fishes in the region (Orlova *et al*., 2009; Ressler, P.H., A. DeRobertis, J. D. Warren, J. N. Smith,S.Kotwicki, In Press). In the Chukchi and Beaufort Seas, euphausiids (*T. inermis and T. raschii*) have been observed but are not considered endemic to the region (Berline, L., Y.H.Spitz, C.J.Ashjian, R. G. Campbell, W. Maslowski,S.E.Moore, 2008). In the Barents Sea a variety of euphausiids have been observed including *T. inermis* and *T. longicaudata*. Examination of the size and life stage of krill revealed that euphausiids are probably advected into the Arctic from the Bering Sea and intrusions of Atlantic water (Berline, L., Y.H.Spitz, C.J.Ashjian, R. G. Campbell, W. Maslowski,S.E.Moore, 2008; Dalpadado *et al*., 2008). Factors that influence the water temperature and the speed and direction of currents through Bering and Fram Straits are likely to influence the availability of euphausiids in the Chukchi Sea and Beaufort Sea regions.

The broad shelf regions of the Barents and Bering Seas support abundant and diverse fish and shellfish populations. Farther north, fewer fish species are adapted to the short growing season, the delay in the emergence of copepods and the cold ocean conditions. In general, dominant pelagic species are smaller sized fish capable of rapid growth in the first year of life (e.g. capelin, *Mallotus villosus*) and in some cases antifreeze proteins to tolerate cold temperatures (e.g. polar cod, *Boreogadus saida*). Examination of the biogeography of species shows that potentially interacting species partition their habitat vertically and horizontally in response to competition, predation and environmental disturbance (Mueter, 2008; SPENCER, 2008). Habitats are bounded by topographic features, fronts, currents or river plumes, and oceanographic features left by sea ice including salinity fronts, and the cold water mass that forms in summer along the sea floor in the Bering Sea (the cold pool) (Ciannelli and Bailey, 2005; Hollowed, A. B., S. Barbeaux, E. Farley, E. D. Cokelet, S. Kotwicki, P. H. Ressler, C.Spital,C.Wilson, In Revision). Over time fish and invertebrates have evolved life histories to reduce exposure to predation, maximize the probability of temporal and spatial overlap with prey concentrations, and support successful mating (Bouchard, 2011; Hollowed, A. B., S. Barbeaux, E. Farley, E. D. Cokelet, S. Kotwicki, P. H. Ressler, C.Spital,C.Wilson, In Revision; Hunt *et al*., 2011; Mundy, 2011; Sundby and Nakken, 2008).

Examination of historical responses of fish to climate shifts and associated changes in ocean conditions suggests that climate change will impact the growth, spawning and feeding distribution and potentially will cause shifts in species dominance (Gjosaeter, H., B. Bogstad,S.Tjelmeland, 2009; Kenneth F., 2011). Modeling studies project that climate change will shift the bio-climate envelopes of marine fish stocks resulting in an increase in biodiversity in the Arctic (Cheung *et al*., 2009). Retrospective analysis of the spatial distribution of demersal fish species in the North Atlantic shows redistribution of some species along latitudinal and depth gradients that are consistent with bio-climate envelope models (Simpson *et al*., 2011). Numerous studies from the Bering Sea, Barents Sea, West Greenland, and Chukchi Sea have demonstrated that fish respond to climate induced changes in ocean temperature (Hjálmar Hátún *et al*., 2009; Valdimarsson *et al*., 2012) (Wassmann et al. 2011). However, responses to climate change may emerge nonlinear responses in the future because multiple factors influence the spatial distribution and abundance of marine fish throughout its life cycle including: suitable habitat availability, fidelity to spawning locations, diet diversity, physiological responses, spatial temporal overlap with prey, prey density, and competition (Kristiansen *et al*., 2011; Planque *et al*., 2010; Sigler *et al*., 2011).

#### *28.2.2.1.1. Current changes in Arctic seabird populations*

Upwelling or convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds. (i.e.(Irons *et al*., 2008)). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability and, thus, potentially have strong negative impacts on seabird populations (Gremillet D. and Boulinier T., 2009).

Such spatial mismatch between prey base and breeding has been documented for a few seabird populations. The percentage of important prey in the diet of a declining black guillemot (Cepphus grylle) population in the western Beaufort Sea was highly negatively correlated with changes in the distance to the ice edge which was the habitat of the prey (Moline *et al*., 2008).

Even though timing of breeding advanced for Brünnichs guillemots (Uria lomvia) in a colony in the southernmost part of its range in Arctic Canada over a 25 years period, it did not advance sufficiently to match the advance in break up of sea ice which is associated with high prey availability. Less ice cover was correlated with lower chick growth rates and lower adult body mass, suggesting that reduction in summer ice extent had a negative effect on reproduction (Gaston *et al*., 2005b; Gaston *et al*., 2009). Current trends suggest that continued warming should benefit birds breeding on the northern limit of the species range, while adversely affecting reproduction for those on the southern margin.

In contrast, (Byrd *et al*., 2008) could not document any significant correlation between productivity of brünnichs guillemots and common guillemots (Uria aalgae) breeding on the Pribilof islands in the Bering Sea and changes in sea ice extent over a 30 year period. Kittiwakes (Rissa tridactyla and Rissa brevirostris), however, breeding in colonies on the same islands, advanced their timing of breeding by half to almost one day per year and reduced their productivity in correlation with less sea ice and higher Sea Surface Temperatures (SSTs). In the North-Atlantic Svalbard islands, kittiwakes responded differently - by showing a non-significant trend for later egg-laying when SSTs increased and ice cover was reduced (Moe *et al*., 2009).

The circumpolar populations of the two closely related common guillemot and Brünnichs guillemot declined when the SST shift was large and increased when the shift was small, although the effect differed between the Arctic-breeding species and the more temperate-breeding congener (Irons *et al*., 2008). A major ecosystem shift in the Northern Bering Sea ten years ago caused by increased temperatures and reduced seaice cover had a negative impact on benthic prey for diving birds like eiders and these populations in the area have declined (Grebmeier *et al*., 2006).

Karnovksy et al. (2010) projected changes in SST in the Greenland Sea at the end of the 21st century and concluded that 4 of 8 little auk (Alle alle) breeding colonies in the North Atlantic may be negatively impacted as temperatures exceed the thermal preferenda of large copepods (Calanus), their main prey. Little auks in Svalbard also responded by advancing the date for egg-laying when SSTs increased and seaice cover was reduced (Moe *et al*., 2009).

The contrasting results from the relatively few studies of impacts of climate change on arctic seabirds, demonstrates that it is likely that future impacts will be highly variable between species and between populations of the same species. Retreating sea ice and increasing SSTs have favored some species and been a disadvantage to others. While phenological changes and changes in productivity of some breeding colonies related to climate changes have been observed, changes in population size or projected expansion of the northern range accompanied by a contraction of the southern range is not well documented (Gaston and Woo, 2008).

The coupled oceanographic models and ice models project a significant reduction in sea ice extent in this century and increasing SSTs in the Arctic. The high Arctic seabird species partly or completely dependent on the productivity of the sympagic ecosystem or the cold Arctic waters close to the ice-edge, like the ivory gull, Brünnichs guillemots and little auks, will very likely be negatively impacted if the projected changes in these physical parameters occur. A moderate retreat of the marginal ice-zone and earlier break-up of sea ice may improve foraging conditions for some of these sea bird populations in the northernmost part of their range (Gaston *et al.*, 2005a). The distance to suitable nesting localities could be too great (within 200 km) for the birds to utilize the marine productivity in the ice edge zone if a main part of the zone stays over the deep Arctic Ocean during the breeding season.

A general increase in SSTs and retreat of the ice cover will likely improve the environmental conditions and food abundance for sea bird species that have their range in the southern part of the Arctic or south of the Arctic. A poleward expansion of the range of these species is expected during a continued warming (ACIA 2005). Several other factors than climate influence on the dynamics of sea bird populations (Regular *et al.*, 2010), however, and projections of future changes during a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA 2005). At present, the resolution of AOGCMs is not detailed enough to project spatial changes in mesoscale oceanographic features like frontal zones and eddies of importance to sea birds in the Arctic.

#### *28.2.2.1.2. Polar bears*

Understandingthe impacts of climate change on polar bears (Ursus maritimus) has developed extensively recently with both empirical and modelling studies (Amstrup *et al.*, 2010; Durner *et al.*, 2009; Hunter *et al.*, 2010; Laidre *et al.*, 2008; Molnar *et al.*, 2011a; Molnár *et al.*, 2010a). While empirical studies provide the most direct insight into the mechanisms of change, modelling studies allow a more complete understanding of conservation status.

Sea ice is the primary habitat of polar bears and is used for migration, mating, some maternity denning, and access to prey. Annual sea ice over the continental shelves is the preferred habitat due to higher density of prey than offshore areas (Durner *et al.*, 2009). There is high agreement and robust evidence that the primary conservation concern for polar bears, over the foreseeable future or three generations (ca. 36-45 years), is the recent and projected loss of annual sea ice over continental shelves, decreased sea ice duration, and decreased sea ice thickness (Amstrup *et al.*, 2010; Derocher *et al.*, 2004; Durner *et al.*, 2009; Hunter *et al.*, 2010; Rode *et al.*, 2012; Sahanatien and Derocher, 2012; Stirling and Parkinson, 2006; Stirling and Derocher, 1993).

Indicators of subpopulation stress vary geographically reflecting differences in sea ice change and monitoring intensity. Only 2 of the 19polar bear subpopulations,Western Hudson Bay subpopulation (Regehr *et al.*, 2007) and the Southern Beaufort Sea subpopulation (Regehr *et al.*, 2010; Rode *et al.*, 2010a) have data series adequate for clear identification of subpopulation-level effects related to climate change.Other subpopulations lack adequate time series but elements associated with decline are being detected. For example, declining body condition in Baffin Bay was associated with sea ice loss while in the adjacent subpopulation in Davis Strait, a decline in body condition was related to high bear density or sea ice loss (Rode *et al.*, 2012). Similarly, late arrival of sea ice at one denning area in the Barents Sea was associated with lower body mass of both mothers and their cubs at den emergence (Derocher *et al.*, 2011). There is high confidence with moderate evidence and high agreement that the primary conservation concern for polar bears is sea ice change that result in habitat loss and fragmentation causing reduced food intake, increased energy expenditure, and increased fasting (Amstrup *et al.*, 2010; Derocher *et al.*, 2004; Mauritzen *et al.*, 2003; Regehr *et al*., 2007; Sahanatien and Derocher, 2012; Stirling, I., Lunn, N., Iacozza,J., 1999; Stirling and Derocher, 1993). Only moderate evidence exists for the effect of loss of annual ice over continental shelves on polar bears because the effects of climate change on polar bears are complex and only documented in some subpopulations in the early stages of predicted effects. There is robust evidence and high agreement for declining sea ice (i.e., habitat loss) resulting in altered energy status (i.e., body condition) for polar bears that can reduce both individual growth rates and body condition(Rode *et al*., 2010a; Rode *et al*., 2012). There is very high confidence that reduced body condition associated with sea ice loss is a precursor to demographic change. There is robust evidence that reduced body mass linked to longer ice-free period or reduced ice cover over continental shelves results in lower fasting endurance, lower reproductive rates, and lower survival (Molnar *et al*., 2011b; Regehr *et al*., 2007; Regehr *et al*., 2010). There is robust evidence and high agreement that lower body mass lowers reproduction and decreases survival rates which reduce subpopulation growth rate orcause subpopulation decline (Derocher and Stirling, 1998; Derocher and Stirling, 1996; Hunter *et al*., 2010; Regehr *et al*., 2010; Robinson *et al*., 2011; Rode *et al*., 2010a; Stirling, I., Lunn, N., Iacozza,J., 1999). The Southern Beaufort Sea has approximate 1500 bears but is projected to decline to about 1% of this number by 2100 with a probability estimated at 0.80-0.94 with projected warming (Hunter *et al*., 2010). The adjacent Northern Beaufort Sea subpopulation is currently stable, and might have increased, although future decline is predicted if observed sea ice declines continue (Stirling *et al*., 2011). Several additional studies have tentatively linked changing environmental conditions tocannibalism (Amstrup *et al*., 2006), altered feeding (Cherry *et al*., 2009), unusual hunting behaviour (Stirling *et al*., 2008), and diet change (Iverson *et al*., 2006)(Thiemann *et al*., 2008). There is medium confidence that these observations of polar bear are related to changing sea ice conditions.

Declines in survival and reproduction are manifest in subpopulation declines. There is robust evidence and high agreement for downward trends for polar bear abundance in the foreseeable future and such trends are linked to changes in sea ice (Amstrup *et al*., 2010; Durner *et al*., 2009; Molnar *et al*., 2011b; Molnár *et al*., 2010b; Stirling and Parkinson, 2006; Wiig *et al*., 2008). There is very high confidencethat lower reproductive rates and reduced survival rates arerelated to climate change. There is robust evidence for subpopulation declineby over 21% between 1987 and 2004 in Western Hudson Bay related to climate change (Regehr *et al*., 2007). There is moderate evidence for recent decline and longer-term drastic decline by the end of the 21st century in the Southern Beaufort Sea related to sea ice conditions (Hunter *et al*., 2010; Regehr *et al*., 2010). Projected extirpation of approximately two thirds (2/3) of the world’s polar bears is predicted for the middle of this century (Amstrup *et al*., 2008). Aspects of this study were criticized (Armstrong *et al*., 2008) but were refuted (Amstrup *et al*., 2009). The conclusion of (Amstrup *et al*., 2008) is consistent with other studies and has robust evidence with medium agreement. While projected extinction of polar bears has moderate evidence, there isvery high confidence that subpopulation extirpation will occur over a broad geographic area with climate change.

Multiyear ice is used by polar bears in some subpopulations at the maximal ice melt (Ferguson *et al*., 2010). Replacement of multiyear ice by annual ice could increase polar bear habitat (Derocher *et al*., 2004) but there is limited evidence of such habitat improvement. Loss of multiyear ice as a refuge may pose difficulties for some subpopulations although there is limited evidence. Increasing the distance to terrestrial refugia and multiyear ice at maximal melt may have negative consequences such as drowning, cub mortality, and higher energetic demands (Durner *et al*., 2011; Monnett and Gleason, 2006; Pagano *et al*., 2012).

There is robust evidence for changes in sea ice conditions linked to polar bear distribution shifts (Fischbach *et al*., 2007; Gleason and Rode, 2009; Schliebe *et al*., 2008; Towns *et al*., 2010).Later arrival of sea ice at a Svalbard denning area reduced access to pregnant females (Derocher *et al*., 2011). Increases in the number of problem bears was associated with distribution shifts and declines in body condition (Towns *et al*., 2009). There is high agreement that the number of human-bear interactions may increase as sea ice conditions change (Derocher *et al*., 2004; Stirling and Parkinson, 2006; Stirling and Derocher, 1993; Towns *et al*., 2009).

An increasingly terrestrial niche for polar bears was postulated (Armstrong *et al*., 2008; Dyck and Romberg, 2007; Dyck *et al*., 2007; Dyck *et al*., 2008; DYCK and KEBREAB, 2009; Rockwell and Gormezano, 2009; Smith *et al*., 2010). However, earlier studies of terrestrial feeding by polar bears (Derocher, A., Andriashek, D., Stirling,I., 1993; Derocher, A., Andriashek, D., Stirling,I., 1993; Derocher *et al*., 2000; Lunn and Stirling, 1985; Lønø, 1970) ( Russell 1971) indicate that such feeding is not new. Assertions of an increased terrestrial niche for polar bears have been challenged because terrestrial resources are inadequate to compensate for the high-energy content of marine mammal prey (Amstrup *et al.*, 2009; Derocher *et al.*, 2004; Rode *et al.*, 2010b; Slater *et al.*, 2010; Stirling *et al.*, 2008). Limited evidence exists for adaptation of polar bears to major declines in sea ice. There is very high confidence that polar bears will not adapt to climate change in many subpopulations with major loss or alteration of sea ice.

### *28.2.2.1.3. Arctic and subarctic marine mammals*

Arctic and subarctic marine mammals have a dirth of empirical and modelling studies on responses to climate change (Kelly, 2001; Laidre *et al.*, 2008; Ragen *et al.*, 2008). Understanding the possible effects of climate change on Arctic marine mammals varies reflecting differing levels of insight into their habitat requirements and trophic relationships. Many Arctic and subarctic marine mammals are highly specialized, have long-life spans, and are poorly adapted to rapid and directional environmental change (Moore and Huntington, 2008). The predicted changes, however, may not be evident until significant sea ice loss has occurred (Laidre *et al.*, 2008). Two Arctic ice-dependent seals (ringed seals, *Pusa hispida*, and bearded seals, *Erignathus barbatus*) and four ice-associated subarctic species (spotted seal, *Phoca largha*, ribbon seal, *P. fasciata*, harp seal, *Pagophilusgroenlandicus*, and hooded seal, *Cystophora cristata*)use sea ice but none rely on it year-round (Lydersen and Kovacs, 1999). Similarly, walrus (*Odobenus rosmarus*) rely on sea ice for part of their life cycle but commonly retreat to coastal habitats when ice is unavailable.Three species of cetaceans remain in the Arctic year-round (bowhead whale, *Balaena mysticetus*, narwhal, *Monodon monoceros*, and beluga, *Delphinapterus leucas*) with narwhal being the most ice-associated species.

Most studies of climate change and Arctic marine mammals provide a qualitative assessment of climate change concerns and risks.None of the northern marine mammals have adequate demographic time series data to assess population level effects of climate change (Laidre *et al.*, 2008). There is *high agreement* that the effects of climate change on Arctic and subarctic marine mammals will vary. Depending on life history characteristics, distribution, and habitat specificity, climate change will improve conditions for a few species, have minor negative effects for others, and some species will suffer major negative effects (Laidre *et al.*, 2008; Ragen *et al.*, 2008). Resilience to climate change in Arctic and subarctic marine mammals will vary and some ice-obligate species should survive in regions with sufficient sea ice and some possibly adapting to ice-free coastal areas (Moore and Huntington, 2008). Moore and Huntington (2008) suggest that less ice-dependent species may be more adaptable and could benefit from a longer feeding period but an increase in seasonally migrant species could increase resource competition.

An analysis of the sensitivity of eleven Arctic and subarctic marine mammals to climate change suggested that feeding specialization, dependence on sea ice, and reliance on sea ice for access to prey and predator avoidance determined vulnerability (Laidre *et al.*, 2008). There is *medium agreement* on which species' life histories are most susceptible to climate change. Hooded seals and narwhal were identified as most at risk and ringed seals and bearded seals as least sensitive by (Laidre *et al.*, 2008). Kovacs et al. (2010) shared concern for hooded seals and narwhal and had serious concerns for the future ofringed seals and bearded seals. Higher vulnerability of narwhal to climate change has *robust agreement*although only *limited evidence*. Physiological specialization by narwhal suggests they may have limited ability to respond to climate change induced habitat alteration (Laidre and Heide-Jørgensen, 2005) (Williams et al. 2011). Species that spend only part of the year in the Arctic, such as the gray whale (*Eschrichtius robustus*) and killer whale (*Orcinus orca*) may benefit from reduced sea ice cover due to increases in prey availability (Ferguson *et al.*, 2012; Higdon and Ferguson, 2009; Laidre *et al.*, 2008) (Matthews *et al.*, 2011; Moore, 2008). Expansion of killer whales into the Arctic was postulated as a possible cause of a trophic cascade with the polar bear-seal predator-prey linkage being replaced with killer whales as the top predator (Higdon and Ferguson, 2009) although there is *limited evidence* of a trophic cascade at this time.

There is *limited evidence* although *moderate agreement* that generalists and pelagic feeding species may benefit from increased marine productivity resulting from reduced sea ice while benthic feeding ice-dependent species that rely on continental shelf habitats may dopoorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary specialists such as walrus are expected to do poorly with reduced ice (Kelly *et al.*, 2010; Kovacs *et al.*, 2010; Laidre *et al.*, 2008). Walrus rely on ice or land near foraging areas for resting and loss of sea ice may affect feeding. Field observations provide some insight into mechanisms of impact. Harp seal breeding habitat was affected by reduced ice duration and shifts in reproductive habitats and an increase in the frequency of poor ice years could reduce survival of young (Bajzak *et al.*, 2011). Changes in ice dynamics were identified as the cause for walrus calves being separated from their mothers during rapid ice retreat and such events may effect recruitment (Cooper *et al.*, 2006). Continued warming might reduce access to continental shelf habitat and negatively affect access to forage for lactating walrus (Kelly, 2001). While there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, and development) (Burek *et al.*, 2008).

There is *high agreement* that the effects on Arctic and subarctic marine mammals will vary spatially and temporally with some populations affected earlier than others making trends and effects difficult to detect (Kelly, 2001; Laidre *et al.*, 2008). There is *high agreement* that many Arctic and subarctic ice-associated marine mammals will be affected by sea ice loss with altered species distributions, migration patterns, behaviour, interspecific interactions,demography, population declines, and vulnerability to extinction but there is *limited evidence* of changes at this time.

### *28.2.2.2. Antarctic*

Organisms inhabiting the polar oceans differ from those in the rest of the world's oceans because they are adapted to colder conditions and many have a dependency on the annual advance and retreat of the sea ice. As the sea surface warms, pelagic species will naturally migrate southward, as expected, for example, from the close relationship of zooplankton assemblages with the different frontal zones (Hunt and Hosie, 2005); evidence is accumulating to conclude that zooplankton distributions have shifted south over the last 50 years in the Indian sector of the Southern Ocean (Takahashi *et al.*, 1998) (Kawaguchi *et al.* in prep). Bentho-pelagic species such as notothenid and channichthyd fish are cold-adapted and many are restricted to shallow (< 500 m) shelf areas around subantarctic islands. As a consequence, these species may be vulnerable to localised extirpations if the water temperature in their depth range increases. There is no evidence to date of impacts on these distributions.

Reduced pH of Southern Ocean waters is considered with medium confidence to have resulted in reduced thickness of shells in foraminifera (Moy *et al.*, 2009). Acidification impacts on zooplankton are currently uncertain, but laboratory experiments show that krill larval development may be impeded (Kawaguchi *et al.*, 2011).

Antarctic krill, *Euphausia superba*, is the dominant consumer of primary production in large parts of the Southern Ocean, feeding primarily on diatoms, whereas other herbivores, such as salps and copepods exploit smaller size classes. Changes in the biomass or production of Antarctic krill can have ramifications throughout the food web, both at upper and lower trophic levels because it is a foundation prey species, particularly dominating the Atlantic sector (Atkinson *et al.*, 2009; Murphy *et al.*, 2007; Nicol *et al.*, 2000), and is likely to mediate the flux of nutrients and carbon from lower to upper trophic levels (Holm-Hansen *et al.*, 2004), and possibly as a source of iron for primary producers through a process of whales consuming krill and returning iron to the surface waters in its faeces (Nicol *et al.*, 2010).

The distribution of Antarctic krill (*Euphausia superba*) and the 'krill-based' foodweb is influenced by the winter extent of sea ice, upon which krill is dependent on sea ice for reproduction, survival and recruitment, and, in some sectors, the location of the southern ACC front (Atkinson *et al.*, 2004; Atkinson *et al.*, 2009; Jarvis *et al.*, 2010; Loeb *et al.*, 1997; Nicol *et al.*, 2000; Nicol *et al.*, 2000; Nicol and Allison, 1997; Nicol, 2006) (Nicol and Raymond 2012). Foodwebs based on copepods and myctophid fish are common in subantarctic regions (Duhamel *et al.*, 2011) (Hulley and Duhamel 2011). The potential for alternative fish-based food webs to replace krill-dominated ones has been considered to be feasible by (Murphy *et al.*, 2007); these linkages are feasible when krill is in low abundance.

In the Scotia Sea, densities of Antarctic krill, which is the dominant consumer of phytoplankton in large parts of the Southern Ocean, have been estimated to have declined by approximately 30% since the 1980s (Atkinson *et al.*, 2004), in parallel with declines in the extent and season duration of winter sea ice in the region. The degree to which the overall abundance of krill has declined is still a matter of conjecture because the results are based on densities measured using different nets and different times, with results often biased downwards, particularly in krill swarms (Nicol and Brierley 2010). However, the likely dependence of Antarctic krill on the annual extent of winter sea ice indicates strong grounds for concern that the krill population in this key area where 70% of the population is found (Atkinson *et al.*, 2009) may have already changed and will be subject to further change. Assessments of long term change in krill populations will require standardised methodologies, and consistent and agreed analytical techniques that can make the most of the available data.

Recent simulation modelling of krill productivity and dynamics show the plausibility of the positive relationship between sea ice extent and recruitment of krill at the Antarctic Peninsula (Wiedenmann *et al.*, 2009). However, such a decline may be offset by increased productivity arising from increased water temperature in that area (Wiedenmann *et al.*, 2008). That said, the latter study also showed that krill productivity may decline in the South Georgia area as a result of increasing temperatures. The combined effects of changing sea ice, temperature and food have not been investigated.

The switch from a krill-based food web to a copepod- and fish-based food web in times of low abundance of krill in around subantarctic islands in the southwest Atlantic suggests that the latter may become more dominant around these islands in the future (Shreeve *et al.*, 2009; Trathan *et al.*, 2007; Waluda *et al.*, 2010). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow *et al.*, 2007; Loeb *et al.*, 1997). The trophic efficiency of these longer food webs in the absence of krill is less (Murphy *et al.*, 2007) and the long-term implications of this for higher trophic levels are unknown.

The changes in the physical habitat of the WAP, including the movement south of the sea ice extent, are believed to be resulting in a shift of the krill-dominated food web (krill, Adélie penguins and ice-breeding seals) to higher latitudes and the replacement of this food web at lower latitudes with one composed of species that that do not depend on sea ice and are more able to exploit a range of prey items, for example gentoo penguins (Costa *et al.*, 2010; Ducklow *et al.*, 2007; Trivelpiece *et al.*, 2011). The mechanisms driving these changes are currently under review (Melbourne-Thomas et al, submitted). This shift may be accompanied by an overall decline in the productivity of the WAP shelf (Montes-Hugo *et al.*, 2009), although this may be tempered by increased inputs of iron through changes to ocean processes in the region (Dinniman et al., submitted).

A contributing factor to the reduction in Adélie penguins may be increased snow precipitation which accumulates in the breeding colonies (Patterson *et al.*, 2003). Increased wetting of chicks in the colonies due to increase precipitation has been shown to significantly decrease survival, especially when accompanied by reduced food supply (Chapman et al., in press).

Notably, emperor penguins have abandonded one of their most northerly breeding sites on the Antarctic Peninsula (Trathan *et al.*, 2011), although the causes of this are unknown .

Many Southern Ocean seals, penguins and flying birds are exhibiting strong responses to a variety of climate indices, with many, but not all, species showing a negative response to warmer conditions (Barbraud and Weimerskirch, 2001a; Barbraud and Weimerskirch, 2001b; Barbraud and Weimerskirch, 2003; Forcada *et al.*, 2005; Forcada *et al.*, 2006; Fraser *et al.*, 1992; Fraser and Hofmann, 2003; Jenouvrier *et al.*, 2003; Jenouvrier *et al.*, 2005; Jenouvrier *et al.*, 2005b; Trathan *et al.*, 2007; Trathan *et al.*, 2006). In contrast to these trends and for those populations on the WAP, Adélie penguin populations are increasing in the Ross Sea (Smith Jr. et al. 2011) and eastern Antarctica (Nicol and Raymond 2012) where sea ice conditions in summer are closer to their long term average.

Even though populations of Antarctic fur seals are recovering from over-exploitation, their responses to climate variability, particularly at South Georgia where populations have increased to levels approaching their pre-exploitation levels, show strong negative response to an increasingly warm environment (Forcada *et al.*, 2005; Forcada *et al.*, 2008).

Long term downward trends in the populations of marine mammals and birds in the subantarctic of the Indian sector of the Southern Ocean have been interpreted as a region-wide shift to a system with lower productivity (Jenouvrier *et al*., 2005b; Lea *et al*., 2006; Weimerskirch *et al*., 2003). Similarly, studies of bird populations on the coast of Adélie Land in eastern Antarctica have shown declines in abundance and shifts in their breeding phenology, which have been assumed to be related to climate change impacts (Barbraud and Weimerskirch, 2006; Croxall *et al*., 2002; Jenouvrier *et al*., 2005a; Jenouvrier *et al*., 2005; Jenouvrier *et al*., 2005b; Jenouvrier *et al*., 2009).

Movement south of the frontal systems, and therefore movement of productive foraging areas, in the Indian sector have been attributed as causes of declines in King penguin colonies on subantarctic islands in that sector (Weimerskirch *et al.* in press).

While large seabirds, such as albatross and petrels, may have lesser constraints over the areas they forage within during the breeding season, they still show significant responses to climate variability (Barbraud and Weimerskirch, 2003; Barbraud *et al*., 2008; Barbraud *et al*., 2011; Inchausti *et al*., 2003; Jenouvrier *et al*., 2005a; Nevoux and Barbraud, 2006; Nevoux *et al*., 2010a; Nevoux *et al*., 2010b; Olivier *et al*., 2005; Peron *et al*., 2010; Pinaud and Weimerskirch, 2002; Rivalan *et al*., 2010; Rolland *et al*., 2008; Rolland *et al*., 2009a; Rolland *et al*., 2009b; Rolland *et al*., 2010) (Barbraud and Weimerskirch 2006b) but the long term ramifications of these affects are not clear.

The relative importance of climate change impacts compared to other population trends remain to be determined. For example, albatross and petrel colonies have also been declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall *et al*., 2002). Also Antarctic fur seals have been recovering from their near extirpation since the early 1900s; their substantial recovery occurred from the 1950s onwards during the period of reduction in sea ice extent in the region. Baleen whale populations are also beginning to increase after near extinction in the 20th Century (Nicol *et al*., 2008). However, for regions such as eastern Antarctica, populations of humpback whales that breed off Australia and feed in the region, are increasing quite rapidly suggesting that food availability is currently not limiting (Zerbini *et al*., 2010). Although there is insufficient information on the changes in population sizes of any of the other species of whales off East Antarctica (Nicol *et al*., 2008), it indicates that declines in other taxa may be attributable to changes in the ecosystem other than krill.

### *28.2.3. Terrestrial Ecosystems*

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 120 000 years) mainly driven by natural climate change. Significant altitudinal and latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period (Lorenzen *et al*., 2011; Mamet and Kershaw, 2012; Salonen *et al*., 2011).

Since IPCC FAR (Anisimov *et al*., 2007), evidence of climate change impacts on Arctic ecosystems has become more apparent and more compelling. There has been an increasing awareness of the importance of extreme events, mismatches among the responses of various trophic levels to climate change that could result in trophic cascades, and the importance of changes in the Arctic's cryosphere for ecosystems (AMAP 2011).

#### *28.2.3.1. Phenological Responses*

There is medium confidence that phenological responses attributable to warming are apparent in Arctic terrestrial ecosystems. Compared to temperate regions, there is a general lack of long-term phenological studies from the Arctic. Phenological responses to warming vary from little overall trend in the Swedish sub Arctic (Molau *et al*., 2005), despite accelerated recent warming (Callaghan *et al*., 2010), to dramatic earlier onset of plant reproductive phenophases of up to 48 days in west Greenland (Callaghan *et al*., 2011a; Post *et al*., 2009). Other substantial changes include earlier clutch initiation dates in birds and earlier emergence of arthropods in northeast Greenland (see Figure 28-2).

[INSERT FIGURE 28-2 HERE
Figure 28-2: Advancement of phenological events in high-Arctic Greenland. a) location of the study area Zackenberg, North-east Greenland. b) Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initation dates (birds). Red dots are statistically significant, blue dots are not (Høye *et al.*, 2007).]

### *28.2.3.2. Observed Changes in Tundra Vegetation*

There is very high confidence that the abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have increased substantially over large – but not all – parts of the Arctic tundra in recent years. It is very likely that most of this increase in deciduous shrubs can be attributed to Arctic warming, but in northwest Eurasia a significant portion of the graminoid increase seems tied to steadily intensifying reindeer grazing/trampling coupled with large-scale hydrocarbon extraction in recent decades (Kumpula *et al.*, 2012; Kumpula *et al.*, 2011)(Forbes et al. 2009). There are independent lines of evidence for the often substantial increase in plant growth and range expansion based on different techniques and observational scale.

Recent assessments of changes in plant productivity (NDVI) from satellite observations between 1982 and 2008 show a substantial greening over large parts of the Pan-Arctic (Bhatt *et al.*, 2010; Walker *et al.*, 2011; Zhang *et al.*, 2008) (Figure 28-3) with the greatest increases of 10 to 15% over the North American high Arctic and along the Beaufort Sea, and in northern Canada (Pouliot et al 2009). In contrast, decreases in NDVI were generally observed in Beringia and occurred locally in the western Russian Arctic. However, the east European Arctic (Nenets Autonomous Okrug) registers a significant increase in NDVI during this same time period (Bhatt *et al.*, 2010; FORBES *et al.*, 2010; Raynolds *et al.*, 2008) (Macias-Fauria et al. in press).

[INSERT FIGURE 28-3 HERE
Figure 28-3: Trends for (a, right) summer (May-August) open water and annual MaxNDVI and (b,left) summer (May-August) open water and land-surface summer warmth index (SWI, the annual sum of the monthly mean temperatures >0 °C) derived from AVHRR thermal channels 3 (3.5-3.9 μm), 4 (10.3-11.3 μm) and 5 (11.5-12.5 μm). Trends were calculated using a least squares fit (regression) at each pixel. The total trend magnitude (regression times 29 years) over the 1982-2010 period is displayed (Bhatt *et al.*, 2010).]

The positive trends in NDVI are associated with increases in the summer warmth index (sum of the monthly-mean temperatures above freezing expressed as ºC per month) that have increased on average by 5ºC per month for the Arctic as a whole. However, the even greater 10 to 12ºC per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI, indicating that other factors than increased warming also affect NDVI and plant growth. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity particularly in the central and northern portions(Walker *et al.*, 2009), and partly from *in situ* increases in shrub height and biomass, which occur more generally in riparian and other snow-protected habitats on Yamal and in the neighbouring Nenets Autonomous Okrug (FORBES *et al.*, 2010) (Macias-Fauria et al. in press). Small rodent cycles reduce NDVI in sub Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson *et al.*, 2012). This indicates that the changing NDVI signal should be interpreted with care in general. Increases in land surface temperatures and NDVI in some areas have been related to earlier retreat of coastal sea ice in early summer (Bhatt *et al.*, 2010), but the relationship between sea ice and NDVI is restricted to early spring in northwest Eurasia. During the growing season peak, NDVI in this region corresponds much more closely to persistent synoptic-scale air masses over West Siberia associated with Fennoscandian weather systems via the Rossby wave train (Macias-Fauria et al. in press).

Increased greening in parts of the Arctic determined by NDVI has been largely confirmed by multi-decadal on-ground observations of vegetation change (Callaghan *et al.*, 2011b; Myers-Smith *et al.*, 2011), and meta-analysis of control plots of warming experiments (Elmendorf *et al.*, 2012 online). Since IPCC AR4, increasing evidence from these studies that range in scale from landscape to experimental plots, shows that one of the greatest vegetation changes is the areal expansion, in-filling (densification) and increased growth of woody plants (trees and shrubs). Shrubs have generally expanded their ranges (Myers-Smith *et al.*, 2011) and/or growth for example in Alaska (Tape et al. 2001; Sturm et al.

2006), the Yukon region of Canada (Myers-Smith *et al*., 2011), southeast Yukon (Danby and Hik, 2007), the Canadian high Arctic (Hill and Henry, 2011; Hudson and Henry, 2009), the Swedish sub Arctic (Hallinger *et al*., 2010; Hedenås *et al*., 2011; Rundqvist *et al*., 2011), and the northwestern Russian Arctic (FORBES *et al*., 2010)( Macias-Fauria et al. in press). In the latter case, nomadic Nenets reindeer herders have observed the aforementioned increases in the height of deciduous shrubs and have had to adjust their reindeer management regime in response (FORBES *et al*., 2010)(Forbes and Stammler 2009; Macias-Fauria et al. in press). Changes in growth of shrubs have varied from dramatic, i.e. 200% area increase in study plots (Rundqvist *et al*., 2011) in sub arctic Sweden to early invasion of a fell field community on west Greenland plots by low shrubs (Callaghan *et al*., 2011a). Structural changes within the tundra zone can result when low erect shrubs (e.g. *Salix*, *Alnus* spp.) increase significantly in height *in situ*. There is strong evidence that this has occurred in the past in Beringia (Edwards *et al*., 2005) and is in progress now in the northwestern Russian Arctic (Macias-Fauria et al. in press).

Changes in species diversity could not be detected in the long-term study from Ellesmere Island in Canada (Hill and Henry, 2011; Hudson and Henry, 2009). However, other multi-decadal studies (see references in (Callaghan *et al*., 2011b)) show small changes in plant community composition at sites in Canada, Greenland and Sweden that indicate responses to warming and drying. Furthermore, aspen tree invasion has been recorded at a sub Arctic tree line (Van Bogaert *et al*., 2010).

Snow bed habitats have decreased in sub arctic Sweden (Björk and Molau, 2007; Hedenås *et al*., 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub Arctic (Danby *et al*., 2011), through subtle changes in plant community composition in west and southeast Greenland (Callaghan *et al*., 2011a; Daniëls and De Molenaar, 2011) to 70 year stability of a plant community on Svalbard (Prach *et al*., 2010).

Although early experimental studies projected that mosses and lichens would be disadvantaged by climate warming (Cornelissen *et al*., 2001; Lang *et al*., 2012)(van Wijk et al. 2003), (Lang *et al*., 2012)showed that Arctic warming on two continents has consistent negative effects on lichen diversity and mixed effects on bryophyte diversity. (Hudson and Henry, 2009) reported significant increases in bryophyte biomass between 1981 and 2008 on Ellesmere Island. In contrast, moss communities on Iceland were stable during experimental summer warming and growth (Jonsdottir et al. 2005) and photosynthetic activity of a bryophyte was significantly reduced by simulation of acute mid-winter warming events in a sub-Arctic heath (Bjerke *et al*., 2011). Although significant recovery of lichens has been recorded in Finnmarksvidda (Tömmervik 2012), Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than winter consumption as forage. Lichen recovery is a decadal process and depends on appropriate moisture levels (Klein and Shulski, 2009) coupled with an absence of grazing/trampling pressure in the snow-free season (Forbes and Kumpula, 2009). Lichens, unlike bryophytes, were unaffected by extreme warm events in winter in the sub Arctic (Bjerke *et al*., 2011).

A meta-analysis (11 sites: (Walker *et al*., 2006)) and a synthesis (61 sites: Elmendorf et al. 2011) of experimental warming studies of up to 20 years duration in tundra sites worldwide, showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al. (2011) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly like herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density. A meta-analysis of some of the control plots of these experiments showed a biome-wide trend of increased height of the plant canopy and maximum observed plant height for most vascular growth forms; increased abundance of evergreen, low-growing and tall shrubs; and decreased abundance of bare ground. Intersite comparisons indicated an association between the degree of summer warming and change in vascular plant abundance, with shrubs, forbs and rushes increasing with warming. However, the association was dependent on the climate zone, the moisture regime and the presence of permafrost.

### *28.2.3.3. Changes in Tree Line*

Palaeorecords of vegetation change indicate that the northern tree line should extend upwards and northwards during current climate warming (IPCC FAR) because tree line is related to summer warmth (e.g.(Harsch *et al.*, 2009)). Although the tree line has moved northwards and upwards in many Arctic areas, there s high confidence that the tree line has not shown a general circumpolar expansion in recent decades. The existing evidence suggests varying patterns of re-location resulting from several co-occurring drivers.

An expansion of the tree line as a response to warming has been observed in many areas e.g. (Chapin III *et al.*, 2005; Kullman and Öberg, 2009; Lloyd, 2005; Shiyatov *et al.*, 2007) but in some areas, the location of the tree line has not changed or has changed very slowly (Holtmeier *et al.*, 2003; MacDonald *et al.*, 2008; Masek, 2001; Payette, 2007). A global study by (Harsch *et al.*, 2009) showed that only 52% of all 166 global tree line sites had advanced over the past 100 years. In many cases tree line has even retreated (Cherosov *et al.*, 2010; Dalen and Hofgaard, 2005; Kullman, 2005; Vlassova, 2002).

This diversity of response is also seen at the small scale. Within one area undergoing the same degree of climate warming (sub arctic Sweden and Siberian taiga), tree line has shown increase, decrease and stability in neighboring locations (Lloyd *et al.*, 2011; Van Bogaert *et al.*, 2011). These variable responses clash with process-based understanding in model projections and relate to local drivers of change that interact with or negate direct effects of climate warming (see below).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in (Callaghan *et al.*, 2005)) and shifts upslope by 2 to 6 m per year ((Moen *et al.*, 2004) and northwards by 7.4–20 km per year (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert *et al.*, 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are in the range of 1 to 2 m year (Kullman and Öberg, 2009; Shiyatov *et al.*, 2007) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3–10 m year (Kharuk *et al.*, 2006).

Evidence for densification of the forest at the sub Arctic tree line is robust and consistent within Fennoscandia (Hedenås *et al.*, 2011; Rundqvist *et al.*, 2011; Tømmervik *et al.*, 2009) and Canada (Danby and Hik, 2007). Dendroecological studies indicated enhanced conifer recruitment during the twentieth century in the northern part of the Siberian taiga (Briffa et al. 2008) and tree growth was well correlated with warm summer temperature (Lloyd *et al.*, 2011; MacDonald *et al.*, 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/8 and 2009/10 (Rundqvist *et al.*, 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik *et al.*, 2009). Also, in at least one location, a tree species not present in 1977 has invaded the tree line (Rundqvist *et al.*, 2011; Van Bogaert *et al.*, 2010). However, model projections of displacement of deciduous forest by evergreen forest (Wolf *et al.*, 2008)( Wrammeby et al. 2010) have not so far been validated.

Decrease in the deciduous mountain birch tree line in the Abisko area in Sweden has been related to an outbreak of the autumn moth in the 1950s whereas stability of the tree line was controlled by slope and rock outcrops in a neighbouring area (Van Bogaert *et al.*, 2011). Even where the mountain birch tree line has increased in elevation and shrub (e.g. willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure and earlier land use (Hofgaard *et al.*, 2010; Olofsson *et al.*, 2009; Van Bogaert *et al.*, 2011). There is evidence from Fennoscandia and Greenland that heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g. dwarf birch) growth (Kitti *et al.*, 2009; Olofsson *et al.*, 2009; Post and Pedersen, 2008). However, in cases where tall willow shrubs are already above the reindeer browse line of ≈1.8 m, their transformation into tree size individuals is likely to track warming temperatures rather than grazing intensity (FORBES *et al.*, 2010) (Macias-Fauria et al. in press). The responses of shrubs to warming is particularly important to tree range expansion at treeline because shrubs can facilitate tree seedling survival, for example by reducing seedling herbivory (Grau *et al.*, in press).

Climate warming might also have negative impacts on northern forests where growth is largely made possible by moisture supplied from melting of the winter snowpack (Yarie, 2008). In most of the boreal forest region, temperature increases have made the snow-accumulation season shorter, particularly in spring, and the warm season longer (Callaghan *et al*., 2011c), so that less of the annual water budget is from the spring pulse of snowmelt. Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (the "browning of the boreal forest:(Goetz *et al*., 2005; Verbyla, 2008)) and making them more susceptible to insect pest outbreaks (see references in (Callaghan *et al*., 2011c)).

#### *28.2.3.4. Changes in Animal Population Cycles*

High-amplitude population cycles of herbivores like lemmings, voles, snowshoe hares and forest Lepidoptera (caterpillars of moths and butterflies) are characteristic processes of tundra and boreal forest ecosystems, influencing considerably the dynamics of vegetation and other animal populations in these ecosystems (Berg *et al*., 2008; Gilg *et al*., 2009; Ims *et al*., 2007; Kausrud *et al*., 2008; Krebs, 2011; Olofsson *et al*., 2012; Rydgren *et al*., 2007).

The documented collapse or dampening of population cycles of voles and lemmings over the last 20-30 years in parts of Fennoscandia and Greenland, can be attributed with high confidence to climate change (Gilg *et al*., 2009; Ims *et al*., 2007; Ims *et al*., 2011; Kausrud *et al*., 2008). A shortening of the snow season and more thaw and/or rain events during the winter season have the potential to increase overall mortality and decrease winter reproduction because snow hardness increases and influence on the subnivean space (Figure 28-4) which provides thermal insulation, access to food, and protection from predators to high latitude rodents (Berg *et al*., 2008; Johansson *et al*., 2011; Kausrud *et al*., 2008). However, the causes of the changes in the lemming and vole cycles are still being debated as other factors than climate change may also be of importance (Brommer *et al*., 2010; Krebs, 2011).

[INSERT FIGURE 28-4 HERE
Figure 28-4: Long-term snow stratigraphy observations from Abisko, sub Arctic Sweden, showing increased incidence of mid-winter thaw events and more complete thaw events leader to a greater incidence of basal hard snow and ice layers (Johansson *et al*., 2011).]

Both the boreal forest and the mountain birch forest of Fennoscandia are regularly subject to large-scale tree mortality from insect outbreaks. Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (ACIA 2005;(Robertson *et al*., 2009)) and for geometrid moths in Fennoscandia (Callaghan *et al*., 2010; Jepsen *et al*., 2008; Jepsen *et al*., 2011), causing more extensive forest damage than before. Outbreaks of insect pests like geometrid moths may even be of a magnitude that reduces the strengths of CO2 sinks in some areas (Heliasz *et al*., 2011).

The latitudinal and altitudinal expansion of the range of the red fox (*Vulpes vulpes*) into the tundra and alpine areas is likely to be a response to warming which has strengthened interspecific competition with the much smaller arctic fox (*Alopex lagopus*) and most likely has contributed to the decline of this species and its population cycles in many Arctic regions (Fuglei and Ims, 2008; Henden *et al*., 2010)(Killengren et al. 2007).

#### *28.2.3.5. Changes in Reindeer and Muskox Populations*

The decline in some reindeer and caribou (both *Rangifer tarandus*) populations over the last 10-15 years have been linked both to climate warming and anthropogenic landscape changes (CAFF, 2010; Post *et al*., 2009; Vors and Boyce, 2009). Even though most of the Arctic has warmed, the overall 33% decline in the populations of wild reindeer has not been uniform. Some of the North American large herds have for example declined by 75-90 percent, while others there and in Russia have been stable and even increased (Gunn *et al*., 2009; Joly *et al*., 2011; Vors and Boyce, 2009)( Forbes et al. 2009).

Large-scale natural climate patterns, like the Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO) may account for the historically synchronous cycles these populations have undergone, and may explain why the present declines are not universal and why climate warming has not acted uniformly on the populations (Gunn *et al.*, 2009; Joly *et al.*, 2011). Gunn et al. (2009) therefore warn against considering all drivers of global change as detrimental to the long-term viability of caribou herds.

A trophic mismatch causing increased calf mortality and drop in female productivity has been documented when timing of parturition in a population of caribou in Greenland did not keep pace with advancement of the plant-growing season and peak forage availability and quality caused by a warmer climate. (Post and Forchhammer, 2008)( Post et al. 2009a). The animals could not compensate for such trophic mismatch by tracking phenological variation across landscapes because the spatial variability in plant phenology was reduced by both experimental and observed warming (Post et al. 2009b). It is speculated that similar warming-induced trophic mismatches have a role in the decline of circumpolar reindeer and caribou populations (Post et al. 2009a).

The increased primary productivity of Arctic ecosystems (see above) may potentially increase the supply of food for Arctic ungulates, although new biomass already above the browse would be inaccessible and therefore superfluous (FORBES *et al.*, 2010). The overall quality of forage may decline during warming, for example if the nitrogen content of key fodder species for ungulates were to drop (Heggberget *et al.*, 2002; Turunen *et al.*, 2009) during warming, complicating prediction of the impacts of vegetation changes on Arctic ungulates. As mentioned above, there are indications that lichen biomass is decreasing over much of the Arctic region (Joly *et al.*, 2009; Turunen *et al.*, 2009; Walker *et al.*, 2006) and Arctic lichens have been shown experimentally to be vulnerable to icing events (Bjerke *et al.*, 2011). However, lichen biomass has been increasing (together with that of mosses, graminoids and dwarf shrubs) in parts of Fennoscandia (Tommervik *et al.*, 2009), while simultaneously decreasing in others (Forbes and Kumpula 2009). Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes on the ungulate populations (Turunen *et al.*, 2009; van Der Wal *et al.*, 2007)( Post and Christensen 2008).

More frequent icing events and thicker snow-packs caused by warmer winters and increased precipitation may restrict access to vegetation and have profound negative influences on the population dynamics of Arctic ungulates (Berg *et al.*, 2008; Forchhammer *et al.*, 2008; Hansen *et al.*, 2011; Stien *et al.*, 2010)(Aanes et al. 2002). Behavioural plasticity may partly buffer such icing events (Hansen *et al.*, 2010). In contrast, warmer winters were shown to enhance the abundance of reindeer in a population in Svalbard because access to vegetation became easier (Tyler *et al.*, 2008) while over the period 1970 to 2006, reindeer calf production in Finland increased by almost one calf per 100 females for each day of earlier snow melt (Turunen *et al.*, 2009). Furthermore, ice was not confirmed as an ubiquitous and potent factor in 31 declines of 12 different reindeer and caribou populations (Tyler, 2010). More frequent icing events have caused heavy mortality in domestic reindeer herds (Forbes et al. 2009) and some of the herders in Yamal in Siberia have lost as much as 25% of the herds in one winter season due to icing. Despite this, the indigenous Nenets inhabiting the area, stressed hydrocarbon development as the main long-term threat to their existence (Forbes et al. 2009).

#### *28.2.3.6. Long-Term Trends and Event-Driven Changes in Ecosystems*

Changes in vegetation and animal populations are driven relatively slowly by long-term climate change but tipping points may be reached quickly by events such as extreme weather, fire, insect pest and disease outbreaks. While the impacts of winter thaw events are well-documented for animals (see above), the severe impacts of tundra fires on vegetation and biospheric feedbacks have been described only recently (Mack *et al.*, 2011). Similarly, experimental and observational determinations of the impacts of extreme winter thaw events on plants, soil arthropods and ecosystem processes have become evident since IPCC 2007 (e.g.(Bokhorst *et al.*, 2011)). For example, results from experimental thaws during winter were validated by a natural thaw in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over an area of at least 1400 km$^2$ (Bokhorst *et al.*, 2009). Studies on relationships between climate change and plant disease are almost totally lacking but a new study demonstrated the effect of increased snow accumulation on a higher incidence of fungal growth on sub Arctic vegetation (Olofsson *et al.*, 2011).

### *28.2.3.7. Environmental Change Responses in Antarctic*

Few robust studies of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems are available. Most attention has been given to rapid population expansion and local-scale colonisation by the two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in the maritime Antarctic (Convey *et al*., 2011; Fowbert and Smith, 1994; PARNIKOZA *et al*., 2009), which remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. One important aspect underlying these changes is thought to be that warming has resulted in a threshold being passed at which successful sexual reproduction (seed set) can take place, changing both the dominant mode of reproduction, and the potential dispersal scale. Similar changes are reported anecdotally in the local distribution and development of typical cryptogamic vegetation of this region, including the rapid colonisation of ice free ground made available through glacial retreat and reduction in extent or previously permanent snow cover. As these vegetation changes creates new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonises them. However, robust baseline survey data and monitoring studies capable of documenting these changes remain critically lacking (Convey, 2006; Convey, 2010), and their establishment must now form an urgent priority (Wall *et al*., 2011). A further urgent need in order to be able to more precisely attribute such biological responses to aspects of environmental change is that of linking well-described large-scale climatic trends with that of microclimates experienced by terrestrial biota at much smaller and relevant physical scales (Convey, 2003; Convey, 2003; Convey *et al*., 2009)(Turner et al. 2009).

Experimental terrestrial field manipulation studies have been used to mimic aspects of climate change predictions in Antarctica. Generally these report that the soil microbial flora, bryophytes and invertebrate fauna respond rapidly and positively to improved environmental conditions (Convey and Wynn-Williams, 2002; Kennedy, 1994; Smith, 1990; Smith, 1993; Smith, 2001; Wynn-Williams, 1996). More recent studies using improved methodologies have shifted the emphasis towards a higher level of integrated understanding. Biological responses have been quantified in terms of plant biochemistry, morphology, life history and ecology, invertebrate population density and diversity, and and at different trophic levels, including the decomposition cycle, across the food web (e.g. Bokhorst 2007ab,2008,2011; Convey 2002; Sinclair 2002; Day 1999,2001). While often subtle, but responses may integrate to give far greater impacts for the community or ecosystem (Convey, 2003; Convey, 2006; Day *et al*., 2001; Searles *et al*., 2001). There is a clear need to recognise the long-term commitment required for such field experiments.

*Changes in sea-ice and ocean's warming on the West Antarctic Peninsula*: The ecosystem of the West Antarctic Peninsula is impacted in a 1000 x 200km large area (McClintock et al. 2008) by changes in the sea-ice serving purely as a habitat (85 days shorter season per year), by secondary effects on the food web or by a combination of both n the following way: (1) Reduction of primary production in the ice; (2) Increase and decrease of primary production in the water column; (3) Shift in phytoplankton from diatoms to smaller species (Schloss et al. 2012); (4) Increase of lantern-fish and salps; (5) overall decrease of krill due to recruitment problems; (6) local increase of krill and Humpback whales (Novacek et al. 2011); (7) decrease of Antarctic silver fish, a trophic key species; (8) Range shift of Adélie, Gentoo, and Chinstrap penguins to the South (Stokstad 2007), with a net shrinking of Adélies and Gentoos(Trivelpiece *et al*., 2011); (9) Range shift of Southern elephant seals to the South (Costa *et al*., 2010) but suffering in the North (McIntyre et al. 2011); (10) increased mortality of benthic organisms due to ice scouring (Barnes and Souster 2011); (11) King crabs appearing locally in a warming benthic habitat (Smith et al. 2012).

### *28.2.3.8. Direct Human Impacts on the Antarctic Terrestrial Environment*

Antarctic terrestrial ecosystems face multiple stressors including direct human impacts, anthropogenic introduction of non-indigenous species, and continuing effects from the recovery of marine megafauna populations (in particular the Antarctic fur seal) from massive human over-exploitation during the Eighteenth and Nineteenth Centuries to now unprecedented levels (Convey and Lebouvier, 2009; Favero-Longo *et al*., 2011; Hodgson *et al*., 1998; Hodgson and Johnston, 1997). However, few studies have quantified human disturbance to Antarctic terrestrial and freshwater ecosystems (Mahlon C Kennicutt II and Andrew Klein and Paul Montagna and Stephen Sweet and Terry Wade and Terence Palmer and Jose Sericano and,Guy Denoux, 2010; Poland *et al*., 2003; Tejedo *et al*., 2009)( Hughes, 2010). Stations, vehicles and their operations clearly generate local pollution, dust, and direct damage to vegetation, soil surfaces and freshwater systems (Convey, 2006; Kaup and Burgess, 2002; Tin *et al.*, 2009). Soil and freshwater ecosystems may become eutrophied through human activities (Ohtani *et al.*, 2000). Even formally protected areas ('Antarctic Specially Protected Areas') are not immune from these impacts (Hughes and Convey, 2010)( Braun et al., in press). A common feature of these studies is recognition that recovery from these types of disturbance to vegetation and soils may take decades, at least.

#### *28.2.3.9. Anthropogenic Transfer of Non-Indigenous Species*

Regional climate warming and associated environmental changes are expected to both increase the frequency at which new potential colonists arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and subsequent probability of their successful establishment. However, human-assisted transfers of biota overcome several of the barriers facing natural colonists, in particular being much more rapid than the natural processes, and in avoiding exposure to the extreme environmental stresses and extended time inherent in transfer at altitude in the atmosphere, or on the ocean surface (Barnes *et al.*, 2006; Clarke *et al.*, 2005; Kharuk *et al.*, 2006). Although few data are available quantifying the relative importance of natural and human-assisted colonisation routes into the Antarctic, at two remote Southern Ocean islands (Gough Island, Marion Island) it has been estimated that the latter has outweighed the former by at least two orders of magnitude since their discovery (Frenot *et al.*, 2005a; Gaston *et al.*, 2003)( Gremmen and Smith, 2004).

The majority of non-indigenous species established in the sub- and maritime Antarctic are very restricted in their distributions (Frenot *et al.*, 2005a). Where environmental changes result in alteration of the physical environment within which terrestrial ecosystems exist – such as glacial retreat forming new beach-heads connecting previously isolated systems – there is potential for unrestricted spread of established non-indigenous species into currently non-impacted areas, as has been documented on South Georgia (see (Cook and Vaughan, 2010)). Direct anthropogenic assistance in local transfer, through poor or non-existent application of biosecurity measures, is also strongly implicated in the subsequent dispersal of established non-indigenous species to new locations (see (Convey *et al.*, 2011; Frenot *et al.*, 2005b)). Whilst it can be reasonably assumed that some aspects of climate change (particularly relating to warming and water availability) may facilitate some established non-indigenous species switching to invasive status, clear documentation of this in specific examples is not available, although plausible examples exist (e.g. and Worland, 2010; Olech & Chwedorzewska, 2011).

The sub-Antarctic islands provide clear warning of the major impacts on Antarctic terrestrial ecosystems to be expected from the anthropogenic introduction of biota (Bergstrom *et al.*, 2009; Convey, 2006; Convey, 2008; Convey and Lebouvier, 2009; Frenot *et al.*, 2005a). A common feature of many of the non-indigenous species already known to be established in the sub-Antarctic is that they belong to ecological functional groups, or introduce trophic or ecological functions, that are poorly or not represented in the native communities, and hence have the potential to change fundamentally the structure and function of these ecosystems (Convey, 2010; Frenot *et al.*, 2005b). While the probability of successful establishment events may be considerably increasesd by regional climate trends in the Antarctic, the subsequent direct impacts of new non-indigenous species on Antarctic terrestrial ecosystems are likely to far outweigh those resulting from climate change itself.

Overall knowledge of the presence, distribution and impacts of non-indigenous species in the Antarctic is poor, and the available data on numbers of such species are likely to be a considerable underestimate, other than for the vertebrates. At the majority of locations baseline survey and monitoring data are unavailable for most invertebrate and lower plant groups while, even for locations and groups where data are available, there are no ongoing programmes monitoring distribution and abundance changes or impacts. The presence of non-indigenous microbiota is particularly poorly known (Convey, 2008; Cowan *et al.*, 2011; Frenot *et al.*, 2005b).

#### *28.2.3.10. Impacts from the Recovery of Marine Ecosystems after Human Over-Exploitation*

The largely uncontrolled over-exploitation of marine vertebrate resources of the Southern Ocean during the Eighteenth, Nineteenth and first half of the Twentieth Centuries (reviewed by Trathan & Reid, 2009) caused major perturbation to these marine ecosystems, such that it is both unclear what their original state was, and whether ecosystem trajectories will result in recovery towards a state similar to the original, with or without additional influences from changing climatic drives. In the context of terrestrial ecosystems, the marine exploitation industries had three main impacts, those of (i) habitat destruction through onshore infrastructure construction, (ii) the associated first phase of introduction of non-indigenous species, and (iii) a potentially massive spike in the quantity of marine biomass and nutrients input to the terrestrial environment (primarily through the dumping of seal and whale carcasses), followed by a longer term alteration to this transfer mediated by changes in the populations of both the target species and carrion feeders (Convey and Lebouvier, 2009). The first two have already been considered briefly above while the latter, although potentially fundamentally important for terrestrial ecosystems often believed to be strongly nutrient limited, has not been a subject of specific study in the Antarctic.

However, one element of post-exploitation recovery that has particular importance for Antarctic terrestrial ecosystems, and may also act in synergy with consequences of regional climate change such as decrease of sea ice extent and duration, is that of the very rapid increase in populations of Antarctic fur seals (*Arctocephalus gazella*) to levels that are currently thought to be at least equal to if not greater than those that existed pre-exploitation. This population recovery has been centred on sub-Antarctic South Georgia, but has led to dispersal of animals far more widely on a seasonal basis. Both here, and throughout the Scotia arc, as well as increasingly further south along the Antarctic Peninsula, increasing numbers of fur seals coming to ice-free areas to rest and moult have led to the rapid destruction of or large scale changes in the previously dominant and typical cryptogam-dominated terrestrial floras (and their associated faunas) over large areas of ground accessible from the coast where the majority of well-developed terrestrial ecosystems are found (Favero-Longo *et al.*, 2011; Hodgson *et al.*, 1998; Hodgson and Johnston, 1997; Lewis Smith, 1988). It has also led to the rapid eutrophication of lake ecosystems accessible to the seals (Butler, 1999; Quayle *et al.*, 2004). This provides an example of a secondary impact of human exploitation of the Southern Ocean marine ecosystem, whose direct consequences for large areas of sub- and maritime Antarctic terrestrial ecosystems already likely far outweighs those of response to regional climate change.

### *28.2.4. Human Populations*

A warming Arctic and the significant changes in the cryosphere are impacting residents across the region through a complex set of physical, environment, cultural, economic, political, and socio-cultural factors operating on and within Arctic communities, which have important implications for the health and well-being of all Arctic populations. These influences are expected to vary significantly among the highly diverse communities which range from small, remote, predominantly indigenous to large northern, industrial settlements. (Chapin et al, 2005; Larsen and Fondahl, 2010) It is estimated that there are between four and 9 million people living in the Arctic depending upon geographic delineation of Arctic which includes original residents (indigenous peoples) as well as a broad spectrum of more recent settlers ranging from subsistence hunters to oil industry personnel to urban office workers. (Huntington et al, 2005; Hovelsrud et al, 2012) During the past century, the composition of Arctic communities and settlements has been shifting dramatically due to seasonal and permanent immigration into the Arctic driven by the development of resources such as oil and gas, fishing, and gold or the necessity to escape problems in homelands outside the Arctic, including some population declines from 2000 to 2005, especially in Russia. (Huntington et al, 2005; Hovelsrud et al, 2012).

Climate change and globalization, contamination, resource development, plus the new activities and residents competing for lands and resources traditionally used by Indigenous peoples, are especially impacting the Indigenous populations of the North and are projected to increase in the future. (Abryutina, 2009; Larsen *et al.*, 2010). The estimated indigenous populations in the Arctic are between 400,000 and 1.3 million. (Hovelsrud et al, 2012; Huntington et al, 2005) Approximate numbers of Indigenous residents are: Canada, 66,000; Denmark, Greenland, 50,000; Norway, Sweden, and Finland, 50,000; Russia, 90,000; and USA, 110,000 (data from 2002 Census; Galloway, 2010) The percent of the populations of indigenous peoples in the Arctic range from 3-4 % in Russia to 80% in Greenland. (Galloway, 2010) Indigenous peoples have been sustained by the region's terrestrial, marine and freshwater renewable resources, including mammals, birds, reindeer, fish and plants for sustenance, cultural, religious, economic, medicinal, and community health for many generations. (Nuttall *et al.*, 2005)(Parkinson, 2009)

However, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, fishing, and herding is increasingly being threatened by climate change and associated multiple stressors.

The Human Population Section (28.2.4) provides a detailed assessment of the impacts of climate-related changes in snow, ice, permafrost, weather, water temperature, loss of habitat plus additional stressors such as poverty, pollution, and territory encroachment on the health and well-being of Arctic residents, with particular attention to Indigenous populations. The health section describes the primary health impacts which include injury and risk from extreme and unpredictable weather; changing ice and snow conditions for safe and predictable hunting, herding, and/or fishing; food insecurity and malnutrition due to decreased access to sources of local foods; increased social and economic problems due to loss of traditional livelihood and culture; contamination of water and food; increases in infectious diseases; permafrost and erosion damage to homes and infrastructure plus loss of homelands and forced relocation of communities. This section focuses on the more vulnerable Indigenous and isolated populations in the Arctic who live in close association with the land as they are already experiencing health disparities and are likely to be more vulnerable to future climate changes. (Larsen *et al*., 2010)(Berner et al, 2005)

*Human Health and Well-Being*

Human health and well-being may be defined as the mental, physical, spiritual, and social well-being plus the absence of disease and infirmity, and includes cultural and social practices as critical contributing factors. (Larsen and Huskey, 2010)(Hild and Stordahl, 2004) To fully understand the potential for projected impacts of climate change on the health and well-being of the diverse communities in the Arctic, it is necessary to take into account a complex suite of underlying interconnected factors including not only additional stressors such as contaminants like POPs (persistent organic pollutants), radioactivity, and heavy metals such as mercury, but also the complicated social, cultural, political, and economic forces operating in these communities such as persistent poverty and lack of health services. (Abryutina, 2009; Ford and Furgal, 2009; Larsen and Huskey, 2010)(AMAP, 2009; UNEP/AMAP, 2011;) Climate change alone is not always the most important factor determining vulnerability in polar communities, but it can be a force that exacerbates other stresses. (Parkinson and Berner, 2009)(Ford et al, 2010; Hovelsrud et al, 2010) In addition, the impacts of these factors influencing community vulnerability vary significantly among the highly varied communities in the Arctic which range from small, remote, predominantly indigenous to large northern, industrial settlements. (Chapin III *et al*., 2005) A significant amount of research has been carried out on the health and well-being of Arctic indigenous populations and, therefore, this section emphasizes both the direct and indirect impacts of climate changes on these more vulnerable segments of the population.

*Direct impacts of climate on the health of Arctic residents*

Direct impacts of climate changes on the health of Arctic residents include extreme weather events (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts). (AMAP, 2009; Berner et al, 2005) Intense precipitation events and rapid snowmelt are expected to impact the magnitude and frequency of slumping and active layer detachment resulting in rock falls, debris flow, and avalanches. (Ford et al, 2010; Hovelsrud et al, 2010) Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration and/or rapid onset of extreme weather events and storms, which, in turn, may create risks to safe travel or subsistence activities, risks to rural and isolated communities, and risk of being trapped outside one's own community. (Andrachuk and Pearce, 2010)( Laidler et al, 2009; 2010) Changing river and sea ice conditions effect the safety of travel for indigenous populations especially, and inhibit access to critical hunting, herding and fishing areas. (Andrachuk and Pearce, 2010)( Ford et al, 2010; Ford, 2009) For example, reductions in land-fast ice plus increased open water area cause less predictable fog and sea-ice conditions, creating treacherous coastal travel conditions and more difficult communications among communities. (Barber et al, 2008)

Cold exposure has been shown to increase the frequency of certain injuries (e.g. hypothermia, frostbite) or accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal, skin). (Revich and Shaposhmikov, 2010). Studies in Northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy, a weakening of the heart muscle or change in heart muscle structure. (Revich and Shaposhnikov, 2010) It is estimated that 2,000 to 3,000 deaths/yr occur from cold-related injury and diseases during the cold season in Finland. These winter-related mortality rates are higher than the number of deaths related to other standard causes in the country during the year (e.g., there are 400/yr from traffic accidents, and 100-200/yr from heat). (Anisimov and Vaughan, 2007) Respiratory diseases among children in Northern Russia are 1.5 to 2 times greater than the national average. It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov et al, 2011; Nayha, 2005). It is also believed that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, some Arctic residents are reporting respiratory and cardio stress associated with extreme warm summer days which has not previously been experienced. (Revich and Shaposhnikov, 2010).

### *Indirect impacts of climate on the health of Arctic residents*

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), the built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion). (Brubaker *et al.*, 2011; Parkinson and Evengård, 2009)( Berner et al, 2005; Maynard and Conway, 2007) Local and traditional knowledge in communities across the Arctic are observing extremes not previously experienced and increasingly unusual environmental conditions (e.g., Ford, 2009; Laidler et al, 2009; Virginia and Yalowitz, 2012). There also appears to be an increase in injuries related to climate changes among residents of northern communities associated with ‘strange’ or different environmental conditions, such as earlier break-up and thinning of sea ice. (Ford, 2009; Ford et al, 2010).

Underlying all climate change impacts and processes, are the complicated stresses from contaminants such as POPs (persistent organic pollutants), radioactivity, and heavy metals (e.g., mercury) which create additional and/or synergistic impacts on the overall health and well-being of the communities. (UNEP/AMAP, 2011; Berner et al, 2005) Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), exposure to contaminants, the risk of infectious diseases in Arctic organisms, and the related increased risks of transmission to residents through subsistence life ways, especially indigenous peoples. (Kraemer et al, 2005; AMAP, 2010; UNEP/AMAP 2011) The consumption of traditional foods by indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants. (Parkinson, 2009)(UNEP/AMAP, 2011) These contaminants such as POPs are known for their adverse effects on humans, particularly, the developing fetus, children, women of reproductive age and the elderly. Thus, contaminants must be a significant part of any climate impact assessment as their potential health effects include serious conditions such as nervous system and brain development problems, interference with hormones and sexual development, weakened immune systems, organ damage, cardiovascular disease and cancer. (Abryutina, 2009)(UNEP/AMAP, 2011).

There are additional concerns regarding radioactivity and climate change because contamination can remain for long periods of time in soils and some vegetation, and because the terrestrial environment can create high exposures for people. (AMAP, 2010) Furthermore, climate changes not only have the ability to mobilize radionuclides throughout the Arctic environment, but can also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events. (AMAP, 2010) Additionally, there is a very high density of potential and existing radionuclide sources in some parts of the Russian Arctic and the risk for accidents is a significant cause for concern. (AMAP, 2010)

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases. (Parkinson and Butler, 2005)(Epstein and Ferber, 2011; Parkinson, 2008;). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia (Ogden *et al*., 2010)(Tokarerich et al, 2011;) and Sweden (Lindgren and Gustafson, 2001), *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean. (Hughes-Hanks et al., 2005). it is also likely that temperature increases will increase the incidence of zoonotic diseases that can be transmitted to humans (Revich et al, 2012; Bradley et al., 2005). Many Arctic zoonotic diseases which currently exist in local host species (e.g., tularemia in rabbits, muskrats and beaver, and rabies in foxes can spread through climate-related mechanisms (such as relocation of animal populations) (Revich et al, 2012; Dietrich, 1981). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, Vibrio parahaemolyticusin, in Alaskan oysters (McLaughlin *et al*., 2005). Finally, there are concerns that the warmer temperatures may raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds. (Revich and Podolnaya, 2011)

The impacts of climate change on food security are critical to human health because subsistence foods from the local environment provide Arctic residents, especially, indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins and essential elements to the diet (Abryutina, 2009; Ford and Berrang-Ford, 2009)(e.g., Ford, 2009). However, climate change is already posing a serious threat to food security and safety for indigenous peoples and the availability of country food because of the impacts on traditional subsistence hunting, fishing and herding. (Andrachuk and Pearce, 2010)(Ford et al, 2010; Ford, 2009; Galloway-MacLean, 2010; Ford et al, 2009) The decrease in predictability of weather patterns as well as low water levels and streams, timing of snow, ice extent and stability are impacting the possibilities for successful hunting, fishing and access to food sources and increasing the probability of accidents. (Ford and Furgal, 2009; Nuttall *et al*., 2005) Populations of marine and land mammals, fish and water fowl are also being reduced or displaced by changing temperatures, ice state, habitats and migration patterns reducing the traditional food supply. (West and Hovelsrud, 2010)(Gearheard et al, 2006)

Furthermore, traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by a warming again reducing food available to the community. (Virginia and Yalowitz, 2012; Hovelsrud et al, 2011) For example, food contamination problems are becoming important wherever thawing of permafrost “ice houses” is occurring for communities and families. (Parkinson and Evengård, 2009)(Hovelsrud et al, 2011) These reductions in the availability of traditional foods are forcing indigenous communities to increasingly depend upon expensive, non-traditional and often less healthy western foods, increasing the rates of modern diseases associated with processed food, such as cardiovascular diseases, diabetes, dental cavities, and obesity. (Berrang-Ford *et al*., 2011)(Ford, 2009; Van Oostdam et al, 2003) A complicating factor in evaluating trade-offs between traditional and market food is that wild foods represent the most significant source of exposure to environmental contaminants.

Climate change is beginning to threaten community and public health infrastructure, most seriously in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought and thawing of permafrost, resulting in loss of reservoirs or sewage contamination. (McClintock, 2009) Salt-water intrusion and bacterial contamination may be threatening community water sources. (Virginia and Yalowitz, 2012) Quantities of water available for drinking, basic hygiene, and cooking are becoming limited due to damaged infrastructure and drought. (Parkinson and Butler, 2005)(Virginia and Yalowitz, 2012) Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure such as sewage lagoons or inadequate hygiene, spreads sewage in villages where the majority of homes have lower water availability because of no in-house piped water source. This, in turn, results in higher rates of hospitalization for pneumonia, influenza, and respiratory viral infections. (Parkinson and Butler, 2005; Parkinson and Evengård, 2009)(Virginia and Yalowitz, 2012) This suggests that reduced water availability because of climate change impacts may result in increase rates of hospitalization among children for respiratory infections, pneumonia, and skin infection. (Virginia and Yalowitz, 2012; Berner et al, 2005(AMAP))

These combined physical, medical, economic, political, socio-cultural, and environmental forces operating on and within Arctic communities today have a important implications for human health and well-being (Curtis *et al.*, 2005)(Ford et al, 2010; Hamilton et al, 2010) The changes in the physical environment which threaten certain communities (e.g., through thawing permafrost and erosion) and which lead to forced relocation of residents or changes or declines in resources resulting in reduced access to subsistence species (e.g., Inuit hunting of polar bear) can be a pathway to rapid and long-term cultural change including loss of traditions. (Anisimov and Vaughan, 2007)(Galloway-MacLean, K., 2010) These losses can, in turn, create psychological distress and anxiety among individuals. (Albrecht *et al.*, 2007; Coyle and Susteren, 2012; Curtis *et al.*, 2005) Additional attention needs to be focused on solutions for the high suicide rates among impacted peoples of the North, particularly, the indigenous populations who are losing the means to practice their traditional customs and maintain their culture, and, therefore, their traditional role in that society. (Albrecht *et al.*, 2007; Coyle and Susteren, 2012)

### *28.2.5. Economic Systems*

Economic activity takes place in both of the polar regions. In the Arctic, economic sectors are confronted with multiple stressors of which climate change is just one (Forbes, 2011; Hovelsrud *et al.*, 2011; Larsen, 2010) (AHDR 2004). Coastal erosion, thawing permafrost, and changing sea-ice conditions, when combined with non-cryospheric drivers of change such as increased economic activity, socio-economic development, demography, governance, health and well-being will result in multifaceted and cascading effects (Hovelsrud *et al.*, 2011).

The Arctic economy consists of a combination of formal and informal sectors, all of which are sensitive to climate change. Formal and market-based economic activity is projected to have both costs and benefits, with some commercial activities becoming more profitable while others will face decline.

Outside of the urban areas indigenous people often mix activities of the formal sector (e.g. commercial fish harvesting, oil and mineral resource extraction, forestry, and tourism) with traditional or subsistence activities, which include harvesting a variety of natural renewable resources to provide for human consumption. Hunting and herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Crate *et al.*, 2010; Larsen and Huskey, 2010; Nuttall *et al.*, 2005; Poppel and Kruse, 2009)(Rasmussen 2005; Poppel 2006; Aslaksen et al 2009). Renewable harvesting is linked both to the subsistence-based informal economy and to the market economy (Glomsrød and Aslaksen, 2006)(Lindholt 2006). It is projected that there will be significant impacts on the availability of key subsistence marine and terrestrial species as climate continues to change, and the ability to maintain one’s economic well-being may be affected. In the early 1990s – initially in western Canada, and later elsewhere - indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to herders, non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes et al. 2009).

In the Antarctic, economic activities include fisheries and tourism. Commercial mining activity does not take place in Antarctica, and fisheries remain the only large-scale resource exploitation activity.

### *28.2.6. Economic Sectors*

#### *28.2.6.1. Arctic*

##### *28.2.6.1.1. Agriculture*

Climate change is *very likely* to have positive impacts for agriculture, including extended growing season, although variations across regions are expected (Hovelsrud *et al.*, 2011). Tree limits in Iceland are now found at higher latitudes than before, and the productivity of many plants has increased. Grain production in Iceland has increased in the last two decades, and work on soil conservation and forestry has benefited from warming (Björnsson et al, 2011). Agricultural opportunities are *very likely* to expand because of a warmer climate, but are *likely* to remain of minor importance to the Arctic economy (Eskeland and Flottorp 2006, 84). Rain-on-snow events and melting and refreezing of snow is *likely* to result in frost damage; increased precipitation and run-off combined with episodes of freezing and thawing which could considerably increase soil erosion in agricultural fields (SWIPA, 2011). In areas with a reduction in snow cover, the growing season may be extended (Grønlund, 2009)(Torvanger et al., 2003; Falloon and Betts, 2009; Tholstrup and Rasmussen 2009). Climate change is *likely* to have economic costs and benefits for forestry (e.g. Aaheim, et al. 2009). The accessibility to logging sites is (an already observed) concern for the forestry industry. There is an observed vulnerability of forestry to changes that affect the condition of roads and thus accessibility during thawing periods (Keskitalo, 2008).

#### *28.2.6.1.2. Open water fisheries*

Fish stocks have been exploited for several centuries in the polar region (Geffen *et al.*, 2011). Commercial fisheries in the polar region of the northern hemisphere are sharply divided between regions of high yield and commercial value such as the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Seas and low volume subsistence fisheries in the coastal regions of the Arctic Ocean (Figure 28-5).

[INSERT FIGURE 28-5 HERE
Figure 28-5: Fishing vessel activity. Source: AMSA, ____.]

In high yield regions, complex management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Hollowed *et al.*, 2011; Livingston and et al., 2011). The performance of these strategies relative to the goal of preventing overfishing and rebuilding overfished stocks differs by region for a variety of reasons including: data quality, enforcement, management policies and strategies for community based management (Gutierrez *et al.*, 2011; Hutchings *et al.*, 2010; Worm *et al.*, 2009). Adopting successful strategies for management of Arctic fisheries will be a high priority to ensure that fisheries are managed based on sound science and sustainable harvest practices in the future (Molenaar, 2009). In regions of high yield fisheries, strategies will be needed to modify existing management practices to account for the expected shifts in distribution and abundance of commercial species to prevent overfishing and sustain fishery resources. As discussed in section 28.2.2.1, several North Atlantic commercial fish species exhibited shifts in their spatial distribution and abundance in response to ocean warming (Valdimarsson *et al.*, 2012) which have lead to non-trivial challenges to international fisheries agreements(Arnason, ). Techniques are under development to project how harvesters will respond to changing economic, institutional and environmental conditions. These techniques track fishers choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). Estimates of future revenues and costs will depend in part on future: demand for fish, global fish markets and trends in aquaculture practices (Merino *et al.*, ; Rice and Garcia, 2011). While attempts to project global changes in small pelagic (e.g. anchovy, sardine, capelin and herring) fish markets have been attempted, extending these to larger fish species will be more difficult.

The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of environmental policy, the abundance of the resource and infrastructure for capturing and processing fish. The remote location, difficulties in accessing fishing grounds especially during winter, and relatively low stock sizes all serve as deterrents to the development of commercial activities in the Arctic Ocean. In the Beaufort Sea, some evidence of range extensions of commercial species including Pacific cod and walleye pollock were observed in the Beaufort Sea (Rand, 2011). However, in the U.S. portion of the Chukchi Sea and Beaufort Sea, a recent analysis showed only three species were found in sufficient densities to support a modest commercial fishery: snow crab (*Chionoecetes opillio*), Polar cod (*Boreogadus saida*) and saffron cod (*Elegins gracilis*) (Stram and Evans, 2009; Wilson, 2009).

As discussed in section 28.2.2.1, it is unclear whether environmental changes in the Arctic Ocean will be conducive to the establishment of fish stocks of sufficient abundance and value to support commercial activity. Advection pathways are favorable to drift from the Atlantic into the Arctic, and the presence of a deep trench lining the Atlantic and the Arctic (Fram Strait) may provide an opportunity for commercial concentrations of fish to colonize the Arctic under ice free summer conditions and increased prey availability. Commercial fishing activity for shrimp and cod already exists north of Svalbard.

### *28.2.6.1.3. Freshwater fisheries*

Several Arctic coastal fishes are targeted for subsistence and commercial use in the Arctic including: chum salmon (*Oncorhynchus keta*), Dolly varden (*Salvelinus malma*), Arctic char (*Salvelinus alpinus*), Arctic grayling (*Thymallus arcticus*) lease cisco (*Coregonus sardinella*) and Arctic cisco (*Coregonus autumnalis*). Fisheries for these species are prized food for native peoples in the Arctic. Commercial transactions from fishing are typically for local markets(Reist, J. D. F. J. Wrona, T. D. Prowse, J. B. Dempson, M. Power, G. Kock, T. J. Carmichael, C. D. Sawatzky,H.Lehtonen and R.F.Tallman, 2006). The quality of catch estimates are reliable for many regions in the southern shelf seas of the Arctic (e.g. eastern Bering Sea, Barents Sea and eastern Canada), however, estimates from the Arctic Ocean are uncertain. Zeller et al (2011) estimated that during the priod 1950 – 2006 the cumulative total catch in the Arctic was higher than had been previously reported by FAO with the highest landings in Russia, followed by the USA, and Canada. The survival of Arctic coastal fishes in the Polar regions depends on a complex suite of environmental conditions (Reist, J. D. F. J. Wrona, T. D. Prowse, J. B. Dempson, M. Power, G. Kock, T. J. Carmichael, C. D. Sawatzky,H.Lehtonen and R.F.Tallman, 2006). Recent studies show that factors that influence the marine exit are critical for survival of salmon and cisco (Moulton, L. L., B. Seavey,J.Pausanna, 2010; Mundy, 2011). Climate change related factors that influence the water level and freshening of rivers will *likely* influence run size of these species (Fechhelm, R. G., B. Streever,B.J.Gallaway, 2007). These impacts could be exacerbated by increased industrialization of the Arctic river systems. Reist et al (2006) hypothesized that climate impacts will expand the availability of suitable habitat for species that typically reside in the margins of the Polar region which could result in colonization of regions to the north, however when or if, this will occur depends on several uncertain processes.

### *28.2.6.1.4. Marine transportation in the Arctic Ocean*

As the extent of multi-year sea ice in the Arctic continues to contract in coming decades (SWIPA, 2011), the opening of new commercial shipping lanes presents socio-economic opportunities. Climate change is expected to lead to an increasingly ice free Arctic Ocean and increased navigability of Arctic marine waters. This is expected to bring economic opportunities to northern, more remote regions (e.g. (Prowse *et al.*, 2009) Peters et al. 2011). New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (Corbett *et al.*, 2010; Khon *et al.*, 2010; Paxian *et al.*, 2010)( Peters et al., 2011). Observations and climate models indicate that in the period between 1979-1988 and 1998-2007 the number of days with ice free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR ) in the Russian Arctic, and by 19 days in the North-West Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980-1999 was 45 and 35 days, respectively (Mokhow and Khon, 2008).The increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific (Østreng 2006, 75). The frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season of natural resources, which is the late spring/summer. In this period, vulnerable natural resources are spread all over the NSR area in the Arctic (Østreng 2006, 74), which may negatively affect the future status of marine, terrestrial and freshwater biota since there will be substantial coastal infrastructure to facilitate offshore developments (Meschtyb, N., Forbes, B., Kankaanpää,P., 2010). Coastal terrestrial and freshwater habitats are especially critical for maintaining the large reindeer herds managed by indigenous Nenets along the Barents and Kara seashores and the loss of access to these pastures and fishing lakes and rivers would likely have knock-on effects throughout the region (Kumpula *et al.*, 2011)(Forbes et al. 2009). Thus, the combined actual and potential socio-economic and social-ecological footprint of commercial shipping is *likely* to be significant (e.g. (Mikkelsen and Langhelle, 2008)). Peters et al. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050, that based on estimated sea-ice extent: there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will be leading to rapid growth in emissions from oil and gas transport by ship (p. 5318).

Increased economic opportunities along with challenges associated with culture, security and environment, are expected in Northern Canada with the increased navigability of Arctic marine waters together with expansion of land- and fresh water-based transportation networks (Furgal C., 2008). An increase in the length of the summer shipping season, with sea-ice duration expected to be 10 days shorter by 2020 and 20-30 days shorter by 2080, is *likely* to be the most obvious impact of changing climate on Arctic marine transportation (Prowse *et al.*, 2009). The reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. These possibilities however also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts on the traditional ways of life of northern residents (Furgal C., 2008).

### *28.2.6.1.5. Infrastructure*

Much of the physical infrastructure and the hunting activities in the Arctic rely on and are adapted to local sea-ice conditions, permafrost, snow and the seasonal and behavioral patterns of the harvested fish and animals, which will be affected by the changing sea-ice condition, rendering them especially climate sensitive(Forbes, 2011; Huntington *et al.*, 2007; Sundby and Nakken, 2008; West and Hovelsrud, 2010) (Martin et al. 2009; Sherman et al., 2009). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower also poses major economic costs and risks, which are more closely linked to the design lifetime of the structure than with melting permafrost. Still, current engineering practices are designed to help minimize the impacts (Prowse *et al.*, 2009). Climatic and other large-scale changes have potentially large effects on Arctic communities, where relatively simple economies (depending heavily on resource extraction and subsidies) leave a narrower range of adaptive choices(Andrachuk and Pearce, 2010; Anisimov and Vaughan, 2007; Forbes, 2011; Ford and Furgal, 2009) (Berkes et al 2003; Ford et al 2010a).

According to Prowse et al. (2009) in Northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Prowse *et al.*, 2009)

### *28.2.6.1.6. Resource exploration*

The Arctic has large reserves of minerals (Lindholt, 2006; Peters et al. 2011) and potentially large reserves of undiscovered sources of raw materials, oil and gas. About one-fifth of the world’s undiscovered oil and gas reserves are located within the Arctic region (Gautier *et al.*, 2009). While oil and gas production has declined in some fields, there have been new discoveries in others (AMAP, 2010). Due to high costs and difficult access conditions, and despite future reductions in sea-ice, it is not clear that future oil and gas production in the Arctic will increase (Peters et al., 2011). Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas(Gautier, 2009; Berkman, 2010).The socio-economic impacts on the Arctic region and local communities of oil and gas exploration activity can be positive or negative (Duhaime *et al.*, 2004; Forbes, 2008; Huntington *et al.*, 2007; Kumpula *et al.*, 2011) (Forbes et al. 2009). Arctic resources will *likely* play a growing role in the world economy. At the same time, increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs and responses to accidents (Hovelsrud *et al.*, 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters et al. 2011).

In non-developed deposits located in the Arctic regions, the proven resources of oil and gas make up 5.3% and 21.7% of the world resources, respectively. Almost all of the explored gas deposits and 90% of the explored oil deposits are located in the Russian part of the Arctic regions. Among them, the greatest one is the Shtokman Deposit in the Barents Sea, discovered in 1988 but not developed until now. It contains about 3,200 billion $m^3$ of gas (Lindholt, 2006). About 50% of oil and gas production in the Arctic is oil; in Canada (59%), Alaska (87%), East Russia (9%), West Russia (46%), and in Norway (84%) (Peters et al., 2011). Projected declines in sea-ice covers leading to development of integrated land and marine transportation networks in Northern Canada, is likely to stimulate further mine exploration and development (Prowse *et al.*, 2009). Reduced sea ice extent is projected to lead to increased Arctic shipping of oil and gas with projections of increased future emissions (Peters et al., 2011)

#### *28.2.6.1.7. Informal, subsistence-based economy*

Inuit and Saami have expressed strong concern about how a rapidly warming climate will affect their respective livelihoods (Forbes and Stammler, 2009). For Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn, earlier melt-out in spring, and thinner, less predictable ice in general (Krupnik and Jolly, 2002). Diminished sea ice translates into more difficult access for hunting marine mammals, as well as greater risk for the long-term viability of polar bear populations (Laidre *et al.*, 2008). Since virtually all Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting, a reduction in these resources represents a potentially significant economic loss (Hovelsrud *et al.*, 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal et al., 2009).

Climate change, which is occurring faster in the Arctic than in other regions of the world, is already affecting the reindeer herding communities through greater variability in snow melt/freeze, ice, weather, winds, temperatures (especially warmer winters), and precipitation, which, in turn are affecting snow quality and quantity – the most critical environmental variables for reindeer sustainability.(Eira *et al.*, 2012)(Magga et al, 2011) Reindeer must forage continually and any significant impediment to their ability to access the plants (e.g. lichens) under the snow cover each day can threaten their very survival. (Kitti *et al.*, 2009)(Magga et al 2011). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow which then block the animals' access to their forage and subsequent starvation. (Bongo *et al.*, 2012; Eira *et al.*, 2012; Maynard *et al.*, 2011). Annual migration patterns between summer and winter pastures are being challenged due to changes in the freeze-thaw cycles of rivers and lakes, with spring thaws occurring earlier and soft ice no longer able to support the reindeer as they try to cross. (Abryutina, 2009; Klein *et al.*, 2005)(Magga et al, 2011) Warmer Arctic temperatures have increased insect harassment causing major interference with foraging. (Kitti *et al.*, 2006) Indirect climate change impacts are also occurring, which also have major implications for reindeer pasture availability and migration routes. With the lack of land-fast ice along the Arctic coasts in recent years, longer summers, and intense pressure to develop oil, gas and minerals in the North, the Arctic regions are becoming far more accessible to humans and industrial development, resulting in additional sources of increasing and irreversible loss of pasturelands. (Bongo *et al.*, 2012; Kitti *et al.*, 2006).

Over the millennia, reindeer herding has developed a strong resiliency to climate change and variability because it is a system which has constantly been subjected to extensive weather-related variations on a day-to-day basis as well as during seasonal migrations. (Klein *et al.*, 2005; Turi, 2008)(Magga et al, 2011) However, in recent years, these successful adaptation strategies which have guided their survival have been challenged by additional external factors such as changing government policies, sharply increasing oil and gas development and mining activities, overall pasture loss, and blocking of migration routes. (Abryutina, 2009)( Magga et al, 2011) The increasing global demand for energy and mineral resources plus an aggressive development of oil and gas fields as well as mining of other resources are encouraging rapid development with its associated infrastructure, pipelines, drill pads, roads, and pollution all across the once-rich pasture lands of the reindeer seasonal migration routes. (Magga et al, 2011; Forbes and Stammler, 2009) In many locations, the associated infrastructure is being built across migration routes in Northern Russia, often blocking pathways to seasonal pastures and eliminating camping and fishing site for herders. (Rees *et al.*, 2008)( Forbes et al, 2009; Degteva et al, 2010)

### *28.2.6.2. Antarctica and the Southern Ocean*

The primary economic activities that currently take place in Antarctica revolve around fisheries and tourism. Scientific activity by a number of nations is also taking place and has the potential to impact upon local habitats and communities. Mineral resource activity is currently prohibited south of 60°S until at least 2048 under the Protocol on Environmental Protection to the Antarctic Treaty. All activities in the region are currently regulated under the governance regimes described in Section 28.2.7, unless sovereign activities in subantarctic territories are exempted from those regulations. Patterns of fisheries and vulnerabilities are likely to be affected by climate change.

#### *28.2.6.2.1. Fisheries*

The Southern Ocean has experienced two centuries of exploitation of marine species. The current fisheries include Antarctic krill, Patagonian and Antarctic toothfish and mackerel icefish(SC-CAMLR 2011). Future fisheries may include grenadiers and myctophid fish, although the latter has proved not to be profitable in the past (Constable, 2011). At present, it is not clear what the prognosis for these fisheries will be into the future, although the Antarctic krill fishery could become the largest fishery in the world, and is the fishery with the greatest opportunity for expansion (Nicol and Endo, 1997). If the current fishery in the southwest Atlantic were to take the Total Allowable Catch of 5.6 million tonnes, it would equate to approximately 6% of existing marine capture fisheries (Nicol et al. 2011). Current catches are approximately 210,000 tonnes (CCAMLR 2011).

The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula. In recent years, the fishery has been taking advantage of the ice-free conditions and taking more of its catch during winter in that region (Kawaguchi *et al.*, 2009) . This changing pattern in the krill fishery will need to be accounted for by CCAMLR in the management strategy for the fishery.

The catch limits for Antarctic krill fishery around Antarctica total 8.6 million tonnes. There is evidence that the fishery is expanding (Nicol et al. 2011). In the future, it is likely that catch levels will be larger than at present but this will depend more on economic rather than environmental constraints in the short to medium term.

At present, CCAMLR takes a precautionary approach in its implementation of the ecosystem approach stipulated within its Convention text (Constable *et al.*, 2000). It sets annual catch limits for each of its fisheries. The catch limits aim to maintain stocks at or above target levels while taking into account uncertainties over stock status and the parameters used to assess current and future dynamics. The target levels for toothfish are set according to targets for top predators – the median status of the spawning stock is aimed to be 50% of the median prior to fishing. The target levels for icefish and Antarctic krill are set according to targets for prey species, which at present is for the median status of the spawning stock to be 75% of the pre-exploitation median.
CCAMLR aims to develop a feedback management procedure for krill fisheries based on indicators of the status of krill and its predators (Constable, 2011; Croxall and Nicol, 2004; Kock *et al.*, 2007; Nicol and de la Mare, 1993). Monitoring is being undertaken through the CCAMLR Ecosystem Monitoring Programme (Agnew, 1997). However, at present this work does not factor in measures to account for climate change impacts on the ecosystem (Constable, 2011; Trathan and Agnew, 2010). Importantly, CCAMLR is yet to adopt an approach that can differentiate between climate change and fishery impacts on the food webs.

#### *28.2.6.2.2. Tourism*

Ship-based tourism is a growing industry in Antarctica. In recent years, the number of tourists visiting Antarctica has risen markedly, with tourist numbers having increased from 7413 in 1996/1997 to 29,530 in 2006/2007 (IAATO, 2007). For example, at Goudier Island (64°49´S, 63°29´W), to the west of the Antarctic Peninsula, tourist numbers have risen steadily during this same time period, having increased from 4292 to 16,004. Tourists visit Antarctica in order to visit wildlife and to experience wilderness. As the numbers of tourists have increased, concerns have been expressed about the potential disturbance caused by visitors, e.g. visitors approaching too close to penguin colonies whilst either on foot or by cruising in Zodiacs. Pollution resulting from tourist vessels is generally minimal, however concerns have been raised over a number of incidents recently when tourist vessels have foundered. Tourism activity on land is expected to increase as more ice-free areas become available, making more likely the introductions of alien species to terrestrial environments.

### *28.2.7. Governance in the Polar Regions*

Dealing with the stresses of climate change and other changing factors in the Polar Regions requires robust governance regimes. The Arctic and Antarctic Regions are governed by quite different regimes that reflect their geographic and political contexts. The Arctic is essentially an ice-covered ocean surrounded by sovereign states whereas the Antarctic is a terrestrial continent that has remained unpopulated except for isolated research stations.

The Antarctic is governed by a Treaty System that originally included the 12 nations who were involved in the Antarctic during the International Geophysical Year of 1957-58. The Treaty, negotiated during the Cold War tensions, was signed in December 1959 and entered into force on June 1961. The primary purpose of the Antarctic Treaty is to ensure "in the interests of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord." The Treaty holds all territorial claims in abeyance. It is generally seen as one of the “success stories” of contemporary international law (Rothwell, 2012). The Antarctic Treaty system is supported by the Scientific Committee for Antarctic Research (SCAR).

The parallel for the Arctic is the Arctic Council which was formally established in 1996 as a high level intergovernmental forum to provide a means for promoting cooperation, coordination and interaction among the eight Arctic States and the Arctic Indigenous communities on common Arctic issues such as sustainable development and environmental protection. The Arctic Council is supported by several Working Groups. The International Arctic Science Committee (IASC) which preceded the Arctic Council, being established in 1990, like SCAR is also under the umbrella of ICSU. The Arctic Council and the IASC carried out the Arctic Climate Impacts Assessment (ACIA, 2004). The most recent activity of the Arctic Council, in conjunction with IASC, was the Snow, Water, Ice and Permafrost Assessment (SWIPA, 2012). An Aeronautical and Maritime Search and Rescue agreement, signed in 2011, is the first legally-binding agreement negotiated under the auspices of the Arctic Council. Despite such achievements, the Arctic Council is still regarded by some as tentative – a “soft law regime” (Rothwell, 2012).

Since climate change, particularly in the Arctic, has been observed to be occurring faster than the global trend, it is not surprising that it has been a preoccupation of both the Antarctic Treaty System and the Arctic Council (Byers, 2010; Rayfuse, 2007).

Climate change might bring increased productivity in some fish stocks and changes in spatial distributions of others. New areas may become attractive for fishing, for example off-shore of Antarctica not presently governed by the Antarctic Treaty and its Convention for the Conservation of Antarctic Marine Living Resources (1982) as well as in ice-free regions of the Arctic where there is no legally binding fisheries conservation and management regime (EU, 2008). The case of whaling in the Southern Ocean is an example (Rothwell, 2012). This might lead to unregulated fisheries and possible conflicts (Distefano, 2008).

Retreating sea-ice in the Arctic is expected to open up new commercial opportunities for gas, petroleum and mineral activities (Borgerson, 2008; Paskal, 2010)(UNDP, 2009). The establishment of Exclusive Economic Zones has proceeded in peaceful fashion and the provisions of the United Nations Convention on the Law of the Sea (UNCLOS) and the UN Commission on the Limits of the Continental Shelf have generally been respected (Gleditsch, 2011). Such regimes can be expected to be important in addressing any competition between the Arctic coastal states for control over outer continental shelf claims.

Retreating ice will also open up new opportunities for shipping as well for a more intensive use of the Northern Sea Route and North-West Passage (Konyshev V.N., 2011). This may increase competition for the control of these passages and, at the same time, emphasize the need for effective pollution prevention regulations such as the Government of Canada’s Arctic waters Pollution Prevention Act of 1970 (Pharand, 1988).

Some scholars have argued that there could be sovereignty-related disputes in support of broad economic interests (Konyshev V.N., 2011) although most observers seem to agree with Haftendorn (2010) that a mad race to the Pole is not very likely, nor is a military conflict among the contenders (Gleditsch, 2011).

These issues and others illustrate the importance of science-based innovation in the conservation, management and governance of Arctic resources. A non-governmental initiative intended to help inform such matters is the Arctic Governance Project (Report of the Arctic Governance Project, 2010).

### *28.2.7.1.Indigenous Peoples, Climate Change, and Traditional Knowledge*

Indigenous populations in the Arctic are considered especially vulnerable to climate change, due to their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall *et al.*, 2005; Parkinson, 2009). Arctic residents in general depend heavily on the region's terrestrial, marine and freshwater renewable resources, including fish, mammals, birds, and plants (Hovelsrud *et al.*, 2011; Nuttall *et al.*, 2005). However, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by climate change. The risks are spatially and temporally heteregenous and encompass potential synergies with other, non-climatic drivers, such as general globalization and resource development (e.g., oil and gas extraction, mining), and the prevalence in many indigenous communities of poverty, marginalization, and resulting health disparities. (Abryutina, 2009; Hovelsrud *et al.*, 2011)(Magga et al, 2011).

Indigenous and local communities as well as scientists must therefore think in terms of multiple stressors, since in any one area there may be significant synergies resulting from combinations of rapid climate and/or land use change coupled, in the worst cases, with non-adaptive forms of governance (Forbes, 2006; Kumpula *et al.*, 2011; Sydneysmith *et al.*, 2010; Tyler *et al.*, 2007). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion which, in turn, are causing such severe loss of land in some regions that a number of Alaskan villages are having to relocate entire communities (Bartsch *et al.*, 2010; Bongo *et al.*, 2012; Brubaker *et al.*, 2011; Mahoney *et al.*, 2009; Weatherhead *et al.*, 2010)(Forbes et al. 2009, 2010; Magga et al, 2011; Macias-Fauria et al. in press).

The historical, accumulated knowledge of Indigenous peoples (also known as indigenous, traditional, or local knowledge which also includes "traditional ecological knowledge" or TEK) is increasingly emerging as a critical source of information for comprehensively addressing the impacts of environmental and other changes as well as the development of appropriate adaptation and response strategies for Indigenous communities. (Nakashima et al 2012; Magga, need date) Reflecting the importance of the incorporation of this knowledge for adaptation and response strategies, the IPCC Fourth Assessment Report acknowledged Indigenous knowledge as "an invaluable basis for developing adaptation and natural resource management strategies in response to environmental and other forms of change" and this IPCC Fifth Assessment includes a number of sections on Indigenous knowledge in several chapters. (e.g., Polar Regions, 28.2 – 28.4 and Human Security, 12, 12.3.2) (Nakashima et al 2012)

Indigenous knowledge has been characterized as "knowledge and know-how accumulated across generations, and renewed by each new generation, which guide human societies in their innumerable interactions with their surrounding environment" (Nakashima et al 2012) and can be considered traditional due to its origins in traditional cultures. (Magga, need date) Indigenous, traditional &/or local knowledge are terms which are considered to be enough alike to be used interchangeably, while other similar terms sometimes convey a more specific definition such as traditional ecological knowledge (TEK), which emphasizes the relationships between living entities and the environment, and farmer's knowledge. (Nakashima *et al.*, 2011; Reinert *et al.*, 2009)( Berkes, 1999)

Indigenous knowledge and TEK consist of beliefs, rituals, and understandings about the dynamic relationships between living entities and the environment, and is a body of knowledge that has evolved through adaptive processes and handed down through generations (Berkes, 2008; Nakashima *et al.*, 2011; Reinert *et al.*, 2009)( Magga 2-pager?). Indigenous knowledge and TEK are useful for detecting and adapting to climate change impacts because climate models often have low resolution at local and even regional scales, and this is precisely the scale at which indigenous observations emerge. Examples include Sámi knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter and spring reindeer rangelands (Eira *et al.*, 2012; Riseth *et al.*, 2011;

Roturier and Roué, 2009). It is worth noting that non-indigenous residents can also have observations critical to tracking and understanding rapid change (Kumpula, T., Forbes, B., Stammler,F., 2010). The IPCC's fourth assessment (Anisimov and Vaughan, 2007) recognized that Arctic Indigenous knowledge, which provides a detailed knowledge base to help understand environmental change over time, was especially useful for observations about climate change and for long-term adaptation. Indigenous Knowledge has also been recognized at the global level in a recent report prepared by UNESCO for the IPCC AR5, which pays special attention to the systematic observations provided by Arctic indigenous communities (Nakashima *et al*., 2011). While Indigenous knowledge and traditional knowledge are important for climate assessments (Green and Raygorodetsky, 2010; Huntington *et al*., 2004; Salick and Ross, 2009)(Ford et al., 2011), not all indigenous community members share the same expert knowledge and Indigenous knowledge and TEK must always be contextualized within its social, political, and cultural contexts (CULLEN-UNSWORTH *et al*., 2011; Huntington *et al*., 2004)(Ford et al., 2009;).

In many cases, Indigenous knowledge, traditional ecological knowledge, and Western science detect the same climate change impacts, thereby increasing confidence about the effects of climate change on Arctic environments and societies. In some instances, however, the interpretations differ and caution is recommended before drawing firm conclusions (Huntington *et al*., 2004). The perception of change at the community level can be as important as scientifically detectable or measurable change in determining whether and how to respond to indirect environmental or more direct anthropogenic drivers (Alessa et al. 2008; Forbes and Stammler 2009). Indigenous knowledge and TEK have long been incorporated into co-management regimes in the North American Arctic (Forbes and Stammler 2009). Its application to date in Eurasian renewable resource management institutions has been mostly limited to marine fisheries (Jentoft 2000), but there have been tentative movements towards co-management style arrangements in e.g. Norwegian reindeer management (Ulvevadet, 2008). In both North America and northernmost Europe, the results to date are mixed and there is ample room for improvement (Berkes and Dyanna, 2001; Berkes, 2009; Kofinas, 2005; Meek *et al*., 2008; Ulvevadet, 2008)(Dowsley 2009; Forbes and Stammler 2009).

At a more basic level, Indigenous knowledge and TEK have proven applications in broadening our understanding of ongoing climate and land use changes and their combined ecological and social implications across the circumpolar North (Kumpula *et al*., 2012; Riseth *et al*., 2011; Sydneysmith *et al*., 2010). At Clyde River, Nunavut, Canada, Inuit experts and scientists note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard *et al*., 2010). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability and timing of river freeze-thaw patterns from increasing temperatures (Eira *et al*., 2012; Maynard *et al*., 2011; Oskal, 2008)(Magga et al, 2011). On the Yamal Peninsula in West Siberia, detailed Nenets observations and recollections of iced over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch *et al*., 2010).

In Deline, Northwest Territories, Canada, there has been an increase of forest fires caused by lightning strikes, which may be the result of long-term climate change rather than just available fuel or weather conditions (Woo, M., Modeste, P., Martz, L., Blondin, J., Kotchtubajda, B., Tutcho, D., Gyakum, J., Takazo, A., Spence, C., Tutcho, J., di Cenzo, P., Kenny, G., Stone, J., Neyelle, I., Baptiste, G., Modeste, M., Kenny, B., Modeste,W., 2009). At Baker Lake, Nunavut, Canada, afternoon temperatures over the last 20 years have fluctuated much more during springtime than they had during the previous 30 years (Weatherhead *et al*., 2010). In the Canadian Arctic, there is also agreement between Inuit knowledge and scientific studies about the thinning of multiyear sea ice; the shortening of the sea ice season; the declining extent of sea ice cover, with Inuit experts reporting less predictability in the sea ice and more hazardous travel and hunting at ice edges; a decrease in the quantity of multiyear and first-year sea ice; an increasing distance of multiyear ice from the shore; and variability and uncertainty in sea ice during transition months of the year, when freeze-up and breakup occur (Aporta *et al*., 2011; Department of Environment and Government of Nunavut, 2011; ITK, 2007; Krupnik and Ray, 2007; Laidler, 2006; Nichols, T., Berkes, F., Jolly, D., Snow, N., Sachs Harbour (N.W.T.),T., 2004)( Ford et al., 2009). While research demonstrates the important ways in which Indigenous knowledge and TEK can contribute to the detection of climate change, there are often discrepancies between Indigenous knowledge and TEK and scientific observations that indicate uncertainty in the identification of climate change impacts (see Box 18-4; (Gearheard *et al*., 2010; Huntington *et al*., 2004; Wohling, 2009; Woo, M., Modeste, P., Martz, L., Blondin, J., Kotchtubajda, B., Tutcho, D., Gyakum, J., Takazo, A., Spence, C., Tutcho, J., di Cenzo, P., Kenny, G., Stone, J., Neyelle, I., Baptiste, G., Modeste, M., Kenny, B., Modeste,W., 2009).

While Arctic indigenous peoples are facing unprecedented impacts to their lifeways from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they have already implemented creative ways of adapting (Alexander *et al.*, 2011; Bongo *et al.*, 2012; Cruikshank, 2001; CULLEN-UNSWORTH *et al.*, 2011; Forbes, 2006; Green and Raygorodetsky, 2010; Krupnik and Ray, 2007; Salick and Ross, 2009)(Magga et al, 2011). They are combining Indigenous knowledge with western scientific knowledge about the ecology and its interrelationships with economic and cultural systems to develop the resilience of ecological and social systems and to identify those factors which can enhance that system's potential for self-sufficiency and sustainable development (Eira *et al.*, 2012; Maynard *et al.*, 2011; Nakashima *et al.*, 2011; Reinert *et al.*, 2009)(Forbes et al. 2009; Gearheard et al, 2006'). Examples of indigenous adaptation strategies have included changing resource bases, shifting land use and/or settlement areas, combining technologies with Indigenous knowledge, changing timing and location of hunting, gathering, herding, and fishing areas, and improving communication and education (Bongo *et al.*, 2012)(Galloway, 2010). Local and state governance regimes or other institutions too rigid to accommodate relevant Indigenous knowledge or local knowledge are likely to increase vulnerability to rapid change (Tyler *et al.*, 2007), whereas flexible institutions responsive to Indigenous knowledge and local knowledge in real time can enhance resilience(Kumpula *et al.*, 2012; Meek *et al.*, 2008; Sydneysmith *et al.*, 2010) (Forbes et al. 2009).

#### *28.2.7.2. Reindeer, Climate Change, Development, and Adaptation*

Interactions between reindeer (*Rangifer tarandus* L.) and humans date from the late Pleistocene onward and wild and semi-domestic animals continue to be highly valued by indigenous and non-indigenous peoples throughout the Arctic for a diversity of purposes (Forbes and Kumpula, 2009)(Müller-Wille et al. 2006). The latest data point to independent nodes of domestication in Fennoscandia and northwest Russia (Røed *et al.*, 2008). Evidence for active management of reindeer herds, such as the use of leading fences/enclosures and corrals for handling animals, dates back two or three thousand years (Røed *et al.*, 2008)(Müller-Wille et al. 2006). However, more intensive reindeer husbandry has developed relatively recently, from about the 17th century onward (Baskin, 2010; Ingold, 1980; Krupnik, 1993)(Müller-Wille et al. 2006). Over centennial time scales, external pressures on reindeer herding societies alongside climate change have ranged from taxation, cultural and religious assimilation policies, and competing forms of land use such as forestry, agriculture, hydropower, mining, and hydrocarbon extraction(Forbes, 2006; Ingold, 1980; Krupnik, 1993; Tyler *et al.*, 2007) (Ingold, 2009; Müller-Wille et al. 2006). This section focuses primarily on adaptation of reindeer herding to climate change and development in the late 20th and early 21st centuries.

Contemporary reindeer management functions as a coupled social-ecological system characterized by a nomadic or semi-nomadic lifestyle undertaken by family- or shift-based, indigenous and mixed ethnicity communities (Forbes, 2006)(McCarthy et al, 2005; Magga et al, 2011). Migration routes within and among seasonal pastures vary widely from tens to several hundred kilometres. The reindeer lies at the very core of these communities, providing primary food, economy, way of life, clothing, mythologies, ceremonies, status, festivals and the basis for a strong political discourse among increasingly powerful competing land users (Forbes, 2006; Oskal, 2008; Paine, 2009; Stammler, 2005),

Climate change, which is occurring faster in the Arctic than in other regions of the world (Callaghan *et al.*, 2011a; Wang, 2009) (Post et al. 2009), is already affecting the reindeer herding communities through greater variability in temperature, and precipitation. This increased variability affects overall weather patterns and exerts strong influence on snow quality, quantity and duration (Callaghan *et al.*, 2011b; O N Bulygina and V N Razuvaev and,N.N.Korshunova, 2009; Olga N Bulygina and Pavel Ya Groisman and Vyacheslav N Razuvaev and Vladimir,F.Radionov, 2010) – the most critical environmental variables for reindeer sustainability (Eira *et al.*, 2012; Riseth *et al.*, 2011; Roturier and Roué, 2009)(Magga et al, 2011). Reindeer must forage continually and any significant impediment to their ability to access the plants (e.g. lichens) under the snow cover each day can threaten their very survival (Kitti *et al.*, 2006)(Magga et al 2011). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow which then block the animals' access to their forage and subsequent starvation (Bartsch *et al.*, 2010; Bongo *et al.*, 2012; Eira *et al.*, 2012; Maynard *et al.*, 2011). Annual migration patterns between summer and winter pastures are being challenged due to changes in the freeze-thaw cycles of rivers and lakes, with spring thaws occurring earlier and soft ice no longer able to support the reindeer as they try to cross and by the appearance of new infrastructure such as oil and gas pipelines, roads, and buildings. (Abryutina, 2009; Klein *et al.*, 2005)(Magga et al, 2011). Warmer Arctic temperatures have increased insect harassment causing major interference with foraging (Kitti *et al.*, 2006). Indirect climate change impacts are also occurring, which have similarly important implications for reindeer pasture availability and migration routes. With the lack of land-fast ice along the Arctic coasts in recent years, longer summers, and intense pressure to develop oil, gas and minerals in the North, the Arctic regions are becoming far more accessible to humans and industrial development, resulting in an additional sources of increasing and irreversible loss of pasturelands (Bongo *et al.*, 2012; Kitti *et al.*, 2006)( Forbes et al. 2009).

Over the millennia, wild and semi-domestic reindeer population have developed a strong resiliency to climate change and variability because, in fact, it is a species which has constantly been subjected to extensive weather-related variations on a day-to-day basis as well as during seasonal migrations (Klein *et al.*, 2005; Turi, 2008)(Magga et al, 2011; Müller-Wille et al. 2006). As herding has developed and intensified across much of northern Eurasia over the past few centuries, the resulting linkages between humans and reindeer have proven resilient in many regions yet collapsed or declined significantly in part of post-Soviet Russia (Baskin, 2010; Jernsletten and Klokov, 2002; Krupnik, 2000; Ulvevadet and Klokov, 2004). However, in recent years, these successful adaptation strategies which have guided their survival have been challenged by additional external factors such as changing government policies, sharply increasing oil and gas development and mining activities, overall pasture loss, and blocking of migration routes(Abryutina, 2009; Forbes, 2006; Hausner, 2011; Marin, 2006; Riseth and Vatn, 2009; Stammler, 2008) (Magga et al, 2011). In fact, the increasing global demand for energy and mineral resources plus an aggressive development of oil and gas fields as well as mining of other resources are encouraging rapid development with its associated infrastructure, pipelines, drill pads, roads, and pollution all across the once-rich pasture lands of the reindeer seasonal migration routes(Kumpula *et al.*, 2012; Kumpula *et al.*, 2011) (Magga et al, 2011; Forbes and Stammler, 2009; Forbes et al. 2009). In many locations, the associated infrastructure is being built across migration routes in Northern Russia, often blocking pathways to seasonal pastures and eliminating camping and fishing site for herders (Kumpula *et al.*, 2012; Kumpula *et al.*, 2011; Rees *et al.*, 2008)( Forbes et al, 2009; Degteva et al, 2010). This is especially important as it is well-known that female reindeer and their calves will avoid humans and their activities as well as physical infrastructure. Nomadic populations of Nenets herders in northern Russia cite these reasons when stating that hydrocarbon extraction represents a greater immediate threat to their continued viability on the tundra relative to the types of extreme weather associated with a warming climate (Forbes and Stammler 2009; Forbes et al. 2009).

Of particular concern today, it is estimated that the Arctic may contain approximately 25 % of the world's remaining undeveloped petroleum resources (Forbes, 2000). For example, Yamal in Western Siberia has approximately 90 % of Russia's gas reserves, but at the same time is the most productive area of reindeer herding in the world (Forbes and Kumpula, 2009; Jernsletten and Klokov, 2002; Stammler, 2005). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to the loss of "available room for adaptation" for reindeer husbandry (Nuttall *et al.*, 2005)(Forbes et al. 2009). Furthermore, it is anticipated that there will be sharp increases in future oil and gas and other resource development in the Russian North and other Arctic regions – along with its associated infrastructure, pollution, and other by products of development – which will, in turn, reduce the availability of available pasturelands for the reindeer and the indigenous communities associated with them (Forbes, 2006; Jernsletten and Klokov, 2002) (Forbes, 2000; Derome and Lukina, 2010). Together with the symptoms of ongoing climate warming cited above, these factors present major concerns for the future of reindeer husbandry, the well-being of the Arctic indigenous and other communities, especially the reindeer herding communities, and the ability of these communities to adapt to future changes (Kumpula *et al.*, 2012; Kumpula *et al.*, 2011)(McCarthy et al, 2005; Forbes et al. 2009; Magga et al, 2011).

## 28.3. Key Projected Impacts and Vulnerabilities under Different Climate Pathways

### *28.3.1. Hydrology and Freshwater Ecosystems*

*28.3.1.1.Arctic*

Accompanying projected increases in Arctic river flow (see WGII Chaper 3) is a shift to earlier timing of spring runoff (Dankers and Middelkoop, 2008; Hay and McCabe, 2010)(Pohl *et al*., 2007) and an increase in the magnitude of spring snowmelt, particularly in areas with winter temperatures <-30ºC (Adam *et al*., 2009). Based on the results of a study on the Canadian Archipelago (Lewis and Lamoureux, 2010), spring fluxes of sediment are also projected to increase with spring flows (+100 to 600% by the end of the 21st century based on CGCM3 A1b and A2 scenarios, respectively). Such estimates are considered conservative, however, because the modelling did not consider the potential for enhanced permafrost thaw.

Although snow, freshwater ice and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). In the case of small permafrost streams, however, even if the thickness of their hyporheic zones does not substantially deepen, longer projected periods of flowing water will modify nutrient and organic matter processing in this important biological stratum (Greenwald *et al*., 2008; Zarnetske *et al*., 2008). In terms of broader aquatic productivity, long-term negative impacts of increased sediment load could outweigh any positive effects associated with increased nutrient loading (Bowden *et al*., 2008).

Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov *et al*., 2007). Studies in the Lena and Kolyma rivers indicated that water pollution by oil is one of the key factors currently affecting the pelagic ecosystems in the coastal zone, which is likely to increase under warmer climatic conditions (Nikanorov *et al*., 2007; Nikanorov *et al*., 2011a; Nikanorov *et al*., 2011b; Nikanorov *et al*., 2011c).

Changes to the dynamics of spring freshet on large Arctic rivers is also projected to change from a reduction in their south to north thermal gradients and, hence, severity of river-ice breakup and ice- jam flooding (D. and Kirsten, 2010). Such a conclusion is based on GCM-ensemble projections of air temperatures (2041–2070 & 2071–2100) along the 4 largest arctic rivers, Lena, Ob, Yenisei and Mackenzie compared to current (1979–2008) conditions. One caveat made on such a projection is the, as yet to be fully evaluated, complicating effect on break-up dynamics of the above noted increases in the magnitude of spring snowmelt.

A reduction in ice-jam flooding would have positive benefits for river-side northern communities and infrastructure but it could also alter the ecology of delta-riparian (Lesack and Marsh, 2010) and coastal-marine (Emmerton *et al*., 2008) ecosystems. The quality of river water entering the marine environment during the spring period is also projected to be affected with the reduction or loss of stamukhi lakes and their distinct microbial assemblages, which play a key functional role in processing river inputs to the marine ecosystems (Dumas *et al*., 2006; Galand *et al*., 2008).

Future changes to lake-ice regimes are also projected to affect lentic ecology. Based on a study of hypothetical 20-m deep lakes in the Northern Hemisphere (between 40° and 75°N), projections from a one-dimensional lake model driven by output from the CGCM3 indicate that future (2040–2079 compared to 1960–1999) lake conditions will be characterized by an overall increase in lake-water temperature, and earlier and longer-lasting summer stratification. Other projections include: freeze-up delayed 5-20 days, break-up advanced by 10-30 days, thickness decreased 10-50 cm, and cover composition modified by changes in snow loads with white ice changing by -20 to +5 cm - the higher latitudes being an area most increase because of the combination of increases in winter snowfall and thinner ice cover that would promote enhanced white-ice formation.

The loss or reduction in duration of ice cover on lakes and corresponding changes in their thermal regimes are likely to affect a number of aquatic processes. Paleolimnological research has shown for a site in the Siberian Arctic that periods of highest primary productivity were associated with warm, ice-free summer conditions, while the lowest rates were coincident with periods of perennial ice (Melles *et al*., 2007). The projected changes in snow and white-ice coverage are also likely to affect levels of secondary productivity, such as in fish (e.g., Borgstrøm and Museth, 2005; (Prowse *et al.*, 2007)). Patterns of species richness and diversity are also projected to change with alterations to ice and open-water durations, with increased open water periods favouring the development of new trophic levels and colonization of new aquatic species assemblages (Vincent *et al.*, 2009). For some lakes, however, the loss of ice will result in the loss of suitable habitat, both in availability and quality (Vincent *et al.*, 2008). For example, lake-ice duration has a controlling influence on the levels and mixing of dissolved oxygen (e.g.(Laurion *et al.*, 2010)). The above-noted projected shifts to increased summer stratification will increase the possibility of oxygen depletion and even anoxia in the bottom waters and reduce the habitat availability for high oxygen-demanding biota during such periods. By contrast, with greater atmosphere-water gas exchange resulting from longer open-water periods, the occurrence of winter kills of resident fish are expected to be reduced and produce cascading effects on lower trophic levels (Balayla *et al.*, 2010).

In addition to habitat alterations, geochemical responses of Arctic lakes will be altered. As observed for certain Arctic thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Laurion *et al.*, 2010)(Metje and Frenzel, 2007). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc *et al.*, 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Laurion *et al.*, 2010; Walter *et al.*, 2007a; Walter *et al.*, 2008; Walter *et al.*, 2007b).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (Solomon *et al.*, 2007), indicates that there will be a 4-27% decrease (0.9-6.4 TgC $yr^{-1}$) in OC burial in lake sediments across the entire northern boreal zone by the end of the 21st Century (Gudasz *et al.*, 2010). Although these estimates are based on an assumption that future organic carbon delivery will be similar to present-day conditions, even with enhanced delivery as to be generated by thawing permafrost, higher water temperatures will increase organic carbon mineralization and thereby lower burial efficiency. The amount of burial will also depend on lake depth and mixing regimes. In the case of warming shallow lakes that are not thermally stratified, there will be a greater opportunity for water-sediment mixing and hence, greater carbon recycling back into the water column. Alternatively, in lakes that become increasingly thermally stratified lakes, carbon sinking below the thermocline is unlikely to return to surface waters until the fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (FLANAGAN *et al.*, 2006).

Changes in ice cover, thermal regimes and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures will likely enhance, for example, the methylation of mercury and modify food-web and energy pathways, such as through enhanced algal scavenging (a major foodweb entry pathway for mercury) resulting in increased mercury bio-availability to higher trophic levels (e.g., predatory fish) (Carrie *et al.*, 2010; Outridge *et al.*, 2007)(AMAP, 2011).

#### *28.3.1.2. Antarctic*

Currently the most vulnerable region in terms of climate change is the Antarctic Peninsula, where temperatures are rising by ~0.55 °C per decade; six times the global mean (Vaughan *et al.*, 2003). In West Antarctica recent instrumental measurements and ice core data have revealed that surface temperatures are rising significantly (Steig *et al.*, 2009)(Schneider and Steig, 2008) and in East Antarctica a re-assessment of temperature measurements has revealed that the continent-wide average near-surface temperature trend is positive (Steig *et al.*, 2009). At present, the ‘ozone hole’ is buffering global warming in East Antarctica and when it closes (towards the middle of the 21st century), warming is predicted to accelerate there as well (Turner *et al.*, 2009b).

Although the Antarctic continent is unusually cold as a result of its polar location and ice sheet, the northern Antarctic Peninsula and maritime Antarctic are within a few degrees of the melting point, so a small shift in temperature regimes can have widespread ecosystem impacts. These range from catastrophic and immediate impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Hodgson, 2011; Smith *et al.*, 2006), to more gradual impacts associated with changes in the amount and duration of catchment ice and snow cover, accelerated glacier melting, and declining volumes of precipitation falling as snow.

As in Arctic lakes, the most marked changes are expected to be associated with changes in the thickness and duration of seasonal ice cover, longer melt seasons and larger volumes of water flowing into the lakes (Lyons et al. 2008). A longer ice free season may cause changes in a lakes mixing regime and release of solutes from the sediments, increased light (including ultraviolet), higher water temperatures, increased $CO_2$ exchange and conditions more favorable for the growth of the plankton, periphyton and benthic communities (Hodgson and Smol, 2008). However in some systems the very high light irradiances experienced during the summer can substantially inhibit algal blooms under ice free conditions (Tanabe *et al.*, 2007). In shallow lakes this favors the growth of benthic cyanobacteria species that can synthesise a number of light screening compounds (Hodgson et al 2004). In other lakes, increases in meltwater supply may reduce light penetration due to an increase in suspended solids, and it remains uncertain whether this will offset the increases in the underwater light regime predicted as a result of extended ice free periods (Quesada *et al.*, 2006).

In glacial forelands increased melting of glaciers has increased water supply to lake catchments. With the exception of two species of flowering plants, vegetation is usually limited to mosses, lichens and microbial communities so nutrient levels are typically low compared with sub-Antarctic and Arctic catchments. This can limit the supply of allocthonous carbon and catchment derived nutrients to the lakes by overland and subsurface flow. Nevertheless, under a warming climate an increase in this catchment microbial biomass would be expected both from increased water supply and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved organic carbon delivery to lakes. This organic supply will promote growth and reproduction in the benthos and plankton. Another observation is that where more melt water is available, input of freshwater into the mixolimna of deeper lakes can increase stability and this, associated with increased primary production, will lead to higher organic carbon flux. Such a change will have follow–on effects including potential anoxia, shifts in overall biogeochemical cycles and alterations in the biological structure and diversity of ecosystems (Lyons, 2006). Conversely, in shallow lakes where water is heated above the 3.98°C maximum density only very moderate winds will be required to cause wind–induced mixing through the ice free periods influencing plankton communities, gas exchange and biogeochemical processes.

Increased temperatures may promote growth and reproduction, but may also contribute to drought and associated effects. At individual locations the susceptibility of lakes to these effects can be predicted from the sedimentary record of past warm periods (e.g.(Hodgson *et al.*, 2005)). Away from glacial forelands, future regional patterns of water availability are unclear, but increasing aridity is likely in some areas of the continent in the long-term (Robinson *et al.*, 2003) (Hodgson et al., 2006). On sub-Antarctic Marion Island a substantial decrease in rainfall has seen dramatic changes in mire communities (Smith, 2002). Lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007).

Climate changes can also impact on species distributions. Unlike much of the Arctic which is connected to lower latitude landmasses, the Antarctic is isolated by steep oceanic and atmospheric thermal gradients, and circumpolar currents and winds which collectively have provided formidable barriers to dispersal. The most obvious example of restricted dispersal is the absence of freshwater fish south of the Antarctic convergence. These barriers have resulted in major restrictions in colonization pathways and as a result Antarctic and sub-Antarctic freshwater ecosystems are very different, and in some cases more vulnerable, than their Arctic counterparts.

For some organisms with good dispersal capabilities, the onset of cold glacial conditions on the continent has resulted in their local extinction, and then (re) colonisation from refuges in the maritime and sub-Antarctic islands and from the higher-latitude southern-hemisphere continents (South America, Australasia) during warm interglacials (Barnes *et al.*, 2006; Clarke *et al.*, 2005). Analyses of biological and biogeochemical markers in a lake in the Larsemann Hills (East Antarctica) show a more productive biological community and greater habitat diversity during the warmer conditions of the last interglacial, together with a diatom flora that is today found in the sub- and maritime Antarctica. From the composition of these interglacial sediments it is safe to predict that future elevated temperatures will allow the sub- and maritime Antarctic taxa to re-invade and establish self-maintaining populations on the continent (Hodgson *et al.* 2006).

For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman *et al.*, 2010). Molecular data shows that at least some of these species have evolved on the continent over multiple glacial interglacial cycles (Fernandez-Carazo *et al.*, 2011; Sabbe *et al.*, 2003; Taton *et al.*, 2006; Vyverman *et al.*, 2007; Vyverman *et al.*, 2010)(Peeters et al 2012 ) and allows for the possibility that Antarctic lakes may contain species that are relicts of Gondwana (cf.(Convey and Stevens, 2007)). These species cannot be replaced from lower latitudes if they were to experience continental extinction as a result of climate changes.

Climate changes are just one of a series of stressors acting on these systems, and must be viewed in the context of human impacts. For example, human activities, rather than natural colonisation processes, are responsible for many of the non-indigenous species being introduced to the sub-Antarctic islands and some parts of the Antarctic continent, although there have been no reports of non-indigenous species surviving in freshwater habitats (Convey, 2008; Frenot *et al.*, 2005b; Greenslade and Van Klinken, 2006). These leave Antarctic ecosystems vulnerable to the impact of colonization by competitors. Furthermore, the combination of increased human visitation across the entire Antarctic region, and the lowering of dispersal and establishment barriers implicit through climate warming, are expected to act synergistically and result in a greater frequency of both transfers and successful establishments. Human activities can also have a direct impact on lakes. For example, increases in silt, nutrients and rock crushing by tracked vehicles from a scientific base has resulted in an increase in heterotrophic microbial activity and conductivity in one Antarctic Lake (Kaup and Burgess, 2002)(Ellis-Evans et al., 1997) and elevated phosphorus and ammonium from wastewater inflow in others (Haendel and Kaup, 1995). Lakes have also been adversely affected by road activities (Harris, 1991)( Lyons et al. 1997) causing increases in silt inputs and nutrient loading (Kaup *et al.*, 2001). Contamination from scientific programmes, including diesel, radioisotopes and camp site residues have also been reported (Vincent 1996). Elsewhere, human impacts on the marine ecosystem are impacting on lakes. For example on Signy Island in the South Orkney Islands, rapid eutrophication has occurred in recent years as a result of increasing populations of seals (which have successfully exploited the food resources formerly used by the whales) transferring marine nutrients into their catchments (Butler, 1999; Pearce *et al.*, 2005).

### *28.3.2. Oceanography and Marine Ecosystems*

#### *28.3.2.1. Arctic*

Arctic marine ecosystems are complex and it is likely that climate change will impact these marine ecosystems, however, predictions of the magnitude and spatial extent of ecosystem change are uncertain and confidence in projections declines at higher trophic levels. Regions at lower latitudes have a rich basis of scientific literature and long time series from which provide the foundation for scientific conclusions. Farther north, the cost and infrastructure needed to conduct research in the region results in fewer researchers working in the area and fewer empirical observations for drawing statistical inference and conclusions.

Recently scientists have attempted to extend the AR4 projections to track how changes in the physical and chemical environment will impact marine foodwebs (See Dedicated Volumes in Progress in Oceanography Volume 90(2011), and ICES Journal of Marine Science Volume 68, issue 6). In the Arctic Ocean, coupled bio-physical models have been used to forecast changes in lower trophic levels under changing climate conditions (Zhang *et al.*, 2010). In the Bering Sea and Barents Seas, several of modeling efforts have extended forecasts to include higher trophic levels (Huse, 2008)(Mueter et al. 2011).

There is robust evidence, high agreement within the scientific community, and statistical evidence that global warming will very likely reduce ice cover and earlier ice breakup will result in a longer growing season (Wang, 2009; Wassmann, 2011)( SWIPA 2011). There is evidence that the Bering Sea will warm by 2 degrees celcius by 2050 (Hollowed et al. 2009). It is likely that the northern Bering Sea shelf will remain ice covered in winter and that the cold pool will remain present in the northern Bering Sea shelf (Stabeno et al. 2010). There is medium agreement and medium evidence that Arctic waters will become stratified due to glacial runoff and solar heating. Lower certainty is assigned to issues of stratification because it is unclear how climate change will impact the strength of inflow of Atlantic water into the Arctic and it is unclear how glacial runoff and solar heating will interact spatially within the Arctic (Wassmann *et al.*, 2011).

There is evidence that that pH of the Arctic Ocean my decline and simulation models project a drop in pH of 0.45 in this century based on the A2 scenario (Steinacher *et al.*, 2008b). These conditions will result in waters being undersaturated with respect to Aragonite a condition that may impact shell formation in some Arctic species.

There is limited evidence and medium agreement that in the short-term, a longer growing season will enhance primary productivity in the Arctic (Arrigo *et al.*, 2008a). There is limited evidence and medium agreement that enhanced production and earlier onset light will lead to an associated extension of the growing season for copepods, especially *Calanus hyperborus, C. glacialis*, and *M. longa* (Suethe et al. 2007). There is insufficient information to predict when, or if, changes in the growing season and ocean conditions will provide conditions necessary for overwintering success for euphausiids in the high Arctic. Changes in stratification and the number of ice free days in the Arctic will ultimately lead to a build-up of pelagic secondary consumers which will result in a reduction in the amount of carbon deposited on the sea floor. These changes will provide a greater prey base for fish and baleen whales that depend on copepods and euphausiids for prey. Changes in stratification and the number of ice free days in the Arctic could lead to a build-up of pelagic secondary consumers which may result in a reduction in the amount of carbon deposited on the sea floor (Grebmeier *et al.*, 2006). These changes would provide a greater prey base for fish and baleen whales that depend on copepods and euphausiids for prey. However, if cold water, lipid-rich copepods like *C.hyperboreus* and *C. borealis* are replaced by the smaller and less lipid-rich copepods like *C. finmarchicus*, the energy content of pelagic prey may decrease.

The effects of climate change on fish and shellfish production and distribution are uncertain and the evidence and consensus regarding outcomes differs by species and region. While changes in the distribution and abundance of fish and shellfish have been observed in the Arctic and its surrounding seas, the absence of a historical baseline in the Arctic Ocean inhibits attribution of observed changes in that region to climate change.

The waters off the coasts of Europe are likely to provide the greatest potential for increased production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. There is good evidence and medium agreement that boreal species such as Norwegian cod, herring and Greenland halibut are capable of expanding their range into the Arctic (Drinkwater, 2011; Sundby, 2008). Historical records show Atlantic cod can adapt to local conditions by shifting key vital rates (diet, growth rate, maturity schedule and survival rate) and reproductive periods to accommodate differences in regional prey availability, predator avoidance and environmental conditions (Sundby and Nakken, 2008)(Vikebo et al. 2007, Ormseth and Norcross 2007). Based on simulation modeling, there is evidence that climate change will affect the Barents Sea ecosystem and these changes will alter the distribution of capelin spawning and feeding grounds under different AR4 carbon emissions scenarios (Huse, 2008). A key factor governing this expansion will be the availability of pelagic prey.

Fewer commercial fish species from the Pacific are expected to colonize the Arctic because of the shallow depth of the Bering Strait, the continued formation of the cold pool in the northern Bering Sea, and the comparatively weaker flow into the Arctic. There is medium evidence and medium agreement that increased summer sea surface temperatures will cause a decrease the abundance of energy rich zooplankton in the eastern Bering Sea. Decreased availability of energy rich zooplankton is expected to result in lower survival of walleye pollock stocks in the eastern Bering Sea (Hunt *et al.*, 2011) (Mueter et al 2011). There is medium agreement that walleye pollock in the eastern Bering Sea will shift their distribution in response to shifts in ocean temperature. The persistence of winter ice formation and the associated formation of the cold pool in the northern Bering Sea will deter range expansions of sub-Arctic species into the Arctic Ocean (Stabeno et al. 2011, Sigler et al. 2011).

#### *28.3.2.2.Antarctica and the Southern Ocean*

Movement of the frontal systems and associated oceanographic mesoscale features such as eddies and filaments where increased productivity attracts top predators may not only cause a shift southward of many pelagic taxa but also make it energetically inefficient for some land-based predators to pursue those prey from their more northerly breeding sites (Weimerskirch et al. submitted). Such an outcome is not usually considered among the consequences of climate change impacts but could have dramatic implications for populations of marine predators on subantarctic islands.

Projections show that the loss of summer sea ice from the west Antarctic Peninsula are expected to result in ice-dependent seals declining in WAP and being replaced by southern elephant seals and/or other seal species that are not dependent on sea ice (Costa *et al.*, 2010). Importantly, the change in duration of the winter sea ice season and a possible continued change in timing of the season could impact on the potential productivity of phytoplankton because of the mismatch in timing of optimal growing conditions at the time of sea ice melt and the available light (Trathan and Agnew, 2010). This mismatch in timing can also propagate through the food web to impact on krill and upper trophic levels that depend upon krill.

Changes in winter sea ice extent in areas where there has always been little sea ice may have a more pronounced ecological effect than proportional declines in areas where there has historically been extensive sea ice in winter. For example, the East Antarctic marine system has extensive sea ice in winter and large areas of open ocean in summer and these characteristics will influence how the ecosystems respond to future changes.

For Antarctic krill, the prognosis overall is ambigous. Krill will naturally respond to warming with an increased metabolic rate but its overall growth rate is dependent on having enough food to support it. The changes in temperature at the Antarctic Peninsula will enhance the productivity of krill but the response is likely to be negative at South Georgia because of the already warmer temperatures in that area (Wiedenmann *et al.*, 2008). It may well be that with warming, the South Atlantic islands with their krill-based systems may come to resemble more the fish-based ecosystems of the Indian Ocean sector (Trathan *et al.*, 2007).

However, regional variation of factors that could impact directly on krill both positively and negatively will likely result in region-specific responses. Also, the response could be affected by the ability of krill to adapt physiologically and behaviourally. Recently, it has been shown that krill can exploit the full depth of the ocean, thus their potential habitat is far greater than once thought (Schmidt et al. 2011). The combined effects of changing sea ice conditions and its possible effects on productivity as well as on krill survivorship, reproduction and recruitment remain to be investigated. As well, new research is showing that the survival of larval krill may be negatively affected by increasing ocean acidity (Kawaguchi *et al.*, 2011).

### *28.3.3. Terrestrial Environment and Related Ecosystems*

#### *28.3.3.1. Arctic*

Projections of future ecosystem distribution and production are based on one of two approaches: field experiments that simulate future environments such as increases in summer air temperature, soil temperature, precipitation, UV-B radiation, atmospheric CO2 concentrations, soil nutrients, snow depth, snow cover duration and or facilitation/competition from pre-existing species, and mathematical models. Both approaches have uncertainties. However, both approaches concur that climate warming will result in a generally northward migration of vegetation zones dominated by the particular responsiveness of woody plants – both shrubs and trees.

Model projections include equilibrium models based on climate and vegetation zone distributions and also dynamic vegetation models based on physiological and ecological processes.

Many models project a general northward movement of the boreal forest under a warming climate, that will displace between 11% and 50% of the tundra within 100 years (Callaghan *et al.*, 2005; Wolf *et al.*, 2008) (Vygodskaya et al., 2007; Sitch et al., 2008; Tchebakova et al., 2009) in a pattern similar to that which occurred during the early Holocene climatic warming

The BIOME 3 equilibrium model applied to Europe and northern Asia projected general displacement of tundra by forest that amounted to between 10 and 35% (the minimum in Scandinavia and the maximum in central-Northern Siberia) (Harding et al. (2001). Estimates of displacement of tundra by forest from similar models varied up to a maximum of 50% (ACIA 2005). A recent model for Russia projected that as early as the first quarter of the 21st Century, changes will occur in the boreal zones of the European part of Russia and the Western region (Anisimov et al., 2011). By 2060, tundra vegetation will be displaced from the mainland and from further towards the East where it will remain only in the Far East and Primorye.

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production of particularly woody plant functional types stimulated by climate warming and $CO_2$ fertilization together with a north-easterly shift of vegetation zones (Wramneby et al., 2010): boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia. The most dramatic changes in vegetation structure were projected to occur in the Scandes Mountains where the succession progresses from tundra vegetation through deciduous forest to evergreen forest (Wramneby et al., 2010). Another projection for the Barents Region included more plant functional types, particularly various shrub growth forms and plant communities associated with open ground that are more characteristic of northern regions (Wolf et al., 2008). Over the next 100 years, this transient model also projected an increase in the northwards and upwards ranges of boreal needle-leaved evergreen forest and an increase in net primary production and leaf area index. As in the study by Wramneby et al. (2010), shade intolerant broadleaved summergreen trees were projected to extend to higher latitudes and altitudes. However, in contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modelled to decrease in extent over the next 100 years after an initial increase (Wolf et al. (2008). This is thought to be a result of displacement by forest at their lower /southern limits and restriction of appropriate land at higher altitudes. Also counter-intuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonisation at a rate exceeding displacement of tundra by shrubs in the south. A discrepancy in the model was an overestimation of forest in the Kola Peninsula that cannot be explained by climate alone.

Both studies calculated the magnitude of the effects of vegetation change on biospheric feedbacks to the climate system. These included the negative feedbacks of $CO_2$ sequestration and increased evapo-transpiration and the positive feedback of decreased albedo (Wolf et al., 2010; Wramneby et al., 2010).

Although the models generally agree qualitatively with expectations from historic vegetation changes, recent changes and results of climate change simulation experiments in the field, there are considerable uncertainties in the projected rates of change. Van Bogaert et al. (2010) compared maximum rates of annual projected forest advance of 20 km with the maximum observed rate of 20 m. Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. However, projections suggest increases in the ranges of the autumn and winter moths that have outbreaks in populations resulting in the defoliation of birch forest (Ims reference) and a general increase in the “background” (non-outbreak) invertebrate herbivores that may consume more vegetation than the outbreak species in the longer term (Wolf et al., 2008).

### *28.3.3.2. Predicted Terrestrial Biological Response to Climate Change in Antarctica*

Two lines of evidence have been applied to help generate predictions of climate change responses - observational ecological studies, and a range of laboratory and field environmental manipulations. Manipulation approaches are often primarily used to examine shorter term ecophysiological or biochemical responses to changes in environmental stresses, rather than community level and biodiversity responses, which generally take longer to become apparent and stabilise. While they are subject to methodological limitations (Bokhorst *et al.*, 2011; KENNEDY, 1995), manipulations are the only practicable means of achieving even partially realistic medium- to long-term studies at remote and inhospitable locations. Recent studies have made considerable advances in overcoming earlier limitations (BOKHORST *et al.*, 2007; Bokhorst *et al.*, 2007; Convey and Wynn-Williams, 2002)(Day et al., 1999). Several reviews of the findings of these studies in the Antarctic have been published (Bokhorst *et al.*, 2011; Convey, 2001; Convey *et al.*, 2003; Convey, 2010; Kennedy, 1996).

The combination of the magnitude of changes being experienced in parts of Antarctica and the generally simple terrestrial ecosystems present is expected to lead to easily identifiable consequences. As a broad generalisation, environmental amelioration (i.e. warmer temperatures and increased water availability) is predicted to lead to (i) increased rates of successful local and long distance colonization, and (ii) local-scale population expansion, leading to (iii) increased terrestrial diversity, biomass and trophic complexity, (iv) more complex ecosystem structure, and (v) a switch from the current dominance of physical environmental variables to biotic factors (e.g. competition, predation) driving ecosystem processes. In particular circumstances, these two environmental variables may also interact to increase abiotic stress levels (e.g. warming resulting in increased desiccation, increased cloud cover leading to lower temperatures, reduced cloud cover leading to more frequent freeze-thaw events, etc.), resulting in the opposite consequences. Changes in other stressors, such as increasing radiation linked either with changes in insolation/cloud cover or the formation of the ozone hole may also lead to negative consequences for biota and foodwebs, through requiring resource allocation to mitigation strategies.

### *28.3.3.3. Direct Human Impacts on Antarctic Terrestrial Biodiversity*

In global terms, the numbers of visitors who land or spend time on Antarctica is low relative to other continents. However, only 0.34% of the continent's area is ice-free (equating to about 44,000 km$^2$) (British Antarctic Survey, 2004), and only a small proportion of that area is found in the coastal regions where terrestrial ecosystems are best developed (Table 1 in (Convey and Lebouvier, 2009); approximately 6,000 km$^2$ being within 5 km of the coast). Here, terrestrial ecosystems reach their greatest stage of development, charismatic megafauna congregate, and research stations are preferentially constructed through ease of logistic access and proximity to research locations. These factors combine and drastically magnify the potential for human impact upon the very ecosystems and biological communities that are the target of research and public interest (Tin et al., 2009).

The contemporary intensity of human activity on the Antarctic continent and surrounding sub-Antarctic islands is in most cases greater than it has been throughout history since their discovery and initial exploration, only one to three centuries ago (Frenot *et al*., 2005b)( Tin et al., 2009), although the industrial exploitation of marine resources from certain sub-Antarctic islands, particularly South Georgia, provide exceptions to this generalisation (Convey and Lebouvier, 2009). The research and associated logistic activities of the 40+ national operators representing signatory nations of the Antarctic Treaty System account for ~5,000 persons visiting the continent each year. Numerically, these are divided fairly evenly between operations in the northern Antarctic Peninsula region (including the South Shetland Islands) where the majority of national research stations are established, and Victoria Land where, despite the fact that only three stations are present, one of these (McMurdo) has a typical summer population of over 1,000 staff. Other research stations are dispersed widely along the East Antarctic coastline and, increasingly, in the continental interior.

Tourist numbers have been increasing rapidly since the 1980s, though are currently stable or decreasing slightly most likely as a temporary response to global economic recession. Currently, over 30,000 tourists each year visit and land in Antarctica, supported by a further 10-15,000 ship's crew and service personnel. The large majority of these visit the northern Antarctic Peninsula and islands of the Scotia arc, typically landing at a small number of well-known locations (Lynch et al., 2010). Lynch et al.'s study highlights the concentrated nature of these activities, with 55% of landings in this area taking place at only 8 locations, the majority of these receiving approaching 10,000 individual visitors in recent years, and two (Port Lockroy, Half Moon Island) receiving up to 16,000. However, while there are clearly more tourists than national operator personnel expressed on either an annual or a specific location basis, the latter typically spend considerably longer periods on the continent.

### *28.3.3.4. Anthropogenic Transfer of Non-Indigenous Species*

Overall trends of increasing numbers of humans visiting Antarctica and the sub-Antarctic islands, being involved in a wider range of activities, and visiting progressively more isolated locations, are likely to continue. Thus it is inevitable that numbers of propagules of non-indigenous biota arriving in the region are likely to increase, although this can be mitigated to some extent by increasing awareness of biosecurity issues and methodologies (i.e. identifying the problem before something is released into the Antarctic environment), and clearer management and response procedures developed and implemented by the Antarctic Treaty Parties (Antarctic continent) or relevant sovereign nations (sub-Antarctic islands) (Hughes & Convey, in press). Thus, even in the absence of significant environmental change, increased numbers of non-indigenous species are likely to become established in the region, a proportion of which will become invasive and have deleterious impacts on native species and ecosystems. In parts of Antarctica where environmental change trends result in less extreme challenges for biota (i.e. generally where warming and/or increased water availability occur), these are likely to act in synergy with increased propagule pressure, further increasing the number of non-indigenous biota that become established, and the chance of these achieving invasive status. Furthermore, where environmental changes result in alteration of the physical environment within which terrestrial ecosystems exist – such as glacial retreat forming new beach-heads connecting previously isolated systems – there is potential for further spread of established non-indigenous species into new non-impacted areas (see (Cook and Vaughan, 2010)and Convey et al., 2011).

It is also important to recognize that the same risks apply to the transfer of biota that are native (and by definition adapted) to one part of Antarctica to other parts of the continent where they are not native (Convey et al., 2000; Chown & Convey 2007), not least as it is now recognized that Antarctica contains strong and ancient biogeographical regions and boundaries (Convey, 2008; Convey *et al*., 2009). This risk is exacerbated by the increased ease of movement now available within the continent, combined with the larger logistical footprint typifying many national operators.

As is already illustrated by numerous instances on the sub-Antarctic islands (see 28.2.3 above), non-indigenous species have the potential to introduce new trophic or ecological functions into communities which have otherwise often evolved in isolation, and contain an unique and often highly endemic native terrestrial biota (Convey, 2010; Frenot *et al*., 2005b). Some such changes are already documented, such as the introduction and spread of non-indigenous invertebrate predators to sub-Antarctic systems with no natural equivalent (Convey *et al*., 2011)( French Kerguelen ref), and that of non-indigenous detrivores that either open up new routes of organic matter decomposition, or potentially lead to step changes in the rate of nutrient release and recycling (Chown Marion ref; Hughes & Worland 2010). Synergies between non-indigenous species, or between indigenous and non-indigenous species (such as that between pollinating insects and pollination-requiring flowers on South Georgia; (Convey, 2010)), or between plant fungal or viral diseases and insect vectors such as aphids (Marion or Kerguelen refs), provide examples of new biological interactions in the region that have potential to lead to step changes in ecosystem structure and function.

Unlike the Arctic, it is largely inappropriate to consider any element of the Antarctic terrestrial environment providing a simple north-south transect or latitudinal gradient in environmental conditions, particularly when also considering the underlying biogeographical patterns and boundaries and the physically isolated and island-like nature of many terrestrial ecosystems. Thus, there is no realistic prospect of current environmental change trends leading to a progressive southwards movement of entire terrestrial assemblages or ecosystems. Work on sub-Antarctic Marion Island has, however, examined the movement of upper and lower altitudinal boundaries under changing climatic conditions (McGeoch ref) in simple terms finding that communities did not move 'en masse', and that there was little consistent response between species at the 'leading' and 'trailing' edges.

Across terrestrial ecosystems of much of the Antarctic, and particularly of the Antarctic Peninsula and Scotia arc archipelagoes, current environmental change predictions lie within what is known of the ecophysiological capacities of the affected biota. In these areas further climate amelioration is expected to (as is already being seen) relax constraints on biological activity, leading to increases in biomass and extent of existing communities. At present there is no indication that the magnitude of these environmental changes will surpass any environmental boundaries for these biota, and hence result in any form of limitation of their occurrence from their current distribution (e.g. southwards movement of current northern boundaries). As noted earlier, in particular locations it is possible that specific combinations and synergies between different environmental parameters might result in local limitation.

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals (see

28.2.3 above) are likely to have far greater importance over the timescale under consideration than are those attributable to climate change itself (Convey and Lebouvier, 2009; Convey, 2010)( Turner et al., 2009).

### *28.3.4. Economic Systems*

Projections of the economic costs of climate change impacts in the Arctic are limited, but current assessments suggest that there will be both economic benefits and costs (Forbes, 2011) (e.g. SWIPA 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud *et al.*, 2011).

Local communities are exposed to the effects of climate change thru multiple pathways such as changes in weather (temperature, wind, precipitation), via impacts on the natural systems and from their effects on infrastructure and the food sector (NorAcia 2010, 112). Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (Ibid. 118). While regions throughout the Arctic share characteristics that distinguish their economies from non-northern regions, they also vary significantly; i.e. by the type, quality, and quantity of industrial resources produced; by the importance of the indigenous population and the local economy; and by the different national economic and political systems (Larsen and Huskey, 2010)(e.g.Huskey 2010). Communities with the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture and economy (Clark et al 2008).

Economic cost estimates have been made for the case of the Alaska economy, and they suggest that the heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries, renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). From the present to 2030, permafrost thawing, amplified flooding and coastal erosion from global warming could add considerably to future costs of public infrastructure in Alaska (SCEIGW 2010). Melting tundra can cause oil pipelines to buckle and break, causing spills (Epstein et al. 2008). A significant part of Alaska's economy is tourism. Loss of wildlife and habitat, such as spruce tree forests, could lead to a loss of tourism income (NWF 2009). Reductions in seabird and marine mammal populations with unusually warm sea temperatures, and declining salmon harvests could negatively affect tourism, native peoples' way of life, and the Alaskan salmon industry (SCEIGW 2010). It has been estimated that the Shishmaref, Kivalina, and Newtok tribal lands will be unliveable due to storm damage and coastal erosion in a number of years. The cost to re-locate these communities is estimated to be significant. These estimates do not include the costs of social upheaval associated with relocation of tribal groups that have occupied these territories for over 4,000 years (Williams et al. 2007).

### *28.3.5. Economic Sectors*

#### *28.3.5.1. Fisheries*

Predicting the impacts of climate change on future fisheries is difficult because it is unclear whether the responses of marine species observed in the past will continue in the future, and because it is difficult to predict the response of fisheries to shifts in supply. O'Neill et al. (2010) provide a model to simulate demand for a composite food commodity under global demographic projections. In dollar terms, food expenditures rise steadily in these scenarios, driven by economic growth and demographic factors of urbanization and population growth. In biophysical terms, population growth alone could account for a 50% increase in seafood demand by 2050 relative to current global production levels (Rice and Garcia 2011).

There is strong evidence and considerable data showing historical links between climate driven shifts in ocean conditions and a north eastward shift in the distribution and abundance of Norwegian cod and herring stocks in the Barents Sea (Drinkwater 2011). In limited cases, coupled bio-physical models have been used to predict future commercial yield or shifts in fishing locations however these predictions are uncertain (Ianelli et al. 2011). Deductive reasoning can be used to identify candidate species that may colonize the Arctic Ocean. Criteria for these species would include: (1) historical evidence of colonization of new spawning grounds, (2) life history characteristics to adapt to the short growing season in a low temperature environment, (3) physiological characteristics (such as blood antifreeze) that would allow overwintering, and (4) evidence of an eclectic diet that would allow them to take advantage of available prey, (5) shifts in the seasonal productive cycle that would support large concentrations of pelagic copepods and or euphausiids. Information is available to assess the first 4 criteria, but however, current observations and understanding of biophysical processes governing seasonal production in the Arctic Ocean are limited.

### *28.3.5.2. Forestry and Farming*

A warmer climate is *likely* to impact access conditions and plant illnesses. In the case of Northern Norway, about half of the arable land area is covered by forest and 40% of it is marsh (Grønlund, 2009). If these areas were to be harnessed for farming, it would be at the cost of forestry production or by drying up the marshlands, which would contribute to more greenhouse emissions. Larger field areas could contribute to land erosion through rainfall and predicted unstable winters, and would likely increase conditions for plant illnesses and mushrooms (Grønlund, 2009). A warmer climate will increase vulnerability of forests to the threat of new illnesses and pests, and increase the distance to all-year roads (Grønlund, 2009). If the winter season were to shorten as a result of climate change, this would negatively affect access to logging sites, which is best when the frozen ground makes transportation possible in sensitive locations or areas that lack road. If the weather then i.e. changes when logging has already taken place, sanding of the road becomes necessary in order to ensure transportation within a specific timeframe, which carries significant economic costs (Keskitalo, 2008). Any impact on the carrying capacity of the ground or road accessibility will thus affect forestry economically. Challenges may also include limited storage space for wood (Keskitalo, 2008). Any change and need for larger storage, would lead to extra costs. A warmer climate may also have positive effects on forestry: In the case of Finland where forestry is of great economic importance, the risk of snow damage to forest is estimated to decrease with about 50% towards the end of the century (Hovelsrud *et al.*, 2011).

### *28.3.5.3. Infrastructure*

Northern safety, security, and environmental integrity are much dependent upon transportation infrastructure. Ice as a provisioning system provides a transportation corridor and a platform for a range of activities and access to food sources (i.e. subsistence hunting and fishing on and around ice, oil and gas development) in the Arctic (Eicken et al 2009, 123). While much of the infrastructure in the Arctic, including railways, airports, roads, buildings, communications towers, energy systems, and waste disposal sites for communities, as well as large-scale facilities and waste-containment sites, have been built with weather conditions in mind, much of it remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents (Governments of Yukon, Northwest Territories, and Nunavut, 2008. A Multi-Modal Transportation Blueprint for the North in National Round Table on the Environment and the Economy 2009, 51; NorAcia 2010, 115).

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent upon the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter. Communications towers and energy transmission infrastructure located in remote permafrost areas are becoming increasingly susceptible to the risk of failure and, since accessibility may also be an issue and the cost of redundancy is prohibitive, the threat posed by this hazard will likely become increasingly significant. Energy pipelines built over permafrost could be at risk of rupture and leakage, and warmer temperatures are already resulting in shorter winter road seasons. Failure of frozen-core dams on tailing ponds due to thawing and differential settlement, or thawing of tailings piles associated with climate warming, could in its turn result in contaminants being released into the surrounding environment, causing subsequent disastrous and irreversible degradation of sensitive habitat and human health. In the long term marine and freshwater transportation will need to shift its reliance from ice routes to open-water or land-based transportation systems. Of appropriate community adaptations to the predicted changes relocation is one option to deal with persistent flooding and bank erosion (Furgal C., 2008)(National Round Table on the Environment and the Economy 2009, 61-62;). The implications for the sea-ice system may prove to have other major impacts as well, including environmental and socio-economic or geopolitical change which may substantially modify types of services offered and their uses by competing interests. Changing sea-ice (multiyear) conditions are suspected i.e. to have a regulating impact on marine shipping and coastal infrastructure through possible hazards on them (Eicken et al 2009, 123).

#### *28.3.5.4.Inland Transportation, Communication, and Drinking Water*

By adapting transportation models to integrate monthly climate model (CCSM3) predictions of air temperature and temperature, combined with datasets on land cover, topography, hydrography, built infrastructure, and locations of human settlements, estimates have been made about changes to inland accessibility for northern landscapes northward of 40ºN by mid-21st Century (Stephenson *et al.*, 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000 kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000-2014) for eight circumpolar countries was projected to be -14%, varying from -11 to -82%. In absolute terms, Canada and Russia (both at -13%) account for the majority of declining winter-road potential with ~$1 \times 10^6$ $km^2$ being lost.

Climate change impacts have increased the demand for improved communication infrastructure and related services (e.g. cellular and improved citizens band radio (CB) service), and community infrastructure for the safety and confidence in drinking water (National Round Table on the Environment and the Economy 2009, 52; Communities of Inuvialuit Settlement Region et al., 2005). The access, treatment and distribution of drinking water has been and is generally dependent upon a stable platform of permafrost for pond or lake retention, a situation that is currently changing. Several communities have reported the need for more frequent water-quality testing both municipal systems and untreated water sources to ensure its availability (Furgal C., 2008). Demands on infrastructure and building costs is *likely* to increase with the impact of warming and thawing permafrost.

#### *28.3.5.5.Terrestrial Resource Management (Oil and Gas, Mining, Forestry in the Arctic)*

The most recent assessment of undiscovered petroleum resources is the Circumpolar Arctic Resource Appraisal (CARA) completed in 2008 by US Geological Surveys. The USGS (2008) estimated the Arctic undiscovered petroleum resources to 413 billion barrels of oil equivalents (bboe), about 22 per cent of global undiscovered conventional oil and gas resources. The share of oil (including natural gas liquids) was estimated to 134 bboe (15 per cent of global oil resources) and 279 bboe of gas (30 per cent of global resources). Hence the Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate benign fuel than coal. The petroleum resources are unevenly distributed among Arctic regions and states. Figure 28-6 shows the allocation of oil and gas on regions. Arctic Russia is the major petroleum region with about 40 per cent of total Arctic oil and 70 per cent of total Arctic gas resources. Alaska is second with 28 per cent of oil and 14 per cent of gas.

[INSERT FIGURE 28-6 HERE
Figure 28-6: (top) Regional distribution of Arctic undiscovered oil resources (including NGL), and (bottom) regional distribution of Arctic undiscovered natural gas resources (including NGL). Source: Statistics Norway, 2010.]

Sea ice retreat and thawing permafrost will have potential direct and indirect impacts on resource exploitation. Longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Disappearance of ice roads may restrict onshore exploration activities. Among indirect impacts on resource exploitation are changes related to changing ecosystems and changes in distribution and abundance of species. This may lead to stricter environmental regulations and requirements (e.g. AMAP. Oil and Gas Activities in the Arctic 2007). Conservation management and protected areas designed to address the effects of human actions are well developed and extensive in the Arctic. Future debates about Arctic climate change will almost certainly focus on whether current institutions are sufficiently flexible, resilient, and robust (e.g. AHDR 2004).

Of particular concern today, it is estimated that the Arctic may contain approximately 25 % of the world's remaining undeveloped petroleum resources (Forbes, 2000). For example, Yamal in Western Siberia has approximately 90 % of Russia's gas reserves, but at the same time is the largest area of reindeer herding in the world. Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to the loss of "available room for adaptation" for reindeer husbandry (Nuttall *et al.*, 2005)(Forbes, 2009). Furthermore, it is anticipated that there will be sharp increases in future oil and gas and other resource development in the Russian North and other Arctic regions – along with its associated infrastructure, pollution, and other by products of development – which will, in turn, reduce the availability of available pasturelands for the reindeer and the indigenous communities associated with them. (Forbes, 2006; Jernsletten and Klokov, 2002) (Forbes, 2000; Derome and Lukina, 2010). All of these factors present major concerns for the future of traditional reindeer husbandry, the well-being of the Arctic indigenous communities, especially the reindeer herding communities, and the ability of these communities to adapt to future changes. (McCarthy et al, 2005; Magga et al, 2011)

The USGS 2008 study revised its assessments with respect to regional resource allocation compared with its own 2000 assessment. USGS (2008) lowered their estimates for oil resources in Norway, Greenland and Russia and raised the estimates for Alaska and Canada. Gas estimates were lowered for Norway and raised for all other regions. For the Arctic as a whole, USGS (2008) assessed the undiscovered petroleum resources to 8.5 per cent below their previous estimate (USGS 2000), whereas Wood Mackenzie (2006) estimated petroleum resources at only 40 per cent of the USGS (2008). These different estimates illustrate the considerable uncertainty around the level of resources in the Arctic, but all come up with estimates that positions the Arctic as a major global petroleum region.

Tables 28-1 and 28-2 show arctic oil and gas production by 2010 and their share in global supply.

[INSERT TABLE 28-1 HERE
Table 28-1: Arctic oil production in relation to non-OPEC and global supply, reference scenario (%).]

[INSERT TABLE 28-2 HERE
Table 28-2: Arctic gas in relation to MENA and global supply, reference scenario (%).]

Arctic Russia and Alaska are the major producers of oil. Greenland has a large potential, but not yet any production.

The Arctic is also rich in other natural resources, such as minerals and fish. Figure 28-7 Illustrates the dominant contribution of natural resource based industries to regional GDP in the Arctic (2005, To be updated).

[INSERT FIGURE 28-7 HERE
Figure 28-7: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010. [TO BE UPDATED]]

In Arctic Russia the extraction of energy alone contributes close to 60 per cent of regional GDP (see Figure 28-8). In Alaska and Arctic Canada the energy and minerals contribute 30-38 per cent, whereas fishing and fish processing are the major elements in Faroe Islands, Greenland and Iceland.

[INSERT FIGURE 28-8 HERE
Figure 28-8: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.]

#### *28.3.5.6. Anticipated New Resource Exploitation Development in the North*

GCMs generally underestimate the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve etr al., 2007). Mokhow and Khon (2008) used a sub-set of climate models that better than other GCMs reproduce the observed sea ice dynamics to project the duration of the navigation season along the NSR and through NWP under the moderate SRES-A1B emission scenario. According to their results, by the end of the 21st century NSR may be open for navigation 4.5±1.3 months per year, while the NWP may be open 2-4 months per year (Figure 28-9). The models did not predict any noticeable changes of the ice conditions in the NWP until the early 2030s.

[INSERT FIGURE 28-9 HERE
Figure 28-9: Projected duration of the navigation period (days) over the North-West passage (1) and Northern Sea route (2). Source: Mokhow and Khon, 2008.]

Analysis indicated that by the end of the 21st century transportation costs from Europe to Asia along the NSR may be up to 15% less than the transit through Suez Canal (Mokhow and Khon 2008). Apart from the less restrictive requirements to the ice class of the cargo vessels and decreased demand for ice-breaker’s support due to longer open water season this will stimulate the development of the navigation along the NSR and in the longer term also through NWP (Peresypkin and Yakovlev, 2007 from Mokhow and Khon), although in the following two decades commercial shipping in the NWP is unlikely.

## 28.4. Adaptation in the Polar Regions

There is general agreement that peoples, both indigenous and non-indigenous living in the Arctic regions have through time adapted well to high natural variability in environmental and climatic conditions (Huntington *et al.*, 2007; West and Hovelsrud, 2010)( Forbes and Stammler, 2009; Wenzel, 2009; Ford et al., 2010b) but less so with respect to social and economic marginalization and globalization (Tyler *et al*., 2007)(Crate and Nuttall 2009). The challenges have more recently been exacerbated by climate change which pose a greater risk than before to the adaptive capacity of communities (Rybråten and Hovelsrud, 2010)(Crate and Nuttall 2009). Adaptation to climate change occurs in the context of, and is inextricable linked to societal change; and climate is likely not the most important driver of vulnerability in polar communities nor is rarely the sole or primary stimulus for taking adaptive action (Berrang-Ford *et al*., 2011; Hovelsrud and Smit, 2010). Climate change is instead a driver that exacerbates other stresses and creates additional risks.

The impacts of climate change on those living in the Polar Regions and their ability to adapt must be seen in the context of other interconnected and mutually reinforcing, stresses and resources such as demography, economy, technology, culture and health (e.g.(Hovelsrud and Smit, 2010)). Research distinguishes between reactive and proactive adaptation. The former as a response to current climate and risk management practices, while the latter refers to planning of adaptive measures to future climate change and extreme events (Füssel 2007, Amundsen et al 2007). As was argued in the AR4, the most effective adaptation options will be those that recognize the nexus between adaptation and sustainable development (Yohe et.al., 2007). One consequence of this observation is the potential of “mainstreaming” adaptation into existing policy processes and priorities (such as those for poverty alleviation, health standards, emergency planning and insurance) leading to “win-win” options (National Roundtable on the Environment and the Economy, 2009).

It is generally agreed that the current rate and magnitude of climate change in the Arctic is already challenging the resilience and adaptive capacity of Arctic communities. This is because the current changes create new and unpredictable conditions beyond what people have been adapting to in the past, and there is a high degree of uncertainty of what will come next. The capacity for adapting to the combined and interactive effects of future climatic and societal change is uncertain (Ford *et al.*, 2010).

As a result of the inertia of the climate system, even with global reductions in greenhouse gas emissions, further changes in the climate can be expected and thus adaptation, particularly at the local level, becomes increasingly imperative. To quote Nordhaus: “mitigate we might, adapt we must” (Nordhaus, 1994). When discussing adaptation to climate change, one must bear in mind that we already adapt every day to climate and weather-related events. Populations in the Polar Regions, particularly indigenous one, have a history of accommodating to environmental change and adapting to new conditions. What climate change is doing is rendering these conditions more unpredictable and irregular. Adaptation to climate change can be regarded as planning under increased risk.

As earlier sections of this chapter have indicated, there is considerable evidence of climate change impacts in terms of changing weather patterns, declining sea-ice, melting permafrost and wildlife patterns (West and Hovelsrud, 2010)(Hovelsrud et al 2010a;van Oort et al 2011). Extreme events, rather, than the incremental changes in climate, have often served to highlight existing vulnerabilities and stimulate adaptive action (Berrang-Ford *et al.*, 2011). Sea-ice is an integral part of many coastal communities and relied upon for transportation between communities and hunting areas. Across the Arctic, hunting and fishing activities are adapted to local sea-ice conditions and significant changes in sea ice and the consequent changes to country food availability and access will have significant impacts on communities (e.g., (Nuttall *et al.*, 2005) Furgal and Seguin, 2006; Ford, 2009c; Ford et al., 2010).

The impact of climate change and the need and capacity for adaptation can best be understood at the local and regional levels where the vulnerabilities are felt first and the resources (physical, economic and institutional) most readily available (Hovelsrud and Smit, 2010). This requires a good understanding of the current socio-economic and political conditions in communities (Keskitalo, 2008). National policy frameworks are important. For example, the high level of social security in Norway means that trends such as depopulation and economic marginalization may take less of a toll on the standard of living of individuals than is the case elsewhere (H. Keskitalo, E., Kulyasova,A., 2009).

As elsewhere, projections of average future conditions from climate models, including biophysical impacts, often lead to technological responses rather than policy responses (Naess et.al. 2005), and there is a general lack of national policies on adaptation as is illustrated by the Nordic countries (Dannevig et al 2012). However, the uncertainties of climate projections, and lack of local downscaling combined with uncertainties in future economic, social and technological developments often act as a barrier to adaptation. These perceived barriers, together with other social determinants such as ethics, values, culture and attitudes to risk, and perceptions of vulnerability can act as a justification for inaction (West and Hovelsrud, 2010)(Adger et. al., 2009). Resolving divergent values across a variety of communities of quite different make-up poses a challenge for the increasingly complex societies and governance systems in Polar Regions. A determining factor in building adaptive capacity will be the flexibility of enabling institutions to develop robust options (Hovelsrud and Smit, 2010)(Forbes et al. 2009;).

### *28.4.1. Adaptation and Indigenous Peoples*

There is ample evidence that for millennia indigenous peoples in the Arctic have adapted to changing conditions in myriad ways including resettling amid favourable environments and along the paths of animal migration routes. Indigenous peoples have developed a remarkable array of coping strategies to deal with the extreme natural variability in the region. They have also been innovative and adaptive in the face of cultural and technological change (Bolton et al., 2011). This has been achieved by detailed local knowledge and skills, the sharing of knowledge and flexible social networks which provide support in times of need. Indeed, the sharing of knowledge, food, equipment and other resources is not only an important cultural activity but can also ensure rapid responses to crises (Ford et. al. 2007). In addition values such as patience, persistence, calmness, respect for elders and the environment have been essential for survival in the harsh conditions of the Polar Regions (Takano, 2004).

Unfortunately, the rapid climate and weather changes that have been experienced recently have challenged the reliability of this indigenous knowledge. This has in some cases created a “loss of order in the world” (Turner et.al., 2008) and insecurity on the part of the knowledge keepers (Berkes and Joly, 2002; Chapin III *et al.*, 2006; Hovelsrud and Smit, 2010). In many ways impacts of environmental change are stripping Arctic residents of their considerable knowledge, predictive ability, and self-confidence in making a living from their traditional resources. This may ultimately leave them as strangers on their own land. This may be especially the case of Northern land-based people who depend on their ability to predict weather, judge the snow conditions, and estimate animal movements and distributions; all of which are becoming more difficult. A hunter who cannot make right judgment about what to hunt and where, cannot stay a hunter for long (Berkes, 2002)(339 but also Fox in the same volume 43-45).

Traditional adaptive capacity has also been threatened by the transition from semi-nomadic hunting groups to fixed communities, especially over the last half-century, (Ford et al, 2010) with modern amenities such as television and southern foods that are affecting lifestyles; by wage-earning opportunities in natural resource exploitation leading to frequent job changes and by a desire among the young for a more Western lifestyle. The increasing diversity of employment is leading to the possibility of indigenous people finding multiple jobs, and hence diversified income but can exacerbate social inequalities (Ford et al, 2010). Unfortunately, however, the current levels of skilled labour and formal education often limit the abilities to take advantage of such adaptive opportunities (Furgal C., 2008). Traditional capacity is also affected by the erosion of inter-generational knowledge transfer, land-based skills, and cultural traditions (Bolton et al., 2011). Some communities have put in place strategies to ensure the continued intergenerational transfer of knowledge through school curricula, land camps, and involvement in community-based monitoring programmes (Hovelsrud and Smit, 2010)( Bolton et al., 2011, Ford et. al., 2007). These programs also generate more community well-being and cultural identity. In addition, for traditional societies landscapes assume symbolic significance and changes brought about by climate change may have profound implications which can act as a barrier to adaptation (Adger et. al. 2009). Forced migration as a response to threats to infrastructure is an adaptation option that has been shown to have deep cultural impacts.

Harvesting of renewable resources (which is often critically dependent on the climate conditions) is still a significant component of Arctic livelihoods in many Polar Regions contributing to food security. With climate change however hunting has become a riskier undertaking. Adaptive responses include taking more supplies when going hunting such as additional warm clothing and extra food; constructing more permanent shelters on the land as refuges from storms; building improved infrastructure to communicate; greater use of global positioning systems (GPS) for navigation; SAR to provide estimates of sea-ice conditions (Laidler *et al.*, 2011), and the use of larger or faster vehicles (Ford et al, 2010). However, in some instances, this can lead to increased risk exposure (Aporto et.al. 2005) and over harvesting (Chapin et al. 2005b). Avoiding dangerous terrain can result in longer and time-consuming journeys which can be inconvenient to those with wage-earning employment (Ford et.al. 2007). These adaptive responses have in part been made possible by the increased incomes mentioned above.

Herding, such as reindeer, has also adapted to changes in the climate by moving herds to better pastures (Bartsch *et al.*, 2010), providing supplemental feeding(P. and M., 2008); (Forbes and Kumpula, 2009) and ensuring an optimal herd size (Forbes et al., 2009). Some Eurasian reindeer herders have created new international, multicultural initiatives which combine traditional knowledge with scientific studies to improve their adaptation strategies. One such initiative, the EALAT (“Reindeer Pastoralism in a Changing Climate”), illustrates a forward-looking adaptation strategy in which reindeer herders are now creating and distributing “co-produced” datasets to improve real-time decision-making and herd management to adapt to the effects of the changing climate plus the increasing human development and changing social conditions and policies. (Bongo *et al.*, 2012)(Magga et al, 2011).

Small scale fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al 2010b) . Climate change will however exert pressures on quota systems and the requirements of multi-agency co-management institutions (Ford *et al.*, 2006)(Ford et. al. 2010).

In some Arctic countries indigenous peoples have won land claims rights and have become key players in addressing the issue of climate change. In some instances this has given rise to tensions over land use such as the contested land uses for traditional livelihoods (e.g. reindeer herding) and new opportunities (e.g. tourism and natural resource extraction) (Forbes, 2006; Hovelsrud and Smit, 2010). Some territorial governments in Northern Canada have developed climate change strategies that promote further adaptation such as providing hunter support programs (Ford *et al.*, 2006)(Ford et. al., 2010). Many communities are already adapting in a reactive manner to climate change (Aporta and Higgs, 2005; Gearheard *et al.*, 2010; Gearheard *et al.*, 2011; Laidler *et al.*, 2011). Many studies have noted the importance of combining scientific knowledge and traditional knowledge in an effort to understand climate change, its impacts and local responses. (Furgal C., 2008; LAFORTUNE *et al.*, 2004; Tyler *et al.*, 2007)( Huntingon 2005; Bolton et al., 2011).

The health of indigenous people is being disproportionately affected by the interactions of ongoing changes in human, economic and biophysical systems, as discussed above, exacerbated by changes in climate (Chapin III *et al.*, 2005). Food security is a particular concern, especially with changes in the availability of traditional foods. The transition to store-bought foods can be expensive and is a concern for health such as obesity. However, with declining sea-ice there is the possibility of access to more fresh foods and warmer weather may also make greenhouse production more viable. Both these possibilities will benefit the health of these people. The factors that influence communities' ability to adapt vary significantly between small, remote, predominantly indigenous communities, regional centres and larger northern municipalities. Adaptation responses include the distribution of traditional foods between communities and the use of community freezers (Ford et al, 2010). Bolton et al. (2011) identified a need for research and policy priorities to be placed on assessing/addressing health factors which may predispose communities to negative impacts of climate change.

Even though the influx of wage employment may enhance the possibilities for adaptive capacity, greater involvement in full time jobs will continue to threaten social and cultural social cohesion and mental well-being by disrupting the traditional cycle of land-based practices (e.g. (FURGAL *et al.*, 2002); Berner et al., 2005), erosion (Furgal C., 2008).

### *28.4.2. Adaptation and Industrial Development*

It is not only indigenous peoples that are being affected by climate and other changes and being forced to adapt. The Polar Regions are becoming increasingly tied economically and politically to global forces such as international fossil fuel and mineral markets. This is bringing in new workers and families and changing economies. It is also helping to diversify employment opportunities.

The extraction of off-shore fossil fuels will require the adoption of design changes to drilling platforms (as were incorporated off the Canadian East Coast such as Hibernia where icebergs are a significant threat). Some of the resources that will be extracted are expected to be transported by ship to southern markets as the reductions of sea-ice extent progresses; other resources will likely be transported by pipelines whose design requirements will need to take climate change into account.

The infrastructure needed for on-shore natural resource extraction will have to take into consideration potential impacts of the changing climate on permafrost and coastal erosion. Processing plants, and particularly waste containment facilities, must be able to maintain their structural integrity over the expected long lifetime of a project (Dyke, 2001). Unless mines are located close to the coast and port facilities resupply is generally limited to winter periods and the availability of ice roads, whereas exploration activities are usually restricted to short summer periods with access by air.

Climate change has increasingly been recognized as a critical factor in the design of major infrastructure projects in northern Canada, and has been incorporated in environmental impact assessments since the late 1990's. A risk-based project screening tool has been developed for considering climate change in northern engineered facilities (Environment Canada, 1998). A study by Canada's National Roundtable on the Environment and the Economy (Government of Canada, 2009) reviewed the use of existing policy tools such as codes and standards, insurance and emergency/disaster management to support wise adaptation of critical infrastructure. The study concluded that there was inadequate technical (including monitoring) information and capacity as well as a systematic assessment of risks to take full advantage of these policy tools. This was in part because of limited interaction between scientists and decision-makers. The lack of systematic assessments meant that often there was unclear responsibility for infrastructure investment and operational decisions.

Adaptation of northern infrastructure to changes in permafrost, resulting from changes in the climate as well as surface disturbances due to construction, will largely involve approaches already in use to reduce the impacts of ground disturbance (Instanes et al, 2005). These include the use of pile foundations (that may need to be deeper to account for climate change), insulation of the surface (which may require thicker gravel pads), clearance of snow (to promote colder winter ground temperatures), adjustable foundations for smaller structures, and increased use of artificial cooling to ensure that foundation soils remain frozen. Recently developed techniques, such as air-convection embankments may also be utilized (Couture et al , 2003). Where permafrost is thin, frozen ice-rich material may be excavated and replaced with thaw-stable material, or intentionally thawed by clearing vegetation and postponing construction for several years until the permafrost has completely degraded and the ground has settled. Finally, an important element of any adaptive response will be monitoring to evaluate infrastructure performance; determine if changes in permafrost conditions deviate from those predicted; and decide whether additional adaptation measures are required (Furgal C., 2008).

Lake and river ice have historically served as natural transportation routes, and modern engineering has led to increasingly sophisticated methods of winter-road construction. Ice roads and ice bridges that are constructed and maintained each winter provide a relatively inexpensive way to supply northern communities and industry, particularly the rapidly expanding oil/gas and mining sector that relies on ice roads to move heavy equipment, materials and fuel. In addition, these ice-roads provide critical travel routes that link communities and facilitate their ability to continue social and cultural activities during winter months as well as provide access to hunting, fishing, and reindeer herding or trapping areas (Furgal C., 2008)(Ford *et al*., 2008). Adapting to the reduced availability of ice roads will involve increasing the ice thickness by surface flooding or spray-ice techniques as well scheduling more transport when the ice is thickest. Further resource extraction development could necessitate the construction all-season roads and/or water-based transportation systems where this is feasible. The initial capital costs of these, however, will likely be very high, especially where they must pass over terrain that might be experiencing permafrost thaw and subsidence.

With the expected extension of the ice-free period on Arctic rivers and lakes and increases in discharge from Arctic rivers (Arora and Boer, 2001) there could be a significant expansion of open-water transport – for example by 50% along the Mackenzie River system. For land-locked locations, however, the only viable option for heavy-load transport is likely to be the construction of land-based road or rail networks.

The resource extraction activities could increase the demand for sustainable renewable energies and electricity transmission networks to serve not only the mines but also communities spread across the Arctic. This could reduce the need for expensively imported fossil fuels (traditionally transported by increasing unreliable ice-roads and river barge shipments) and enhance the well-being of these communities. There is already a significant dependence on hydro-electric power in the Canadian North and there is further potential for more generating power on the major northern rivers as well for micro-hydro facilities (Canadian Dam Association, 2003). As with some existing Canadian hydro-projects, such as in Quebec and Labrador, there is the potential for selling some of this power to southern markets. However, climate change is likely to impact hydrological patterns - for example projected increases in winter run-off from rainfall and enhanced snow melt could affect dam operations (Spence et al, 2005).

In adapting to the expected impacts of changes on the management of natural resources such as forestry, it has been suggested that the principles and practice of sustainable development embody many of the activities that will be required (Spittlehouse and Stewart, 2003). Proactive adaptation, such as selective forest regeneration, is more likely to avoid or reduce damage than reactive responses. As far as fisheries management is concerned, inshore coastal marine and lake-based commercial fisheries and aquaculture operations could to face significant adaptation challenges as a result of changing climate. Options that adopt an ecosystem approach and set attainable goals for sustainable management levels are likely to be more responsive to climate change impacts. As with the forestry sector sustainable management approaches such as area closures, quota limits and gear restrictions to limit both commercial and recreational activities will likely be important tools for dealing with the impacts of changing climate.

Institutional frameworks generally ill-suited to deal with rapidly changing environmental conditions can exacerbate sensitivities to, or impacts of, climate change. More interaction between community-members, policy-makers, and decision-makers can assist in exploring innovative opportunities for resources management and facilitate enhanced adaptive capacity (Bolton et al., 2011). In general adaptive co-management strategies, particularly at the local level, involving indigenous interests and bringing together scientific and traditional knowledge, are becoming increasingly important in adapting to climate change (Chapin III *et al*., 2006; Klein *et al*., 2005)(Parlee et al., 2005, Government of Canada, 2009).

## 28.5. Research and Data Gaps

Our understanding of a region of the globe as large, heterogeneous and complex as the Polar Regions is still imperfect. Monitoring of changes in its physical features and processes by continuous and systematic methods, including remote-sensing, is essential. Although many of the systems in the Polar Regions have previously adapted well to harsh environmental conditions, many are sensitive to rapid change and could tip into new regimes as they cross critical thresholds or experience pronounced step changes.

For human systems, the combined effects of climate-change, globalization and other stresses are producing impacts on northern residents and these also need to be carefully monitored so there is adequate and relevant information for developing appropriate adaptation measures and policies. Projections of the economic costs of climate change impacts in the Arctic are limited. More research is needed on the economic impacts of climate change, including developing models to estimate the economic costs for different sectors and using different climate scenarios.

Increasing evidence indicates that changes in the Arctic are having impacts on global physical and human systems, including via significant feedbacks. These include: effects on the global climate system via changes in thermohaline and atmospheric circulation; the enhanced release of greenhouse gases, such as from land and ocean based sources of methane and carbon, and, intensification of natural-resource exploitation and expansion of international trade. Additional research is required in these areas particularly because the rate of change seems to be accelerating.

Our current level of understanding is not sufficient to determine the extent and direction of climate change effects on Southern Ocean ecosystems as a whole. A major uncertainty is the overall prognosis for sea ice and the consequent positive and negative ecosystem changes that might arise. An important challenge is to develop suitable models that characterise the interactions between biota and to represent responses to changes in the physical environment. Equally important will be to develop suitable field programs to measure climate change impacts on different parts of the ecosystem in order to underpin these models (Trathan et al. 2010). The Southern Ocean ecosystems provide an opportunity where a structured field program could be developed in reference areas, without interference from other human activities, aimed at measuring rates of ecosystem change in order to facilitate assessments of future change (Constable et al. 2009).

## Frequently Asked Questions

[provisional FAQs, with answers forthcoming]

- ***FAQ 28.1: What will be the net socio-economic impact of change in the polar regions?***
- ***FAQ 28.2: Why are changes in sea ice so important?***

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Table 28-1: Arctic oil production in relation to non-OPEC and global supply, reference scenario (%).

| | 2010 | 2050 |
|---|---|---|
| Arctic share of Non-OPEC conventional oil | 16 | 31 |
| Arctic share of total Non-OPEC | 16 | 22 |
| Arctic share of world oil production | 10 | 8 |

Table 28-2: Arctic gas in relation to MENA and global supply, reference scenario (%).

| | 2010 | 2050 |
|---|---|---|
| Arctic share of total production outside Middle East/North-Africa (MENA) | 27 | 22 |
| Arctic share of world gas production | 22 | 10 |

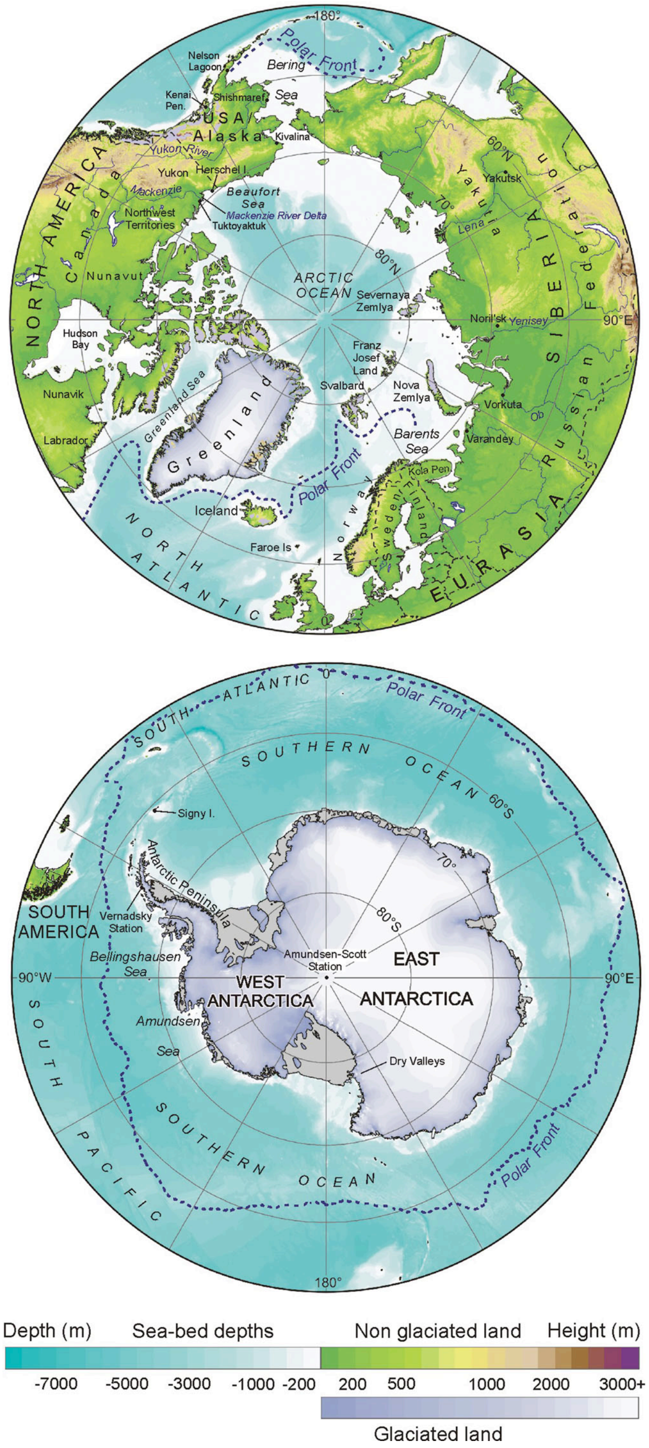


Figure 28-1: Location maps of the North and South polar regions. Source: IPCC, 2007.
[Note: WGII AR4 Figure 15.1 to be updated, including the addition of major currents.
Credit: P. Fretwell, British Antarctic Survey.]

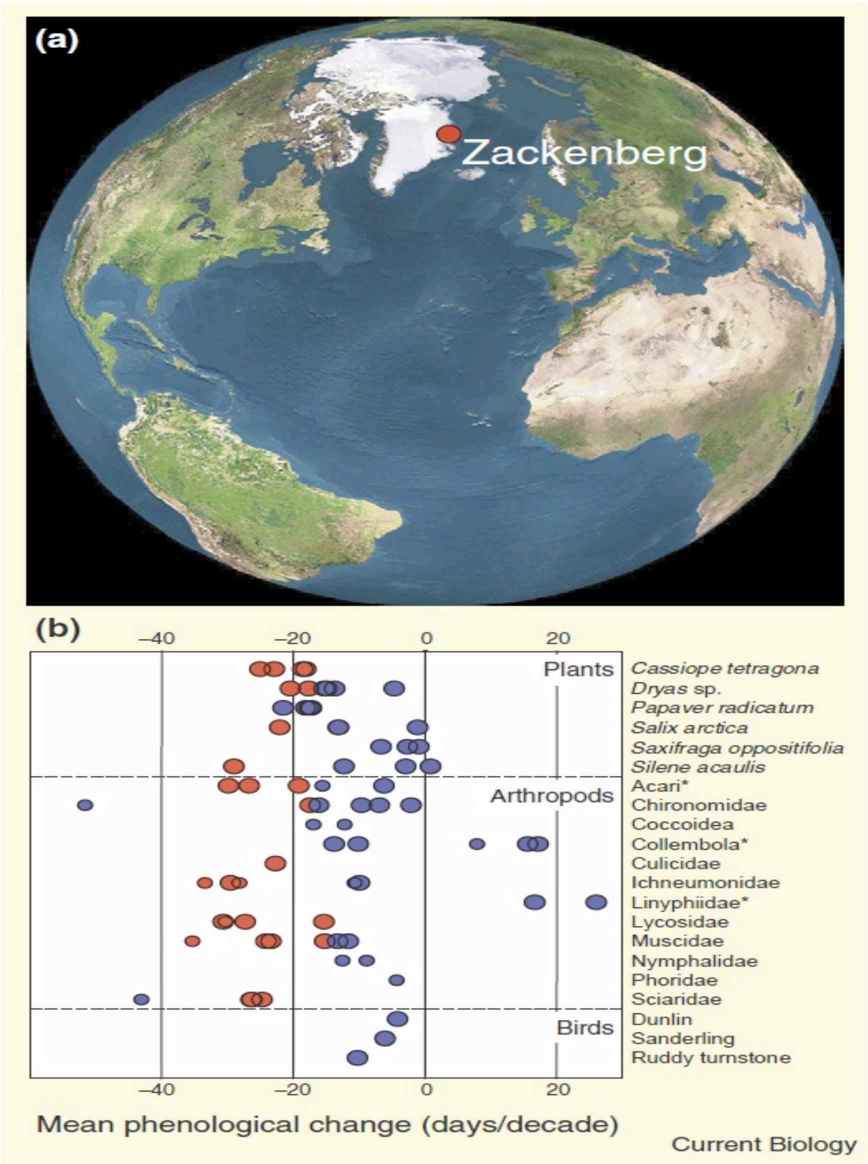


Figure 28-2: Advancement of phenological events in high-Arctic Greenland. a) location of the study area Zackenberg, North-east Greenland. b) Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initation dates (birds). Red dots are statistically significant, blue dots are not (Høye *et al.*, 2007).

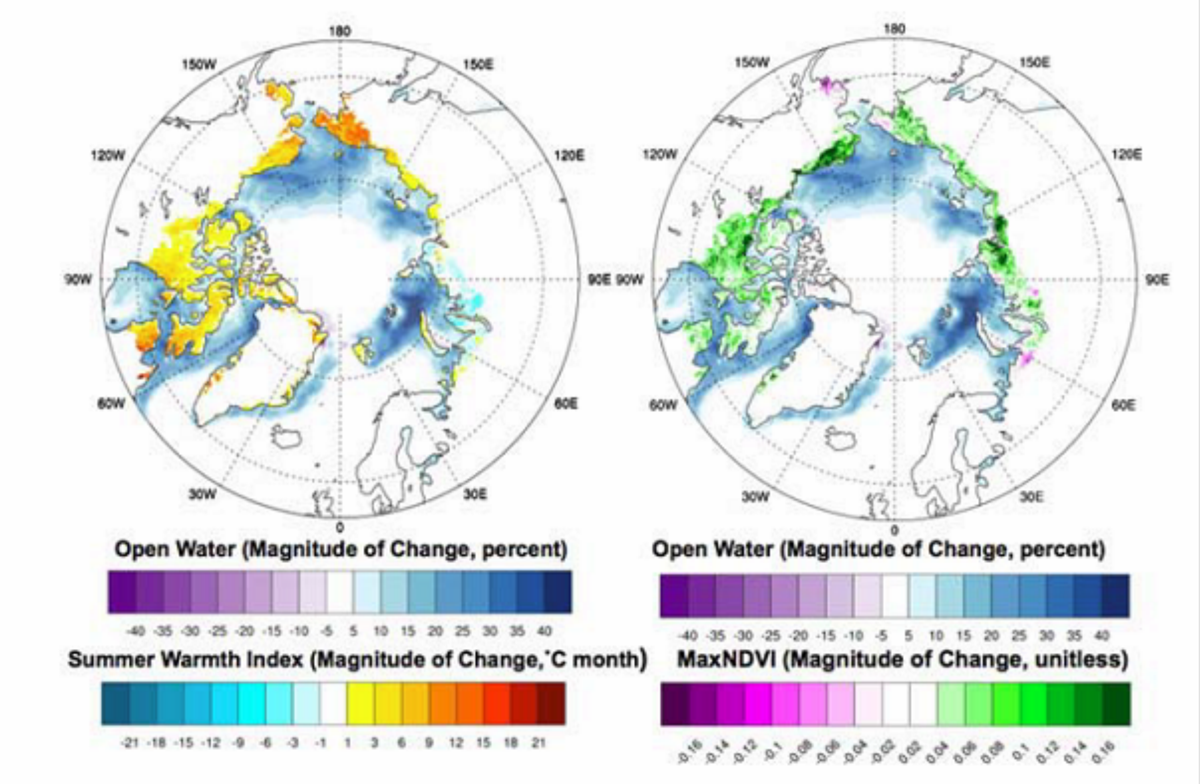


Figure 28-3: Trends for (a, right) summer (May-August) open water and annual MaxNDVI and (b,left) summer (May-August) open water and land-surface summer warmth index (SWI, the annual sum of the monthly mean temperatures >0 °C) derived from AVHRR thermal channels 3 (3.5-3.9 μm), 4 (10.3-11.3 μm) and 5 (11.5-12.5 μm). Trends were calculated using a least squares fit (regression) at each pixel. The total trend magnitude (regression times 29 years) over the 1982-2010 period is displayed (Bhatt *et al.*, 2010).

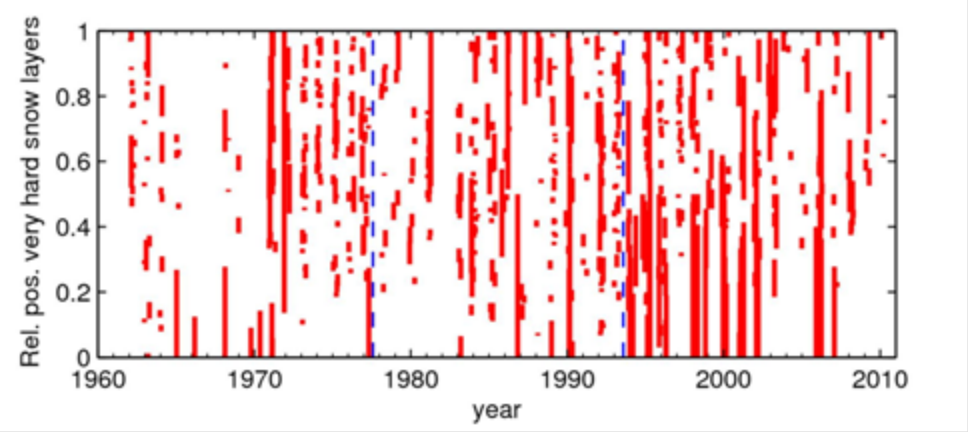


Figure 28-4: Long-term snow stratigraphy observations from Abisko, sub Arctic Sweden, showing increased incidence of mid-winter thaw events and more complete thaw events leader to a greater incidence of basal hard snow and ice layers (Johansson *et al.*, 2011).

Figure 28-5: Fishing vessel activity. Source: AMSA, _____.

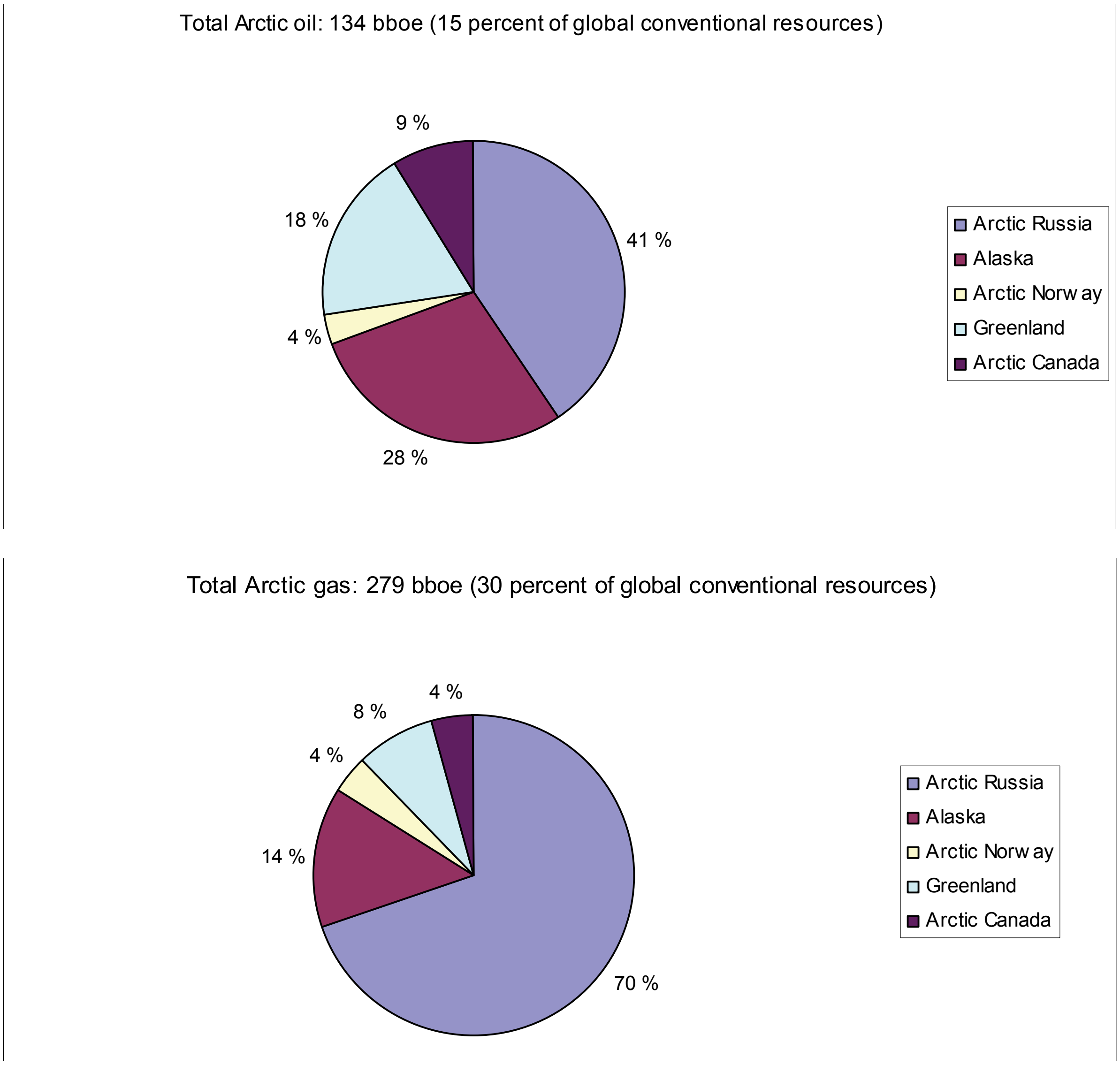


Figure 28-6: (top) Regional distribution of Arctic undiscovered oil resources (including NGL), and (bottom) regional distribution of Arctic undiscovered natural gas resources (including NGL). Source: Statistics Norway, 2010.

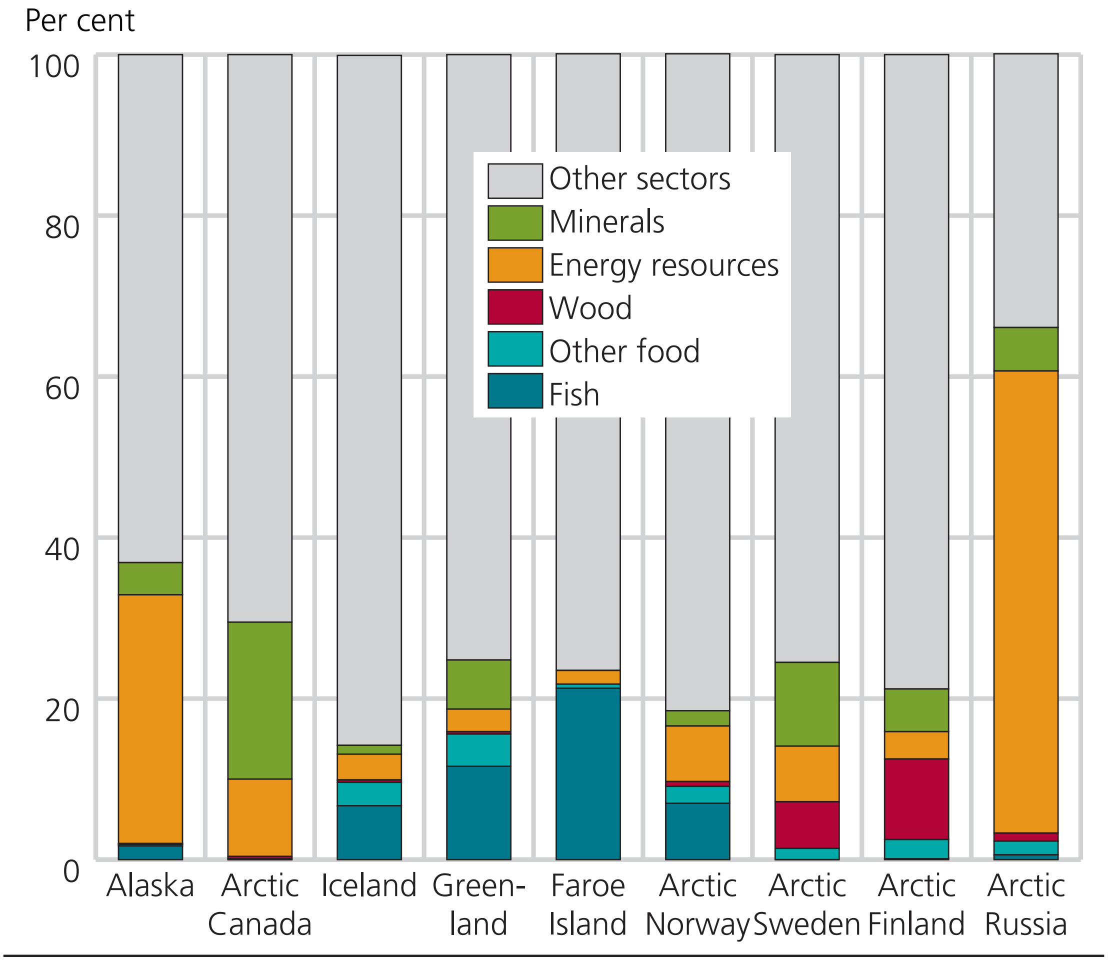
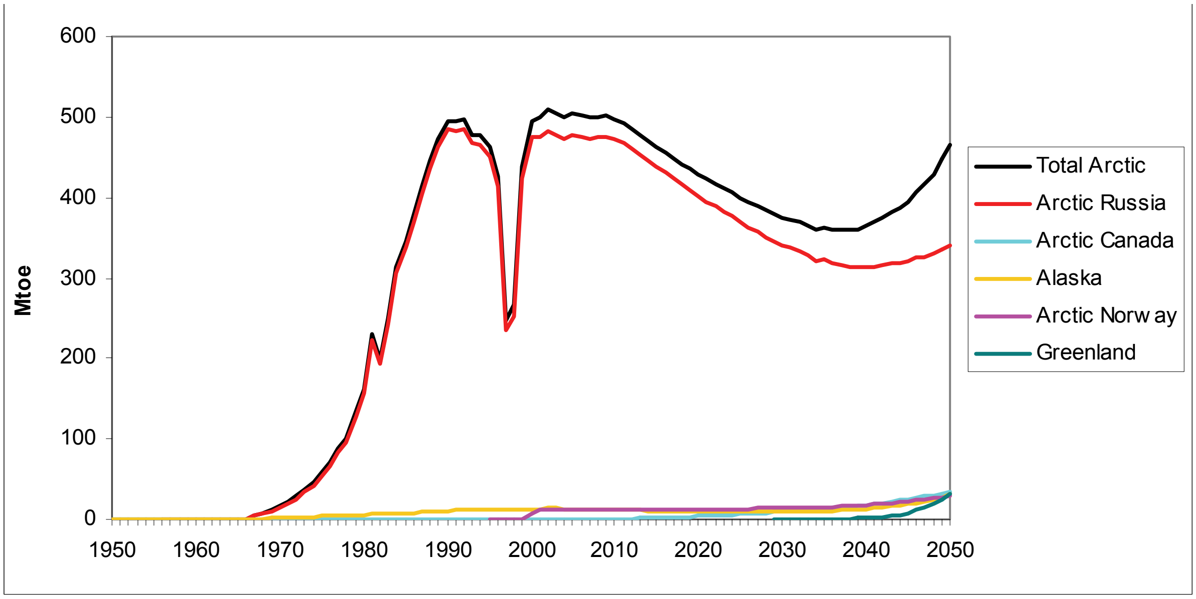


Figure 28-7: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010. [TO BE UPDATED]

**a)**



**b)**

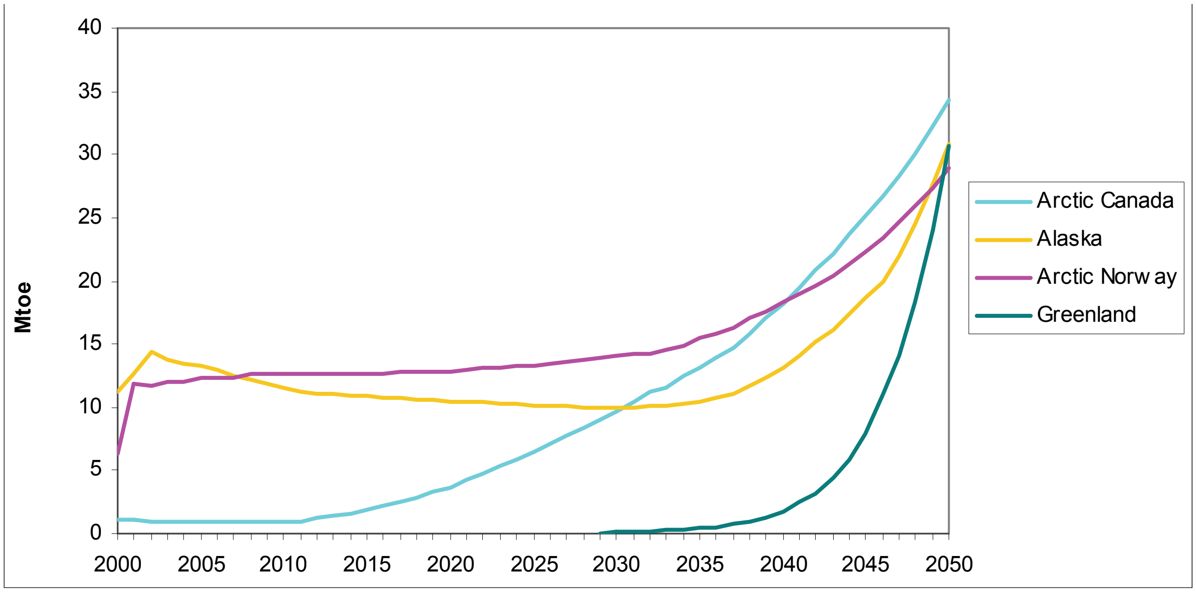


Figure 28-8: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.

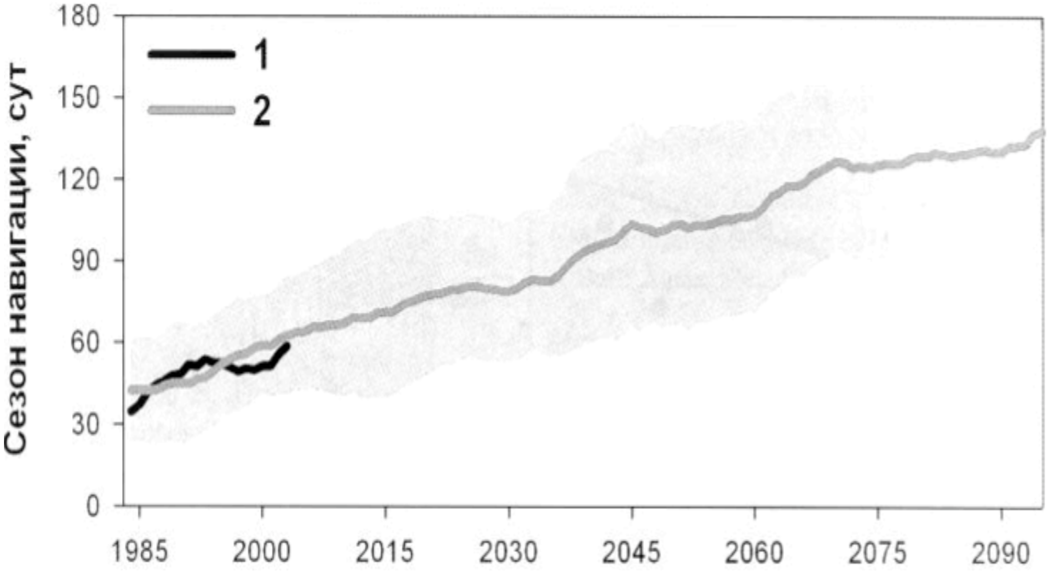


Figure 28-9: Projected duration of the navigation period (days) over the North-West passage (1) and Northern Sea route (2). Source: Mokhow and Khon, 2008.