Chapter 28. Polar Regions

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

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

Contributing Authors
Terry Callaghan (UK), Mark Carey (USA), 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), Anders Oskal (Norway), 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 physical, biological and socio-economic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by factors other than climate change but also demography, culture and economic development. There is evidence that climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). [28.2.5, 28.4]

The rate rather than the magnitude of changes in the polar regions may become more of 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] The decline of Arctic sea-ice in summer is occurring at a rate that exceeds most model projections (*high confidence*). Evidence of similarly rapid rates of change is emerging in some regions of Antarctica, particularly the ice shelves. 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 Chapter 14]

The primary conservation concern for polar bears over the foreseeable future or three generations is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent.

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 sea surface temperature (*high confidence*). [28.2.2] The changing sea ice environments off the Western Antarctic Peninsula and in the Arctic have resulted in measurable changes in phytoplankton communities. 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]

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the Polar Regions. Responses will vary depending on the vulnerability of species to changing ocean conditions. Some marine species have shifted their spatial distribution in response to changing environmental conditions. The response rate and the spatial extent of range shifts will differ by species based on their vulnerability to change and their life history. [28.2.2; 28.3.2] Penguins and flying birds restricted to sub-Antarctic islands will have lower reproductive success because of the added cost of obtaining prey further to the south (*medium confidence*).

Loss of sea ice in summer is expected to enhance secondary pelagic production in the Arctic with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). 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]

Shifts in the timing of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival (*medium confidence*). The breeding cycle of some shellfish and fish in the Arctic coincides with the spring bloom of ice algae and ocean phytoplankton and subsequent secondary production which is considered to enhance survival of the larvae. If the timing between peaks in primary production and secondary production are no longer matched to the timing of spawning or egg release, survival could be impacted with cascading implications to higher trophic level consumers. Higher predators have highly synchronized breeding phenologies in Polar Regions, requiring prey to be available near to land-based colonies at certain times of the year. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). [28.2.2, 28.3.2] Mismatch between the phenology of different trophic levels caused by climate change has also been suggested to be a potential problem for Arctic terrestrial mammals and birds [28.2.3.5], but the scientific documentation for this is weak.

Ocean acidification has the potential to inhibit egg development and shell formation of some zooplankton and krill in the polar regions with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Eggs and larvae of Antarctic krill have been shown to be vulnerable to increased concentrations of CO_2 in the water (*high confidence*). As well, there is increasing evidence that pelagic mollusks (pteropods) are vulnerable to ocean acidification (*medium confidence*). If these effects result in widespread impacts on populations then they will be far reaching on regional foodwebs. [28.2.2, 28.3.2]

Future trends in populations of Antarctic marine mammals and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). [28.3.2.2] 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) and Emperor penguins generally have been associated with long-term physical changes such as sea ice (*medium confidence*). [28.2.2.2]

Climate change is impacting terrestrial and freshwater ecosystems in some areas of the Antarctica and Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). [28.2]

The primary conservation concern for polar bears over the foreseeable future or three generations is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent.

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 (*very high confidence*). 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, but not all, Arctic areas and significant increases in tall shrubs have been observed in many places (*high confidence*). Other factors such as 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 northern boreal forest. [28.2.3.2, 28.2.3.3]

Increased energy availability (warming) in combination with increased water availability is expected to lead to increased productivity, biomass and the development of community complexity in native Antarctic terrestrial biota (*high confidence*). However, these responses are potentially confounded by multiple stressors, including human activities (research stations, tourism etc). [28.3.3.2] 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*). [28.3.3.4]

Summer phytoplankton levels in many Antarctic lakes have increased significantly together with higher nutrient inputs from exposed fell field soils and thawed ground (*very high confidence*). [28.2.1.2] These lakes have experienced extended open-water periods allowing the water and sediments to absorb more solar energy which has further increased lake water temperature during winter. 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*).

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase – especially for many indigenous peoples (*high confidence*). [28.2.4] Impacts include injury and risk from extreme and unpredictable weather including flooding, changing in ice and snow conditions endangering hunting, herding, and fishing; food insecurity and malnutrition due to decreased access to local foods and loss or compromised freshwater sources; permafrost and erosion damage to homes and infrastructure and loss of homelands as well as increased social and economic problems due to loss of traditional livelihood, language, culture and relocation of communities. These impacts are expected to vary among the diverse settlements that range from small, remote predominantly indigenous to large industrial settlements (*high confidence*). Many of these impacts are often related to the fact that a large percentage of northern settlements are along coastlines or beside rivers and lakes.

Food security of many indigenous and rural residents in the Arctic is being impacted by 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*). [28.2.7.1, 28.2.4] There have been noticeable impacts on the livelihoods of indigenous peoples' ways of life particularly their access to traditional foods that have provided sustenance, cultural, religious, economic, and community well-being for many generations. However, Arctic indigenous people have a high adaptive capacity and have begun to develop novel solutions to adapt to climate changes, such as combining traditional and scientific knowledge and co-producing climate studies with scientific partners. [28.2.7.1, 28.2.7.2, 28.4.1]

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] 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. Increased economic opportunities along with 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, 28.4.2]

Significant impacts on the availability of key subsistence marine and terrestrial species are projected as climate continues to change with the ability to maintain economic livelihoods being affected. The informal, subsistence-based economy will be impacted by changing climate (*high confidence*). Indigenous hunters, whalers, walrus hunters and herders are reporting non-predictable conditions resulting from more frequent occurrence of unusual weather events. There *is high confidence* that changing sea-ice conditions will result in more difficult access for hunting marine mammals and greater risk for the long-term viability of polar bear populations. [28.2.6.1.7]

Rising temperatures, leading to the further thawing of permafrost, and changing precipitation patterns have the potential to affect all infrastructure types and related services in the Arctic (*high confidence*). Much of the infrastructure is dependent upon the frozen soil to provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter. [28.2.6.5.1]

Although there is general agreement that both indigenous and non-indigenous people in the Arctic have a long history of adapting to change, the complex inter-linkages between societal, economic, political factors and climatic stresses represent unprecedented challenges for northern communities (*high confidence*). [28.4]

28.1. Introduction

Previous IPCC reports define the Arctic as the area within the Arctic Circle (66ºN), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58ºS (IPCC, 2001). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the Polar Regions in relation to particular subjects, similarly to the approaches adopted in the Arctic Climate Impact Assessment (ACIA) and Antarctic Climate Change and the Environment (ACCE) report (ACIA 2005, Convey et al. 2009; Turner *et al*., 2009; Convey *et al*., 2009). Changes in the physical climate regime in the Polar Regions are addressed in detail in IPCC WG-1 report.

[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.]]

Summary of Knowledge Assessed in other Reports (including IPCC, SWIPA, IPY etc.)

Several recent international climate assessments, including the IPCC (2007), the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (SWIPA, 2011), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner *et al*., 2009), and reports summarizing the findings of the International Polar Year (IPY) 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 focusing on impacts of climate change and briefly addressing the relevant information about changes in the physical climate parameters, which are detailed in the report of the Working Group 1 to the Fifth IPCC assessment.

Arctic

In the past few decades Arctic was characterized by the highest regional rates of changes in selected parameters of the physical climate regime. Such changes are essential for understanding a cascade of the environmental and societal impacts addressed in this chapter. Since 1980 Arctic has been warming at approximately twice the global rate demonstrating the strongest temperature changes (~ 1 °C/decade) in winter and spring, and smallest in autumn (IPCC WG2 2007, SWIPA 2011). Sea ice declined at an unprecedented rate in all seasons reaching the absolute minimum of 3.41 million km^2 in September 2012, which is 18% lower than in 2007, when the previous record of 4.17 million km^2 was recorded. (IPCC WG1 2014; Arctic report card, 2012). The Arctic Ocean is projected to become nearly ice-free in summer within this century, while some models suggest it may happen within the next thirty to forty years (IPCC WG1 Fifth AR). According to SWIPA (2011), the duration of snow cover extent and snow depth are decreasing in North-America while increasing in Eurasia. Since late 1970s permafrost temperatures have increased typically between 0.5 to 2 °C, with warming rates being much smaller for warm ice-rich permafrost at temperatures close to 0 °C than for colder permafrost or bedrock.

These changes in the physical climate regime and cryosphere are already generating widespread ecological, human, and economic impacts, which are projected to intensify in the future. Changes in the cryosphere will cause fundamental changes to the characteristics of Arctic ecosystems and in some cases loss of entire habitats with consequences for people who receive benefits from these resources (SWIPA 2011). In the terrestrial ecosystems the dominant response of Arctic species to climate change will probably be relocation rather than on-site adaptation (IPCC WG2 2007). 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 is projected to increase. According to SWIPA (2011), decreased multi-year sea ice and increased open water will enhance the overall marine production. Many marine ecosystems will be experiencing shifts from light limitation to nutrient limitations as well as shifting balance between the primary production by ice algae and phytoplankton with implications for Arctic food webs. Changing ice patterns and timing will affect mammals, including the polar bears, marine birds and some fish species. Pinniped species that depend on ice (i.e. seals and walrus) will be disadvantaged due to reductions in the sea ice extent. According to model projections, within 50-70 years loss of hunting habitats may lead to extirpation of the polar bears from seasonally ice-covered areas, where currently two thirds of their world population live. Sub-arctic seabirds will be competing with arctic species. Northward expansion of habitats for some temperate species will enhance foraging opportunities for their predators in the High Arctic, at a cost to endemic populations of the Arctic.

There are challenges for human systems, local communities and traditional ways of life. Infrastructure and settlements, particularly on the Arctic coasts, become more vulnerable with increased risks of damage due to the coastal erosion, permafrost degradation, and loss of sea ice (IPCC WG2 2007; SOAC 2011; SWIPA 2011). Human settlements and cities in the Russian Arctic are conventionally located along the rivers, and particular concerns are associated with floods caused by ice jams. This is exemplified by the catastrophic 2001 Lena River flood, which demolished most of the buildings in the city of Lensk. According to SWIPA (2011), floods due to ice jams on Siberian rivers in the coming decade are projected to become 1.2 to 1.5 times more frequent and more severe with 35 to 60% increase in peak break-up water levels. In north-European Russian rivers (Severnaya Dvina, Sukhon, Vyga, Pechora) maximum jam levels might increase by 10-12%, while the frequency of floods would increase by a factor of 1.2, at most. Such changes may have serious implications for settlements and infrastructure on the shores of these rivers, and many of the populated areas are expected to be periodically flooded. Transport options and access to resources are radically changed by differences in the distribution and seasonal occurrence of snow, water, ice and permafrost. Freshwater ice durations over much the circum-polar North have decreased since 1970s in response to earlier break-ups and later freeze-ups, on average 6.3 and 5.8 days/100 years, respectively, with rates in the high Arctic more than 4 times greater than those experienced in more southerly latitudes (SWIPA, 2011). Maximum ice thickness decreased up to 15 cm in rivers within Siberia. Statistically, a long-term mean increase of 2 to 3°C in autumn and spring air temperature produces an approximate 10 to 15 day delay in freeze-up and advance in break-up, respectively. As a result, many of the ice roads may become less viable option than the all-weather roads with implications for significantly increased costs (SWIPA, 2011). There will also be new opportunities such as increasingly navigable Northern Sea Route with up to 125 days per year suitable for navigation by 2050, and predicted up to 15% decline in the heating energy demand in the populated Arctic areas (IPCC WG2 2007). Reduced ice period and thickness of river ice is beneficial for hydropower generation during the low flow winter season, when the energy demand is at its annual maximum (SWIPA, 2011).

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. 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 the availability of 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 2011).

Antarctic

While temperatures over the bulk of the Antarctic continent have not changed markedly in recent decades, the strongest rates of atmospheric warming seen in the Southern Hemisphere are occurring in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration (Mayewski *et al*., 2009; Turner *et al*., 2009; Stammerjohn *et al*., 2012). Although not to the same extent, warming has also occurred in the continental margins near to Bellingshausen Sea, Prydz Bay and the Ross Sea, with areas of cooling in between (Bromwich *et al*., 2013). Land regions that have experienced significant warming have seen considerable glacial recession along with changes in the ice and permafrost habitats in the coastal margins, although changes in snow fall show no trends. The Southern Ocean continues to warm throughout its depth with increased freshening at the surface due to precipitation, leading to increased stratification. The Antarctic Circumpolar Current has moved to the south, the extent of which is regionally variable. Similarly, the magnitude and southward extent of increasing wind-driven mixing associated with increasing SAM is also regionally variable (Sallee *et al*., 2010). Aragonite undersaturation of the Southern Ocean at depths equivalent to the continental shelf will occur within decades, with some regions being affected sooner than others. Undersaturation of the surface waters is likely before 2100, reinforcing previous conclusions of threats to pteropods (pelagic marine molluscs).

Antarctic terrestrial systems have been documented to have changed with increasing habitat from reduction in snow and ice cover resulting in increased abundance of flowering plants. On subantarctic islands there have also been increases in abundance of alien species and consequent negative impacts on local biota.
Antarctic terrestrial ecosystems occur in three generally accepted biogeographic regions; the sub-Antarctic, maritime Antarctic and Continental Antarctica, with generally warmer temperatures, reduced extreme seasonality and greater biodiversity in the sub-Antarctic (Convey, 2006). On the continent, where biological diversity is limited to species that can take advantage of the short periods where temperatures and moisture availability are above physiological and biochemical thresholds, recent research has shown that there are 15 biologically distinct areas (Terauds *et al*., 2012). In many areas there is no visible vegetation with life often limited to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria and lichens (Convey, 2006).

Antarctic freshwater systems are fewer and much smaller than Arctic freshwater systems, comprising lakes, ponds, short streams and seasonally wetted areas (Vincent *et al*., 2008). Antarctic freshwater biota are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some lakes but higher plants are absent on the continent. Planktonic ecosystems are dominated by small algae, bacteria and colourless flagellates. There are few metazoans and no fish. Documented effects of climate change include changing microbial dynamics in lakes as a result of changing nutrients and contaminants. For subantarctic islands, such as Signy Island, increased icefree conditions and temperatures along with decreases in perennial snow cover have led to increased organic and inorganic nutrient inputs to lakes. Fur seal populations have increased dramatically and occupied the increasing available terrestrial areas, resulting in disruption of local systems, including increased nutrients into the areas.

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry and light due to vertical mixing (Massom and Stammerjohn, 2010; Boyd *et al*., 2012; Constable *et al*., submitted). Diatoms are the dominant primary producers, particularly in the coastal waters, which are also the primary contributors to the annual carbon flux in the region. Antarctic marine food webs are dominated by Antarctic krill, *Euphausia superba* (hereafter termed ‘krill’), which primarily consumes large phytoplankton (diatoms) and small zooplankton and are themselves food for many of the fish, squid, marine mammals, penguins and flying birds in the Southern Ocean. Other secondary producers are salps and copepods, which can feed on smaller phytoplankton, and are consumed by smaller fish, such as myctophids. The relative importance of krill varies regionally, being dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers *et al.*, 2012). In the Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current, while in the north the system is dominated by copepods and myctophid fish.

Around the Antarctic continent, the coastal systems are characterised by deep shelf areas (800m) broken by canyons and cross-shelf depressions (Grant *et al.*, 2006). Banks of 300m depth or less are scoured by icebergs. Benthic communities are differentiated by these topographic features (Constable *et al.*, submitted). Coastal polynyas are prevalent, caused by land forms, glacier tongues, bottom topography or grounded icebergs(Massom and Stammerjohn, 2010). These areas are high in productivity with a few areas being important for the formation of Antarctic Bottom Water, which sinks from the surface flowing over the shelf and into deep water, influencing the benthos with its water chemistry and organic particulates.

For these marine ecosystems, few studies were available in AR4 to document and validate the changes resulting from climate change. Those studies reported increasing sponges and their predators, declining abundances of krill, Adélie and Emperor penguins, and Weddell seals and a possible increase in salps in place of krill, noting regional differences in these trends. These changes may have been attributable to declining sea ice or as indirect consequences of recovery of whales and seals from past over-exploitation. The importance of climate change was not able to be determined. Future impacts of climate change included that increases in temperature and reduced sea ice were expected to negatively affect krill abundance and cause a shift in its distribution. As well, many cold-adapted species, though not all, may be vulnerable if water temperatures rise to 5-10oC. Overall, the direct and indirect effects of climate change were considered to be difficult to predict, particularly in relation to an increasing fishery for Antarctic krill.

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC WG2 2007).

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 (1936-1999)(Peterson *et al.*, 2002) could not, for a similar period (1951-2000), 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 (Déry and Wood, 2005).

More recent discharge data (1977-2007) for 19 circumpolar rivers indicates an area-weighted average increase of +9.8% (range –7.1 to +47.0%; 15 of 19 exhibiting increases), with additional evidence of accelerating change in recent years for the combined domain of six selected large basins (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%. Across the Russian Arctic drainage basin, dates of spring maximum daily discharge have also become earlier, particularly in most recent [1960-2001] period analyzed (average -5d; range for four regions +0.2 to -7.1 d), although no consistent trend exists for changes in the magnitude (average -1%; range +21 to -24%) of these daily flows (Shiklomanov *et al.*, 2007). Changes to earlier timing were most pronounced in eastern, colder continental climates that have experienced rises in air temperature. Such upward trends in air temperature, rather than flow regulation, have been identified as the dominant control of such timing shifts (Tan *et al.*, 2011).

Changes have also occurred in winter flows with documented rises in the winter minimum flows for many Eurasian and North American rivers (Walvoord and Striegl, 2007; Smith *et al*., 2007; St. Jacques and Sauchyn, 2009; 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 have increased because of enhanced subsurface flow resulting from permafrost thaw (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 (Rawlins *et al*., 2009a; Rawlins *et al*., 2009b; Landerer *et al*., 2010). 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 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, 2007a). Where water has persisted and lake-water temperatures increased, reductions in organic carbon burial has been attributed to a strong positive relationship with the mineralization of organic carbon in lake sediments (Gudasz *et al*., 2010). Increasing water temperatures can also affect planktonic and benthic biomass in Arctic lakes and lead to changes in species composition (Heino *et al*., 2009; Jansson *et al*., 2010). In a study of a Greenland catchment, warmer conditions have been noted to increase nutrient and humic acid loadings leading to a higher abundance of phytoplankton and zooplankton (crustaceans) and altered species composition (Christoffersen *et al*., 2008).

In the case of permafrost thermokarst lakes, new studies have documented changes in their size and number in various parts of the Arctic (Riordan *et al*., 2006; Hinkel *et al*., 2007; Marsh *et al*., 2009). Their spatial patterns and rates of change, however, are not consistent and may be related to differing thawing state of the permafrost as well as spatial variations in warming (Prowse and Brown, 2010a). 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) , with some documented cases resulting in enhanced lake eutrophication through an ecological shift from pelagic-dominated to benthic-dominated production (Thompson, M., Wrona, F., Prowse,T., 2012).

The ecology of rivers has also been demonstrated to be dependent on changes to their freshwater ice regimes. Reductions in the physical severity of spring 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, 2007). 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 could also 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

Recent compilations of single-year datasets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen *et al*., 2012). In regions where the climate has warmed the physical impacts on aquatic ecosystems include loss of ice cover, increasing periods of open water, increased water column temperatures and changes in water column stratification. Shifts in the water balance can also occur. In some areas a negative water balance has been established due to increased temperate and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes (Hodgson *et al*., 2006a). In other areas, especially glacial forelands, increased temperatures lead to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes. In both cases the balance between precipitation and evaporation can have detectable effects on lake ecosystems through changes in water body volume and lake chemistry (Lyons *et al*., 2006; Quesada *et al*., 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to inter-annual and inter-decadal variability in the water balance, as measured by changes in specific conductance (Verleyen *et al*., 2012). In most cases warming is predicted to increase biological production in lakes. Other effects include dessication of moss banks due to increased evaporation and sublimation rates (Wasley *et al*., 2006), increases in the latitudinal ranges of extant species and increase the likelihood of invasive species becoming established together with increases in community biomass and complexity (Peck, 2005).

In summary, there is *high confidence* that increased temperatures will impact subaerial aquatic ecosystems in Antarctica. The exact nature of these impacts are likely to vary regionally depending on the magnitude of the temperature change, how much change in an area required for the temperature to rise above freezing, the depth to surface area of the lakes and the local hydrology. A great difficulty in documenting change is the absence of long term monitoring in most of Antarctica.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

Climate change is expected to affect physical and chemical properties of Arctic marine ecosystems by: (1) increasing temperatures, (2) altering the timing and extent of sea ice retreat, (3) changing sea water density through increased freshwater supply, (4) reducing sea ice thickness and multi-year ice formation which in turn changes the timing and duration of irradiance in the water column, and (5) ocean acidification (WG 1 Chapters 4 and 11). This section addresses the expected impacts of these physical and chemical changes on marine ecosystems.

Retrospective studies show the Arctic and its neighboring seas are influenced by interannual, decadal, and multi-decadal climate variations (WG 1). These variations in climate forcing are expected to continue in the future (Overland and Wang, 2010) and will continue to influence the ocean conditions in the Arctic (Ogi *et al*. 2010). For example, recent (2007-2012) ocean conditions in the Bering Sea have been cold (Stabeno et al. 2012), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

Observations and model predictions indicate that the carbon cycle of the Arctic Ocean will be impacted by climate change. The processes that influence the inorganic carbon cycle in the Arctic are complex and differ seasonally and regionally (Bates and Mathis, 2009). The mechanisms underlying ocean acidification and the expected rates of change in ocean pH caused by increased CO_2 are documented in WG I Chapter 6 and II Chapters 5, 6, 19 and 30. If some regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as pteropods (small planktonic shelled mollusks), urchins, and clams the growth and survial of these organismswill be impacted (WG I, Chapter 6 Figure 6.28; Chierici and Fransson, 2009; Fabry *et al*., 2009; Yamamoto-Kawai *et al*., 2009). Additional monitoring and process studies are needed to fully understand how these processes will unfold in the future.

28.2.2.1.1. Overview of Arctic marine plankton and fish

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). Large phytoplankton blooms can develop underneath the ice with implications for energy partitioning between pelagic and benthic ecosystems (Perrette *et al.*, 2011; Arrigo *et al.*, 2012). 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 (Hirche *et al.*, 2006; Zhang *et al.*, 2010).

Copepods (small pelagic crustaceans) dominate the mesozoplankton community in the Arctic, where they are preyed upon by larger invertebrate predators, fish, seabirds and marine mammals. Four species of the genus *Calanus* are common, but only two, *C. glacialis* and *C. hyperboreus*, are true Arctic species (Ji *et al.*, 2012). The other two, *C. finmarchicus* and *C. marshallae*, are boreal ex-patriot species that are brought north in the Atlantic and Pacific water inflows, respectively. All four Calanus species feed on phytoplankton, accumulating lipid (wax-esters) during the growth season, and spending some part of the year dormant (in diapause) below the surface layers. All four have reproductive cycles that take advantage of the spring bloom in some way and while the boreal species have annual life cycles, the Arctic species take two or more years to mature and reproduce. Other important large-bodied copepods are *Neocalanus cristatus* and *N. flemingeri* in the Bering Sea, which have life histories and feeding preferences similar to those of the *Calanus* species, and *Metridia longa*, which is abundant throughout the deep waters of the eastern and central Arctic (Kosobokova and Hirche, 2009), and which is active all year round, feeding omnivorously. In the Bering and Barents Seas, a large fraction of the phytoplankton biomass is retained in the pelagic system by zooplankton grazing (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; Riser *et al.*, 2008).

Euphausiids (krill) are not endemic to the Arctic, but are brought into the region in the Atlantic and Pacific inflows. In the Barents Sea, krill (mainly *Thysanoessa inermis* and *T. raschii*) provide an important food source for several species of fish, including cod, haddock and capelin (Ressler *et al.* 2012; Dalpadado *et al.*, 2008; Orlova *et al.*, 2009; Dalpadado *et al.* 2009). In the west, euphausiids are transported north through the Bering Strait towards the Beaufort Sea, where aggregations are consumed by bowhead whales off Point Barrow, Alaska (Berline *et al.*, 2008).

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 (Spebcer, 2008; Mueter and Litzow, 2008). Habitats are bounded by topographic features, fronts, currents or river plumes, and oceanographic features left by sea ice (including salinity fronts) (Ciannelli and Bailey, 2005). 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 (Sundby and Nakken, 2008; Hunt *et al.*, 2011; Mundy, 2011; Bouchard and Fortier, 2011; Hollowed *et al.*, 2012).

Phenological responses (timing of spawning, timing of settlement, duration of growing season, age at maturity)

Changes in ocean temperature, wind-driven upwelling of deep nutrient-rich waters, sea ice thickness, the date of ice breakup and stratification will alter the timing, duration and magnitude of phytoplankton production (Zhang *et al.*, 2010). During the period 1997-2009 a trend towards earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru *et al.*, 2011). This advanced timing of annual phytoplankton blooms coincided with the decreased sea ice concentration in early summer (Kahru *et al.* 2011). Given the short time series and limited studies, there is *medium confidence* that climate change will alter the bloom timing and the duration of phytoplankton trophic production in the Arctic.

There is *medium confidence* based on theoretical relationships and observations that rapid changes in physical and chemical changes in ocean conditions will alter the timing and duration of phytoplankton production. If shifts in timing disrupt the match between copepod hatch dates and spring production this would impact the survival of zooplankton and timing of spring prey availability for their predators (Søreide *et al*., 2010). However, simulation modeling of the Arctic Ocean and its surrounding Seas, showed longer growth seasons and increased summer temperature in the central Arctic favored endemic copepods (*Calanus glacialis* and *Calanus hyperboreus*) (Ji *et al*., 2012). Results from the cruises conducted during the International Polar Year in 2007 and 2008 on the Canadian shelf and adjacent open ocean and the southeast Beaufort Sea, suggest that longer ice free periods in the Arctic could provide for more opportunities for episodic nutrient pulses that would enhance secondary production through the growing season (Tremblay *et al*., 2012). Additional research is needed to understand how climate change will impact seasonal survival of Arctic zooplankton.

There is *medium* to *high confidence* based on observations of fish responses at lower latitudes, that climate change impacts on the physical and chemical environment in the Arctic will cause changes in phenology of some fish and shellfish species in the Arctic marine ecosystems. Several studies document that climate shifts and associated changes in ocean conditions impact the growth, spawning and feeding distribution and of marine fish (Gjosaeter et al 2009; Drinkwater eta l. 2011). The responses of fish to shifts in the timing and duration of growing seasons will vary by species. Some species exhibit an ability to adjust the timing of spawning and rates of growth to local conditions (Ormseth and Norcross, 2009; Kristiansen *et al*., 2011) however, these adjustments occurred over long time periods. However, compared to temperate regions, there is a general lack of long-term phenological studies from the Arctic Ocean and additional observations are needed.

Observed spatial shifts in response to climate

Considerable geographic variation in primary production has been observed (Lee *et al*., 2010; Grebmeier, 2012). Simulation studies revealed that longer growing seasons resulting from climate change will be insufficient to allow expatriate species to become endemic species in the Arctic Ocean (Ji *et al*., 2012). In the Barents Sea, simulation modeling experiments showed that summer loss of sea ice and increased temperature would impact the decrease the production of *C. glacialis* and increase the production of *C. finmarchicus* (Slagstad *et al*. 2011). In the Arctic Ocean, the observational record is often short or of limited spatial scale (Slagstad *et al*., 2011). Additional observations are needed to accurately predict shifts in the range of Arctic and sub-Arctic copepods in response to climate change.

Climate-related changes in the flow of currents into the Arctic will likely change the abundance and distribution of euphausiids. In the Barents Sea, in years when greater intrusions of Atlantic water occurred, higher temperatures and higher levels of euphausiids were observed, with varying species composition (Zhukova *et al*., 2009).

Numerous studies from the Bering Sea, Barents Sea, west Greenland Sea, and Chukchi Sea confirm that fish shift their spatial distribution in response to climate variability (i.e. interannual, decadal or multi-decadal changes in ocean temperature; (Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún *et al*., 2009; Valdimarsson *et al*., 2012). 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). However, responses to climate change may follow 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 (Planque *et al*., 2010; Kristiansen *et al*., 2011; Sigler *et al*., 2011). Coupled bio-physical models have been developed to assess the implications of climate change on the spatial distribution and abundance of multiple life stages of several marine species in the Bering and Barents Seas (Huse, 2008; Parada *et al*., 2010). These models have been successful in reproducing the observed spatial dynamics of the target species and in some cases studies are underway to evaluate their predictive skill. Qualitative vulnerability assessments indicate that the persistence of cold winter conditions in the Arctic coupled with the life history factors noted above will restrict or retard the movement of several sub-arctic fish and shellfish species into the Arctic (Hunt Jr. *et al*., 2013; Hollowed *et al*., In Press). In summary, there is *medium* to *high confidence* based on observations and modeling of fish responses in the Barents and Bering Seas to climate shifts, that climate change impacts on the spatial distribution and volume of suitable habitat will cause shifts in the spatial distribution of some fish and shellfish species in the Arctic marine ecosystems. The spatial extent of these shifts and the time frame for change will depend on the vulnerability of different species to climate change and the strength of the species response. Compared to temperate regions, there is a general lack of long-term comprehensive monitoring of the spatial distribution of fish and shellfish stocks in the high Arctic Ocean.

Observed variations in fish and shellfish production in response to climate

Satellite derived estimates of primary production provide evidence of a 20% increase in primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice free periods (Arrigo *et al*., 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad *et al*., 2011). Studies based on a short, 5 year (2004-2008), time series in the Canadian Basin found that after the spring bloom, increased warming, increased stratification, and decreased nutrients during the Arctic summer may favor smaller phytoplankton over large phytoplankton (Li *et al*., 2009; Morán *et al*., 2010). Additional observations over a broader spatial scale are needed to confirm this relationship. Additional observations will also help to resolve observed differences between in-situ and satellite derived estimates of primary production (Matrai *et al*., 2013). In summary, climate change is expected to extend the duration of the growing season and upwelling is expected to bring nutrients to the surface which would favor phytoplankton production, however, these factors may be offset later in the year by increased stratification and nutrient depletion in summer. Based on this information, there is *medium confidence* that primary production will increase in the Arctic in response to climate change impacts on the duration of ice free periods in the Arctic Ocean.

In the Bering Sea, Observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold years than warm years (Coyle *et al*., 2011). Based on this study there is *low confidence* that climate change will reduce the abundance of C. *marshallae* in the Bering Sea. Additional observations are needed to confirm this response.

Numerous studies have identified statistical links between climate variability and the annual production of zooplankton and fish (Mueter *et al*., 2007; Drinkwater *et al*., 2010). The mechanisms underlying these statistical linkages are often well documented for commercially important species (Bakun, 2010). The vulnerability of different fish and shellfish species to the direct and indirect effects of climate change is governed by the exposure of the species to changing environmental conditions and fishing throughout its life history and across its geographic range (Beaugrand and Kirby, 2010) and the ability of the species to adapt or acclimate to changing conditions (Pörtner and Peck, 2010; Donelson *et al*., 2011). In the eastern Bering Sea and Barents Seas, large interdisciplinary research programs have identified the mechanisms underlying these statistical relationships which provided the foundation for climate change projections for selected species (discussed in section 28.3.2; Brander, 2010; Wiese *et al*., 2012). Observations of the condition of age-0 pollock in the Bering Sea during the last decade showed condition improved in cold years suggesting that overwintering success was higher in years when *C. marshallae* were abundant (Hunt *et al*., 2011). Retrospective studies of ocean conditions and interannual variations in walleye pollock recruitment to the fishery over three decades revealed a dome-shaped functional relationship between temperature and recruitment (Mueter *et al*., 2011).

Other stressors

If the expected changes in summer sea ice occur as described by WG 1, opportunities for increased oil and mineral extraction, shipping, fishing and tourism are expected to occur in the region. These activities will increase the risk of introductions of alien species to the region and the risk of regional pollution.

The implications of ocean acidification on the food web can be considerable. If regions of the Arctic become understaturated with respect to aragonite, and this inhibits shell formation for pteropods, this will have strong consequences on their predators. At the current time it is not possible to fully predict the consequences because it is unclear whether other species, with a similar nutritive value, will replace pteropods. Laboratory experiments showed a decline in the calcification of a pteropod (*Limacina helicina*) in the Arctic under projected ocean warming and acidification (Comeau *et al*., 2010). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable 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

28.2.2.1.2. 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 (e.g. (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*) colony in the western Beaufort Sea was highly negatively correlated throughout the breeding season with changes in the distance to the ice edge which was the habitat of the prey (Moline *et al*., 2008). Since 1990, breeding success and population size have been negatively correlated with summer pack-ice extent.

Even though timing of breeding advanced for Brünnichs guillemots (*Uria lomvia*) in a colony in the southernmost part of its range in Arctic Canada between 1988 and 2007, 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*., 2005; 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 (Gaston *et al*., 2009).

In contrast, (Byrd *et al*., 2008) could not document any significant correlation between productivity of brünnichs guillemots and common guillemots (*Uria algae*) breeding on the Pribilof islands in the Bering Sea and changes in sea ice extent 1976-2006. 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 starting in the mid 1990tiescaused by increased temperatures and reduced sea ice 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 range suitable for their preferred prey, the large lipid-rich Arctic copepods *Calanus glacialis and C. hyperboreus*. Little auks in Svalbard also responded by advancing the date for egg-laying when SSTs increased and sea ice 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 (Wang and Overland, 2009). 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 with *high confidence* 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*., 2005). 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 with *medium confidence* 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.

28.2.2.1.3. Polar bears

Both empirical and modelling studies have been used to understand the impacts of climate change on polar bears (*Ursus maritimus*) (Hunter *et al*., 2010; Amstrup *et al*., 2010; Durner *et al*., 2011). Empirical studies provide the most direct insight into the mechanisms of change but modelling allows improved predictive capacity.

Polar bears evolved from brown bears (*U. arctos*) and despite episodic admixture, the polar bears genome shows Arctic adaptations (Miller *et al*., 2012). Sea ice is the primary habitat of polar bears and is used for migration, mating, some maternity denning, and access to prey. Annual ice over the continental shelves is preferred due to high prey density (Durner *et al*., 2009). There is *high confidence* 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 ice over continental shelves, decreased ice duration, and decreased ice thickness (Stirling and Derocher, 1993; Derocher *et al*., 2004; Stirling and Parkinson, 2006; Durner *et al*., 2009; Amstrup *et al*., 2010; Hunter *et al*., 2010; Rode *et al*., 2012; Sahanatien and Derocher, 2012).

Subpopulation response varies geographically reflecting differences in ice change. Only 2 of the 19 subpopulations, Western Hudson Bay (Regehr *et al*., 2007) and the Southern Beaufort Sea (Regehr *et al*., 2010; Rode *et al*., 2010a) have data series adequate for clear identification of abundance effects related to climate change. Other subpopulations lack adequate time series, but show characteristics associated with decline. For example, between 1977 and 2010, declining body condition in Baffin Bay and Davis Strait was associated with ice loss although high bear density was an alternate cause in the case of Davis Strait (Rode *et al*., 2012). Similarly, late arrival of ice at one Barents Sea denning area was associated with lower body mass of both mothers and their cubs (Derocher *et al*., 2011). There is *high confidence* that the primary conservation concern for polar bears is ice change that result in habitat loss and fragmentation causing reduced food intake, increased energy expenditure, and increased fasting (Stirling and Derocher, 1993; Stirling, I. *et al*. 1999; Mauritzen *et al*., 2003; Derocher *et al*., 2004; Regehr *et al*., 2007; Amstrup *et al*., 2010; Sahanatien and Derocher, 2012). There is *high confidence* for declining ice causing lower body condition that can reduce individual growth rates (Rode *et al*., 2010a; Rode *et al*., 2012) and *very high* *confidence* that reduced body condition is a precursor to demographic change. Reduced body condition may result in lower fasting endurance, lower reproductive rates, and lower survival (Regehr *et al*., 2007; Regehr *et al*., 2010; Molnar *et al*., 2011) and these changes can reduce subpopulation growth rate or cause subpopulation decline (Derocher and Stirling, 1996; Derocher and Stirling, 1998; Stirling et. al., 1999; Regehr *et al*., 2010; Hunter *et al*., 2010; Rode *et al*., 2010a; Robinson *et al*., 2011). The Southern Beaufort Sea is projected to decline by 99% by 2100 with a probability estimated at 0.80-0.94 under A1B (Hunter *et al*., 2010). The Northern Beaufort Sea is currently stable although decline is predicted with warming (Stirling *et al*., 2011). There is *medium confidence* for subpopulation decline by 21% between 1987 and 2004 in Western Hudson Bay related to climate change (Regehr *et al*., 2007). Projected extirpation of approximately two-thirds of the world's polar bears was predicted for mid-century due to ice loss under A1B (Amstrup *et al*., 2008). Aspects of this study were criticized (Armstrong *et al*., 2008) but refuted (Amstrup *et al*., 2009). The two-thirds decline is consistent with other studies and has *robust evidence* with *medium agreement*. Projected extinction of polar bears has *low confidence*. There is *very high confidence* that subpopulation extirpation will occur with the projected climate change for the Arctic

Multiyear ice is used by some polar bears at 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 *low confidence* in habitat improvement. Increasing the distance to terrestrial refugia and multiyear ice at maximal melt may have negative consequences such as drowning, cub mortality, and high energetic costs (Monnett and Gleason, 2006; Durner *et al*., 2011; Pagano *et al*., 2012). Loss of multiyear ice may pose difficulties for some subpopulations although there is *limited evidence*.

There is *high confidence* in *robust evidence* of changes in sea ice conditions changing polar bear distribution (Fischbach *et al*., 2007; Schliebe *et al*., 2008; Gleason and Rode, 2009; Towns *et al*., 2010). Later formation and arrival of autumn ice at a Svalbard denning area reduced access to pregnant females (Derocher *et al*., 2011). Increased human-bear interactions were associated with distribution shifts and declines in body condition (Towns *et al*., 2009). There is *high confidence* that the number of human-bear interactions will increase with warming (Stirling and Derocher, 1993; Derocher *et al*., 2004; Stirling and Parkinson, 2006; Towns *et al*., 2009).

An increasingly terrestrial niche for polar bears was postulated (Dyck *et al*., 2007; Dyck and Romberg, 2007; Armstrong *et al*., 2008; Dyck *et al*., 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith *et al*., 2010). However, such terrestrial feeding is not new (Lønø, 1970; Lunn and Stirling, 1985; Derocher *et al*., 1993; Derocher *et al*., 1993; Derocher *et al*., 2000). Assertions of an increased terrestrial niche for polar bears have been challenged because resources are inadequate to replace the high-energy content of marine prey (Derocher *et al*., 2004; Stirling *et al*., 2008b; Amstrup *et al*., 2009; Slater *et al*., 2010; Rode *et al*., 2010b). *Very low confidence* exists that polar bears can adapt to an increase in terrestrial foods. There is *very high confidence* that polar bears will not adapt to climate change in many subpopulations. Studies have also tentatively linked changing environmental conditions to cannibalism (Amstrup *et al*., 2006), altered feeding (Cherry *et al*., 2009), unusual hunting behaviour (Stirling *et al*., 2008a), and diet change (Iverson *et al*., 2006; Thiemann *et al*., 2008). There is *medium confidence* that these observations of polar bear may be related to changing ice conditions.

28.2.2.1.4. Arctic and subarctic marine mammals

Empirical studies on responses of Arctic and subarctic marine mammals to climate change are limited (Kelly, 2001; Laidre *et al*., 2008) . Understanding of climate change effects on marine mammals varies according to 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). Predicted changes, however, may not be evident until significant sea ice loss has occurred (Freitas *et al*., 2008; 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, *Pagophilus groenlandicus*, and hooded seal, *Cystophora cristata*) use ice but none year-round (Lydersen and Kovacs, 1999). Similarly, walrus (*Odobenus rosmarus*) rely on ice for part of their life cycle but commonly retreat to land when ice is unavailable. Three cetaceans remain in the Arctic year-round (bowhead whale, *Balaena mysticetus*, narwhal, *Monodon monoceros*, and beluga, *Delphinapterus leucas*) with narwhal the most ice-associated.

There is *high confidence* that climate change effects 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 will suffer major negative effects (Ragen *et al*., 2008; Laidre *et al*., 2008). Resilience to climate change will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (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.

Arctic and subarctic marine mammal vulnerability to climate change was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (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 (Laidre *et al*., 2008). Kovacs *et al*. (2010) shared concern for hooded seals and narwhal but had serious concerns for ringed seals and bearded seals. Physiological specialization by narwhal suggests they may have limited ability to respond to 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 ice cover due to increases in prey availability (Moore, 2008; Laidre *et al*., 2008; Higdon and Ferguson, 2009; Matthews *et al*., 2011; Ferguson *et al*., 2012). Expansion of killer whales into the Arctic could cause a trophic cascade with the polar bear-seal predator-prey linkage replaced with killer whales as the top predator (Higdon and Ferguson, 2009) although there is *limited evidence* 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 ice while benthic feeding ice-dependent species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists such as walrus will do poorly with reduced ice Changes in ice dynamics can cause walrus calves to become separated from their mothers during rapid ice retreat and may effect recruitment (Cooper *et al*., 2006). Reduction of summer/autumn ice was identified as the primary extrinsic factor affecting Pacific walrus with predictions of distribution changes and longer-term predictions of high extinction probability (Maccracken, 2012). Retreat of summer ice was suggested to make migration to such habitats energetically unprofitable for ringed seals (Freitas *et al*., 2008). Further, loss of ice in the Baltic Sea was identified as the primary threat to the Baltic ringed seal (Kovacs and Lydersen, 2008). Earlier break-up in the eastern Beaufort Sea had negative impacts on ringed seal pup growth and condition, and possibly on pup survival (Harwood *et al*., 2000). Similarly, in Hudson Bay, earlier spring break-up and changes in snow cover over lairs used for reproduction has reduced ringed seal recruitment in recent years (Ferguson *et al*., 2005). Further, changes in snowfall over the 21st century were projected to reduce the area of ice with sufficient snow for ringed seal lairs by 70% (Hezel *et al*., 2012). Similarly, 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). 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, shipping, and development) (Burek *et al*., 2008).

There is *high confidence*that the effects on Arctic and subarctic marine mammals will vary spatially and temporally, with some populations affected earlier than others and thereby 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 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 for most species.

28.2.2.2. Antarctic

28.2.2.2.1. Vulnerability and change

Evidence is accumulating to conclude that the distributions of Southern Ocean pelagic species (phytoplankton and zooplankton) have moved south with the frontal systems (Hinz, Poulton et al. 2012; Mackey, Atkinson et al. 2012). This is also confirmed by observed range expansion into the Southern Ocean from the north by the coccolithophorid, Emiliania huxleyii (Cubillos, Wright et al. 2007), and the red-tide dinoflagellate Noctiluca scintillans (McLeod, Hallegraeff et al. 2012).

The observed occurrence of lithodid crabs on the continental shelf of the west Antarctic Peninsula (WAP) has been attributed to movement south of warmer waters (Smith, Grange et al. 2012). These crabs will potentially impact the structure and diversity of benthic assemblages because of their ability to crush echinoderms and other taxa along with their bioturbating behaviour. However, direct evidence of the invasion of these crabs or the magnitude of impacts that they may have in the region has yet to be observed. There is no evidence to date of climate change impacts on the distributions of cold-adapted fish, although this remains a valid expectation for many species (Constable et al., submitted).

Physiological responses will vary among polar organisms (Constable et al., submitted) but an important response of many biota will be to ocean acidification (Byrne 2011). Shell thickness in foraminifera in the Southern Ocean are thinner than in the Holocene and there is evidence of a relationship between shell thickness and atmospheric CO2, supporting the hypothesis that ocean acidification will affect this abundant protozoan in the Southern Ocean (Moy, Howard et al. 2009). Recent studies of arogonite-shelled pteropods indicate that they are vulnerable to the effects acidification (Comeau, Alliouane et al. 2012; Comeau, Gattuso et al. 2012) and that shells are thinner from sediment traps in aragonite under-saturated water (below the aragonite saturation horizon - ASH) compared to those captured above the ASH in Subantarctic waters (Roberts, D. et al. 2011). However, the absence of time-series of samples related to change in the depth of the ASH and aragonite saturation generally makes it difficult to conclude how shell composition will be affected by changes to oceanic aragonite saturation (Roberts, D. et al. 2011). There is evidence that shell dissolution has already been observed in surface waters in the Atlantic sector as a result of both upwelling and atmosperhic changes in CO2 (Bednarsek, Tarling et al. 2012). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short term negative impacts need to considered together with an organism’s capacity to adapt in the longer term (Watson, Peck et al. 2012).

Collapse of ice shelves may alter the dynamics of benthic assemblages by opening up areas previously covered by ice shelves and allowing increased primary production as well as colonisation and establishment of new assemblages, such as occurred with the collapse of the Larson A/B ice shelves (Peck, Barnes et al. 2009; Gutt, Barratt et al. 2011). Increased production of icebergs may increase the number of grounded icebergs causing changes in local oceanography and declines in productivity that consequently affects productivity of benthic assemblages (Thrush and Cummings 2011), or they may result in increased scour on shallow banks, disrupting resident benthic assemblages (Barnes and Souster 2011; Gutt, Barratt et al. 2011).

28.2.2.2.2. Productivity and krill

Primary production is expected to be changing regionally in the Antarctic in response to changes in sea ice, glacial melt and oceanography (Arrigo, van Dijken et al. 2008; Boyd, Arrigo et al. 2012). To date, the most compelling results of the effects of change in the physical environment on primary production and microbial assemblages is from the west Antarctic Peninsula region where (Montes-Hugo et al., 2009) reported decreased phytoplankton stocks and productivity (based on time-series of satellite-derived and measured chlorophyll concentrations) north of 63°S i.e., around the Antarctic Peninsula, and increases in these properties to the south of 63°S (see WGII Chapter 6 for discussion). They also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton.

Densities of Antarctic krill have been estimated to have declined by approximately 30% in the Scotia Sea since the 1980s (Atkinson, Siegel et al. 2004), in parallel with declines in the extent and season duration of winter sea ice in the region (see (Flores, Atkinson et al. 2012) for review). 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 observed dependence of Antarctic krill on the annual extent of winter sea ice (Nicol, Worby et al. 2008) indicates strong grounds for concern that the krill population in this key area where 70% of the population is found (Atkinson, Siegel et al. 2009) may have already changed and will be subject to further change.

Analyses of krill population dynamics suggest that changes in recruitment of post-larval krill across the Scotia Sea are linked to variations in surface temperature and sea-ice extent. Recent simulation modelling of krill productivity and dynamics show the plausibility of the positive relationship between sea ice extent and recruitment of krill in the Antarctic Peninsula region (Wiedenmann, Cresswell et al. 2009). However, such a decline may be offset by increased productivity arising from increased water temperature in that area (Wiedenmann, Cresswell et al. 2008). That said, the latter study also showed that krill productivity may decline in the South Georgia area as a result of the increased metabolic costs of increasing temperatures. The combined effects of changing sea ice, temperature and food have not been investigated.

Recently, krill have been discovered to be sensitive to ocean acidification. Experiments have shown that krill larval development (Kawaguchi, Kurihara et al. 2011) and post-larval krill metabolic physiology (Saba, Schofield et al. 2012) may be impeded by elevated CO2 concentrations.

28.2.2.2.3. Food web effects

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 (Trathan, Forcada et al. 2007; Shreeve, Collins et al. 2009; Waluda, Collins 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, Clarke et al. 2012). The trophic efficiency of these longer food webs in the absence of krill is less (Murphy, J. et al. 2013) and the long-term implications of this for higher trophic levels are unknown.

The changes in the physical habitat to the west of the Antarctic Peninsula (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 (Forcada, Trathan et al. 2012) 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 and elephant seals (Costa, Huckstadt et al. 2010; Trivelpiece, Hinke et al. 2011; Ducklow, Clarke et al. 2012; Murphy, Watkins et al. 2012b). The mechanisms driving these changes are currently under review and may be more complex than a simple association with sea ice (Lynch, Naveen et al. 2012; Melbourne-Thomas, Constable et al. 2013). This shift may be accompanied by an overall decline in the productivity of the WAP shelf (Montes-Hugo, Doney et al. 2009), although this may be tempered by increased inputs of iron through changes to ocean processes in the region (Dinniman et al., 2012).

28.2.2.2.4. Marine mammals and birds

The response of marine mammals, penguins and flying birds will be a complex response to a number of direct and indirect effects and may result either increasing or decreasing abundance depending on the regional effects of climate change on their habitats and food. In general, 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 *et al*., 2012; Forcada *et al*., 2012). Adelie and chinstrap penguins have been declining in the north of the Antarctic Peninsula (Lynch *et al*., 2012) while gentoo penguins are increasing in that region. In contrast, Adelie penguins may be increasing in east Antarctica (Constable *et al*., submitted). There is increasing evidence that emperor penguins may be declining throughout the Antarctic (Barbraud *et al*., 2008; Jenouvrier *et al*., 2009; Trathan *et al*., 2011). Declines in seal and seabird populations 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 (Weimerskirch *et al*., 2003; Jenouvrier *et al*., 2005a; Jenouvrier *et al*., 2005b).

Direct effects on penguins include changes in location and conditions of foraging habitats as a result of shifting ocean conditions and sea ice extent near to breeding colonies, as well as increased precipitation in the colonies. Some of these responses may be dependent on local populations or colonies (Lynch *et al*., 2012; Barbraud *et al*., 2012) or may be regional differences. For example, Adelie and emperor penguins are postulated to have dome-shaped relationships between their demographic success and sea ice extent (see (Barbraud *et al*., 2012) for review) rather than a simple monotonic relationship but the nature of such a relationship remains to be determined. A contributing factor to the reduction in Adélie penguins may be increased snow precipitation which accumulates in the breeding colonies and, when accompanied by reduced food supply, can decreases survival of chicks (Chapman *et al*., 2011).

Movement south of the frontal systems, and therefore movement of productive foraging areas, in the Indian sector have been attributed to causing declines in King penguin colonies on subantarctic islands in that sector(Peron *et al*., 2010), while the shift in wind patterns may be causing changes to the demography of albatross(Weimerskirch *et al*., 2012).

As identified in the last assessment, change in some species may be a result of incidental mortality in fisheries or recovery from past over-exploitation, both of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals has been well documented. More recently, there has been confirmation of some Antarctic whale populations recovering, such as humpback whales(Nicol *et al*., 2008; Zerbini *et al*., 2010), suggesting that food is currently not limiting. In contrast, albatross and petrel colonies are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall *et al*., 2012).

28.2.3. Terrestrial Ecosystems

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130 000 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 e.g. (Lorenzen *et al*., 2011; Salonen *et al*., 2011; Mamet and Kershaw, 2012).

28.2.3.1. Phenological Responses

Phenological responses attributable to warming are apparent in Arctic terrestrial ecosystems (*medium confidence*). 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 (Post *et al*., 2009a; Callaghan *et al*., 2011a). Other substantial changes include earlier clutch initiation dates in birds and earlier emergence of arthropods in northeast Greenland (Figure 28-2) (Høye *et al*., 2007).

[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

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 (*very high confidence*). Most of this increase in deciduous shrubs can be attributed to Arctic warming (*very likely*), but in some parts of northwest Eurasia a portion of the graminoid increase seems tied to steadily intensifying reindeer grazing/trampling coupled with large-scale hydrocarbon extraction in recent decades(Forbes and Stammler, 2009; Kumpula *et al*., 2011; Kumpula *et al*., 2012) .

Recent assessments of changes in NDVI (Nomrlaized Difference vegetation Index, a proxy for plant productivity) from satellite observations between 1982 and 2010 show a substantial greening over large parts of the Pan-Arctic (Zhang *et al*., 2008; Bhatt *et al*., 2010; Walker *et al*., 2011; Xu et al. 2013) (Figure 28-3) with the greatest increases in 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 South-western Alaska and easternmost Russia 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 (Macias-Fauria *et al*.,2012 ; Raynolds *et al*., 2008; Bhatt *et al*., 2010; Forbes *et al*., 2010; Xu et al. 2013).

[INSERT FIGURE 28-3 HERE
Figure 28-3: Significant changes ($p < 0:05$) in aboveground tundra phytomass from 1982 to 2010 (Epstein et al. 2012).]

The positive trends (1982-2010) 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(Xu et al. 2013). 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). 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 (Macias-Fauria et al. 2012).

Since IPCC AR4, increasing evidence from 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) (Myers-Smith *et al*., 2011a; Callaghan *et al*., 2011b; Elmendorf *et al*., 2012 aand b) Observations extend back 100 years but most evidence comes from changes that have occurred over approximately the past 20 years.. Shrubs have generally expanded their ranges (Myers-Smith *et al*., 2011a; Callaghan *et al*., 2011b; Elmendorf *et al*., 2012b) and/or growth for example in Alaska (Tape et al. 2001; Sturm et al. 2006), the Yukon region of Canada (Myers-Smith *et al*., 2011a), southeast Yukon (Danby and Hik, 2007), the Canadian high Arctic (Hudson and Henry, 2009; Hill and Henry, 2011), the Swedish sub Arctic (Hallinger *et al*., 2010; Rundqvist *et al*., 2011; Hedenås *et al*., 2011), and the northwestern Russian Arctic(Macias-Fauria *et al*.,2012 ; Forbes *et al*., 2010). 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*., 2012).

Changes in species diversity could not be detected in the long-term study from Ellesmere Island in Canada (Hudson and Henry, 2009; Hill and Henry, 2011). However, other multi-decadal studies (see references in Callaghan and Tweedie, 2011) 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 (Daniëls and De Molenaar, 2011; Callaghan *et al*., 2011a) to 70 year stability of a plant community on Svalbard (Prach *et al*., 2010).

Early experimental studies projected that mosses and lichens would be disadvantaged by climate warming (Cornelissen *et al*., 2001; Van Wijk *et al*., 2004). Lang et al. (2012) showed that Arctic warming on two continents had consistent negative effects on lichen diversity and mixed effects on bryophyte diversity and Tømmervik et al. (2009) documented a significant decrease in lichens in northern Norway in the period 1957-2000 and a slight increase again in the period 2000-2006. 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 recently in Finnmarksvidda (Tømmervik *et al*., 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. 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*., 2012a) 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. (2012a) 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. 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 is *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, 2005; Lloyd, 2005; Shiyatov *et al*., 2007; Kullman and Öberg, 2009) but in some areas, the location of the tree line has not changed or has changed very slowly (Masek, 2001; Holtmeier *et al*., 2003; Payette, 2007; MacDonald *et al*., 2008). 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 the tree line has even retreated (Vlassova, 2002; Dalen and Hofgaard, 2005; Kullman, 2005; Cherosov *et al*., 2010).

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), the tree line has shown increase, decrease and stability in neighboring locations (Van Bogaert *et al*., 2011; Lloyd *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 (Shiyatov *et al*., 2007; Kullman and Öberg, 2009) 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 (Tømmervik *et al*., 2009; Rundqvist *et al*., 2011; Hedenås *et al*., 2011) 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 (Macdonald *et al*., 2008; 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 (Van Bogaert *et al*., 2010; Rundqvist *et al*., 2011). However, model projections of displacement of deciduous forest by evergreen forest (Wolf *et al*., 2008; Wramneby *et al*., 2010) have not so far been validated.

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 (Olofsson *et al*., 2009; Hofgaard *et al*., 2010; 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 (Post *et al*., 2008; Kitti *et al*., 2009; Olofsson *et al*., 2009). 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 (Macias-Fauria *et al*.,2012 ; Forbes *et al*., 2010).

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 (Goetz *et al*., 2005; Verbyla, 2008) and making them more susceptible to insect pest outbreaks (see references in (Callaghan *et al*., 2011c)). Death of trees through drought stress or insect pest activity will increase the probability of fire that will have positive feedbacks on the climate from reduced carbon dioxide uptake, increased carbon dioxide loss from soils and decreased albedo as in tundra fires (Mack et al., 2011). There is evidence that recent warming in combination with snow anomalies has caused increased drought stress and insect damage to northern forests (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 (Rydgren *et al*., 2007; Ims *et al*., 2007; Berg *et al*., 2008; Gilg *et al*., 2009; Krebs, 2011; Olofsson *et al*., 2012; Kausrud et al. 2009;).

The documented collapse or dampening of population cycles of voles and lemmings over the last 20-30 years in parts of Fennoscandia and Greenland (Scmidt et al. 2012), can be attributed with *high confidence* to climate change (Ims *et al*., 2007; Gilg *et al*., 2009; Ims *et al*., 2011; Kausrud et al. 2009). 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 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. 2009).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).

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 (Robertson *et al*., 2009; ACIA 2005) and for geometrid moths in Fennoscandia (Jepsen *et al*., 2008; Callaghan *et al*., 2010; 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 CO_2 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 wild reindeer and caribou (both *Rangifer tarandus*) populations in certain regions of about 30 percent over the last 10-15 years have been linked both to climate warming and anthropogenic landscape changes (Post et al. 2009; Vors and Boyce 2009; Russell and Gunn 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large herds have for example declined by 75-90 percent, while other wild herds there and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Gunn et al. 2009; Vors and Boyce 2009; Joly et al. 2011; Forbes et al. 2009; Forbes 2010; Kumpula et al. 2012).
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; Post *et al*., 2009b). It is suggested that similar warming-induced trophic mismatches have a role in the decline of circumpolar reindeer and caribou populations (Post et al. 2009a). This trophical mismatch has, however, been disputed as well as their extension of their study in Greenland to circumpolar populations (Griffith *et al*., 2010).

The increased primary productivity of Arctic tundra (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 during warming (Turunen *et al*., 2009; Heggberget et al. 2010). As mentioned above, there are indications that lichen biomass, and important winter fodder for reindeer, is decreasing over much of the Arctic region. Arctic lichens have been shown experimentally to be vulnerable to icing events (Bjerke *et al*., 2011). Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes on the ungulate populations (van Der Wal *et al*., 2007; Turunen *et al*., 2009).

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; Miller and Barry, 2009; Stien *et al*., 2010; Hansen *et al*., 2011; Stien et al. 2012). 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), and ice on the grazing areas was not the main reason in 31 declines of 12 different reindeer and caribou populations (Tyler, 2010). 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). 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 (Bartsch et al.

2010). Despite this, the indigenous Nenets inhabiting the area, stressed hydrocarbon development as the main long-term threat to their existence (Forbes and Stammler 2009; Forbes et al. 2009; Kumpula et al. 2012).

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. Antarctic Terrestrial Systems

Climate change will impact Antarctic terrestrial habitats in all three biogeographic regions through changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost and exposure of new habitat through glacial/ice retreat. There are no documented trends in changing surface areas of different habitats or in the exposure of new habitat, a major gap in this assessment.

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 (Parnikoza *et al.*, 2009; Convey *et al.*, 2011), which remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon techniques are now also demonstrating long-term biological effects of Antarctic climate change on moss beds (Clarke *et al.*, 2012). One important aspect underlying these changes is thought to be that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing both the dominant mode of reproduction, and increasing the potential distance for dispersal. Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonisation of ice free ground made available through glacial retreat and reduction in extent or previously permanent snow cover (Olech and Chwedorzewska, 2011). 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. Such hypotheses remain to be confirmed through the establishment of robust baseline survey and monitoring studies (Convey, 2006; Convey, 2010), which are now an urgent priority (Wall *et al.*, 2011). A critical part of such studies will be to link well-described large-scale climatic trends with that of microclimates experienced by terrestrial biota at much smaller and relevant physical scales (Turner *et al.*, 2009).

28.2.4. Human Populations

Although humans have been present in the Arctic for thousands of years, Antarctica has no permanent human settlements; instead, only temporary residents who are either visiting scientists or staff at research facilities. Therefore, this Human Populations Section assesses the risks and impacts of Arctic warming on the diverse human communities across the Arctic where people have been addressing change for centuries. While it is recognized that several large industrial Arctic cities in Russia and elsewhere have serious climate change-related challenges, this section focuses on indigenous, isolated, and rural populations because they are especially vulnerable to climate change due to their dependence on the environment for food, culture, transportation, security, and ultimate survival;

their political and economic marginalization; and existing social, health, poverty, and other disparities. (Larsen *et al.*, 2010; [AR5 12.3]) In addition, a large amount of literature documenting the impacts of climate change on the health and well-being of Arctic indigenous residents has been published since the last report.

The warming Arctic and the significant changes in the cryosphere are impacting residents across the region through a complex set of physical, environmental, 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. (Larsen and Fondahl, 2010) It is estimated that there are between 4 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, scientists, military, and tourists. (Hovelsrud *et al.*, 2011) Approximately two-thirds of Arctic people live in relatively large settlements of over 5,000 residents, the other one-third is scattered in small and often very remote, isolated communities. (Bogoyavlensky and Siggner, 2004; Larsen and Fondahl, 2010) 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 mineral resources or the necessity to escape problems in homelands outside the Arctic, including some population declines from 2000 to 2005, especially in Russia. (Hovelsrud et al, 2011)

Climate change and globalization, environmental 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, 2011) 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 (Galloway McLean, 2010) The percent of the populations of indigenous peoples in the Arctic range from 3-4 % in Russia to 80% in Greenland. (Galloway McLean, 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.

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) 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 and other 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. (Ford *et al.*, 2010) 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.

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (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). (IPCC Special Report: Managing Risk of Extreme Events, 2012; AMAP, 2009) 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. (Kokelj *et al*., 2009; Ford *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, loss of access to critical supplies and services to rural or isolated communities (e.g., food, fuel, telecommunications), and risk of being trapped outside one's own community. (Laidre *et al*., 2008; Brubaker *et al*., 2011b). Changing river and sea ice conditions affect the safety of travel for indigenous populations especially, and inhibit access to critical hunting, herding and fishing areas. (Andrachuk and Pearce, 2010; Derksen *et al*., 2012) 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. 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*., 2010). 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).

28.2.4.2. Indirect Impacts of Climate Change 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). (Maynard and Conway, 2007; Brubaker *et al*., 2011a; Parkinson and Evengard, 2009). Local and traditional knowledge in communities across the Arctic are observing extremes not previously experienced and increasingly unusual environmental conditions (e.g., (Laidler *et al*., 2009; Ignatowski and Rosales, 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 and Pearce, 2010) These climate-driven disruptions in the physical environment are increasingly being shown to cause a variety of serious mental and psychological conditions in many Arctic communities, particularly in vulnerable, already disadvantaged populations. (AR5 Chapter 11; Portier et al, 2010; USARC, 2010)

Underlying all climate change impacts and processes, are the complicated impacts 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) 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. (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. (UNEP/AMAP, 2011) These contaminants such as POPs are known for their adverse neurological and medical 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. (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 *et al*., 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden *et al*., 2010; Tokarevich *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 expected that temperature increases will increase the incidence of zoonotic diseases that can be transmitted to humans. (Revich *et al*., 2012) 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;)

Harmful algal blooms (HABs), are increasing globally and are known to be influenced directly by climate change related factors such as temperature, winds, currents, nutrients and runoff. (Portier *et al*., 2010) These HABs contain biotoxins with significant neurotoxic effects and can be a serious health hazard to humans or animals (paralysis, death) when the toxin is ingested through seafood, direct contact, or sea spray aerosols. (Portier *et al*., 2010; Epstein and Ferber, 2011). 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 and basic nutrition 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 (Ford and Berrang-Ford, 2009; Ford, 2009). However, climate change is already posing an important 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. (Ford *et al*., 2010) 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) 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. (Gearheard *et al*., 2006; West and Hovelsrud, 2010)

Furthermore, traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus reducing food available to the community. (Brubaker *et al*., 2011b) For example, food contamination problems are becoming important wherever thawing of permafrost "ice cellars" is occurring for communities and families and increasingly wet conditions make it harder to dry food for storage. (Hovelsrud *et al*., 2011) These reductions in the availability of traditional foods plus general globalization pressures 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; Brubaker *et al*., 2011b) A complicating factor in evaluating trade-offs between traditional and market food is that wild foods – especially those at the top of the food chain - represent the most significant source of exposure to environmental contaminants. (AMAP, 2011)

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious 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, damage to landfill sites, or sewage contamination. (GAO, 2009) Salt-water intrusion and bacterial contamination may also be threatening community water supplies. (Parkinson *et al*., 2008; Virginia and Yalowitz, 2012) Quantities of water available for drinking, basic hygiene, and cooking are becoming limited due to damaged infrastructure, drought, and changes in hydrology. (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, can result in higher rates of hospitalization for pneumonia, influenza, and respiratory viral infections. (Parkinson and Evengard, 2009) 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.(Parkinson *et al*., 2008; Virginia and Yalowitz, 2012)

Finally, it is now well-documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among the residents. (Portier *et al*., 2010; Coyle and Susteren, 2012; AR5 Chapter 11; Levintova, 2010) The changes in the physical environment which threaten certain communities (e.g., through thawing permafrost and erosion) and which may lead to forced or voluntary relocation of residents or changes or declines in resources resulting in reduced access to subsistence species are often a pathway to rapid and long-term cultural change including loss of traditions. (Galloway-MacLean, K., 2010) These types of losses are, in turn, causing mental health impacts among indigenous and other vulnerable, isolated populations. (Curtis *et al*., 2005; Albrecht *et al*., 2007; Coyle and Susteren, 2012) Psychological impacts are especially acute for individuals and communities who feel intimately connected with the environment and those experiencing cumulative effects from repeated impacts such as natural disasters and extreme weather. (Portier *et al*., 2010; AR5) A specific psychological condition called “solastalgia”- a strong feeling of loss and dislocation when people feel that changes to their environment are harmful - is becoming more common globally. (Albrecht *et al*., 2007; Portier *et al*., 2010) Special concern has been expressed by many communities concerning the unusually high and increasing numbers of suicides in the Arctic especially among indigenous youth, and efforts are under way to try to develop a thorough assessment as well as establish effective intervention efforts. (Albrecht *et al*., 2007; Portier *et al*., 2010; USARC, 2010)

28.2.5. Economic Sectors

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 (Larsen, 2010; Forbes, 2011; Hovelsrud *et al*., 2011).

The Arctic economy consists of a combination of formal and informal sectors. 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 and non-indigenous peoples 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 (Nuttall *et al*., 2005; Poppel and Kruse, 2009; Larsen and Huskey, 2010; Crate *et al*., 2010; Poppel 2006; Aslaksen et al 2009). Significant impacts on the ability of key subsistence marine and terrestrial species are being observed and are expected to continue 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 some herders, whalers and walrus hunters non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Ignatowski and Rosales, 2012; Forbes et al. 2009; www.Aksik.org).

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.

28.2.5.1. Arctic

28.2.5.1.1. Agriculture and forestry

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, for example, are now found at higher latitudes than before, and the productivity of many plants has increased (Björnsson et al, 2011). 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). 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 in the Arctic are likely to expand because of a warmer climate, but are likely to remain of minor importance to the Arctic economy (Eskeland and Flottorp 2006). In areas with a reduction in snow cover, the growing season may be extended (Grønlund, 2009; Falloon and Betts, 2009; Tholstrup and Rasmussen 2009).

Climate change is very likely to have costs and benefits for agriculture and forestry (*high confidence*).

28.2.5.1.2. Open water fisheries

The impacts of climate change will occur within the context of other anthropogenic activities including commercial fishing. Fish stocks have been exploited for 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 28-4).

[INSERT FIGURE 28-4 HERE
Figure 28-4: 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 *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 (Worm *et al.*, 2009; Hutchings *et al.*, 2010; Gutierrez *et al.*, 2011). Sustainable fishing practices are expected to continue in the future and may improve as managers strive to implement an ecosystem approach to management and overfished stocks are expected to rebuild (*medium confidence*). Successful spatial management of shared resources under shifting ocean conditions will require an understanding of the mechanisms underlying observed range shifts (Hannesson, 2013).

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).

28.2.5.1.3. 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*). Commercial transactions from fishing are typically for local markets (Reist *et al*., 2006). The survival of Arctic coastal fishes depends on a complex suite of environmental conditions (Reist *et al*., 2006). Recent studies show that factors that influence the marine exit are critical for survival of salmon and cisco (Moulton et al. 2010; Mundy, 2011). Climate change related factors that influence the water level and freshening of rivers will influence run size of these species (Fechhelm et al 2007).

28.2.5.1.4. Marine transportation in the Arctic Ocean

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 (Paxian *et al*., 2010; Corbett *et al*., 2010; Khon *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 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 throughout the NSR area in the Arctic (Østreng 2006), 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)). In the case of Svalbard, oil spills on have increased due to the growth in activities related to tourism and research. Dangers of a cruise ship or cargo ship running a ground and with subsequent oil spillage is the biggest environmental risk connected to marine transportation at Svalbard (NorAcia 2010). 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 lead to rapid growth in emissions from oil and gas transport by ship.

Increased economic opportunities along with challenges associated with culture, security and environment, are expected in Northern Canada with increased navigability of Arctic marine waters together with expansion of land- and fresh water-based transportation networks (Furgal C., 2008). Based on a study using four water level scenarios, a base case with only seasonal and annual variation in water levels and three climate change scenarios, results suggest that Great Lakes rivers will be impacted by climate change affecting both shipping and nonindigenous species due to expected lower water levels, shorter times of ice cover, and higher surface water temperatures (Millerd, 2007). 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). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett 2012, Levitsky 2011), leading to additional economic activity. (Lack, D. A.; Corbett, J. J., 2012).

28.2.5.1.5. 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 (Huntington *et al*., 2007; Sundby and Nakken, 2008; West and Hovelsrud, 2010; Forbes, 2011) Martin et al. 2009; Sherman et al., 2009). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design lifetime of the structure than with thawing 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 (Anisimov and Vaughan, 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford *et al*., 2010; Forbes, 2011; Berkes et al 2003).

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); Smith and Risebrough 2010).

28.2.5.1.6. 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, and 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 *et al*., 2009; Berkman and Royal United Services Institute for Defence and Security Studies., 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; Huntington *et al*., 2007; Forbes, 2008; 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).

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, may 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 of short-lived pollutants, ozone pre-cursors, and long-lived greenhouse gases (Peters et al., 2011)

28.2.5.1.7. Informal, subsistence-based economy

Inuit and Saami have expressed strong concern about how a rapidly warming climate will affect their livelihoods (Forbes and Stammler, 2009). For Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn, earlier melt-out and faster sea ice retreat 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, and greater risk for the long-term viability of polar bear populations (Laidre *et al*., 2008). Most 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 is 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 (Magga *et al*., 2011; Eira *et al*., 2012). 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 (Maynard *et al*., 2011; Eira *et al*., 2012; Bongo *et al*., 2012). 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 (Klein *et al*., 2005; Abryutina, 2009; Vuojala-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 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 (Kitti *et al*., 2006; Bongo *et al*., 2012).

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. (Forbes and Stammler, 2009; Magga *et al*., 2011) 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; Bongo *et al*., 2012; Forbes et al, 2009; Kumpula et al. 2012).

28.2.5.2. Antarctica and the Southern Ocean

The primary economic activities that currently take place in Antarctica are 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 tourism and the vulnerabilities of the ecosystems to these activities are likely to be affected by climate change (Kawaguchi *et al*., 2009; Constable, 2011; Chown *et al*., 2012).

28.2.5.2.1. Fisheries

Fisheries in Antarctica were reported in AR4. Further analyses since then have shown that the current fishery in the southwest Atlantic, if it were to take the Total Allowable Catch of 5.6 million tonnes, could amount to approximately 6% of existing marine capture fisheries; current catches have been between 100-200,000 tonnes but are now increasing (Nicol *et al*., 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. Catch levels are expected to be larger than at present but this will depend more on economic rather than environmental constraints in the short to medium term.

CCAMLR aims to develop an ecosystem-based feedback management procedure for krill fisheries based on indicators of the status of krill and its predators (Constable 2011). This work has not yet factored in measures to account for climate change impacts on the ecosystem, including whether the ecosystem effects of climate change can be differentiated from the effects of fishing (Trathan and Agnew, 2010; Constable, 2011).

28.2.5.2.2. Tourism

Ship-based tourism is a significant industry in Antarctica. The large majority of tourists visit Antarctica aboard ships, and the industry does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists visiting Antarctica has risen, with tourist numbers landing on shore having increased from 7322 in 1996/1997 to 32,637 in 2007/2008 , with one of the busiest sites being at Goudier Island to the west of the Antarctic Peninsula experiencing at least half of the visits (IAATO 2012). Tourists visit Antarctica in order to view scenery, wildlife, and historic sites, 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 wildlife either on foot or by cruising in small boats. Risks exist of accidental pollution from maritime accidents (a number of groundings and one foundering are recorded), although no significant pollution incidents have occurred in recent decades. Tourism activity is expected to continue to increase, and as more ice-free areas become available as a result of climate change, there is an increasing likelihood of the introductions of alien species to terrestrial environments from tourism and other vectors (Chown, Lee et al. 2012). A combination of mandatory and voluntary management measures are in place under the Antarctic Treaty's Protocol on Environmental Protection (the Protocol) and measures of the Antarctic Treaty Consultative Meeting, aimed at minimizing the impact of such activities. Discharge from vessels is regulated under the Protocol and instruments of the International Maritime Organization.

28.2.6. 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 continental landmass, surrounded by ocean, that has remained unpopulated except for isolated research stations.

The Antarctic is governed by a number of conventions, collectively called the Antarctic Treaty system. The number of States parties to the Treaty has grown from the original 12 nations that were involved in the Antarctic during the International Geophysical Year of 1957-58, to 50 parties today. 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" and "freedom of scientific investigation in Antarctica." The Treaty effectively holds in abeyance all claims to territorial sovereignty in Antarctica. It is generally seen as one of the "success stories" of contemporary international law (Rothwell, 2012). The Protocol on Environmental Protection to the Antarctic Treaty was signed in 1991 and entered into force in 1998. Its objective is the comprehensive protection of the Antarctic environment and dependent and associated ecosystems. The Protocol designates Antarctic Treaty area as a "natural reserve devoted to peace and science", prohibits any activity relating to mineral resources other than scientific research, requires the prior environmental impact assessment of proposed activities, and establishes a range of other environmental standards and requirements. The other active component of the Antarctic Treaty System is the Convention for the Conservation of Antarctic Marine Living Resources, which applies to all marine areas south of the Antarctic Convergence overlapping in jurisdiction with the Antarctic Treaty. Both of these conventions provide mechanisms for managing the effects of climate change in their areas of jurisdiction.

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 peoples' organizations on common 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 the International Council of Science (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 priority subject for the international organisations established under the Antarctic Treaty system and the Arctic Council (Rayfuse, 2007; Byers, 2010). In 2010 the Antarctic Treaty parties convened an Antarctic Treaty Meeting of Experts (ATME) on Climate Change Implications for Antarctic Management and Governance, which examined the ACCE report (Turner *et al*., 2009) and identified 30 recommendations for consideration by the Antarctic Treaty Consultative Meeting (ATCM). The majority of the recommendations related to actions that could be taken by the Parties in Antarctica and within the scope of the Antarctic Treaty system, but several recognised the importance of conveying information about Antarctic climate change to international bodies discussing and climate change. Accordingly, the Parties have begun to contemplate the scope of their role in addressing the implications of climate change for management of the Antarctic Treaty area, possibly including opportunities for enhanced engagement with international organisations discussing climate change action.

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 this is not expected, 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.

28.2.6.1. Indigenous Peoples, Climate Change, and Traditional Knowledge

Arctic indigenous peoples – the original Native inhabitants of the region – are estimated to number between 400,000 and 1.3 million. (Bogoyavlensky and Siggner, 2004; Galloway McLean, 2010). The percentages of the populations of indigenous peoples in the Arctic range from 3-4 % in Russia to 80% in Greenland. (Galloway McLean, 2010) 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; however, the ability of indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change. (Nakashima *et al*., 2011) The risks are spatially and temporally heterogeneous and encompass potential synergies with other, non-climatic drivers, such as general globalization and resource development (e.g., oil and gas extraction, mining) (Vuojala-Magga *et al*., 2011), and the prevalence in many indigenous communities of poverty, marginalization, and resulting health disparities. (Abryutina, 2009).

Indigenous and local communities as well as scientists are therefore forced to 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. (Sydneysmith *et al*., 2010; Kumpula *et al*., 2011). 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 (Mahoney *et al*., 2009; Forbes and Stammler, 2009; Bartsch *et al*., 2010; Weatherhead *et al*., 2010; Brubaker *et al*., 2011b; Bongo *et al*., 2012; Eira *et al*., 2012; McNeeley, 2012; Huntington and Watson, 2012)Bronen, 2011)

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;Vuojala-Magga *et al*., 2011) 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) 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)

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.(Vuojala-Magga *et al*., 2011) 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; Reinert *et al*., 2009; Nakashima *et al*., 2011) 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 reindeer herders' knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter and spring reindeer rangelands (Roturier and Roué, 2009; Riseth *et al*., 2011; Eira *et al*., 2012). While indigenous knowledge is important for climate assessments (Huntington *et al*., 2004; Salick and Ross, 2009; Green and Raygorodetsky, 2010) Ford et al., 2011), not all indigenous community members share the same expert and indigenous knowledge; hence, they face the need to conceptualize their adaptation strategies within their own social, political, and cultural contexts (Ford *et al*., 2011).

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). 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). In both North America and northernmost Europe, the results to date are mixed and there is ample room for improvement (Berkes and Dyanna, 2001; Kofinas, 2005; Ulvevadet, 2008; Meek *et al*., 2008; Berkes, 2009; Dowsley 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 (Sydneysmith *et al*., 2010; Riseth *et al*., 2011; Kumpula *et al*., 2012). 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. (Maynard and Conway, 2008; Eira *et al*., 2012). 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) and NASA's AMSR-e sensor (Bongo *et al*., 2012).

In the Canadian Arctic, there is 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. (Ford et. al., 2009; Aporta *et al*., 2011).

While Arctic indigenous peoples are facing unprecedented impacts to their life ways from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they have already implemented some creative ways of adapting (Cruikshank, 2001; Forbes, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Cullen-Unsworth *et al*., 2011; Alexander *et al*., 2011; Bongo *et al*., 2012)). For example, 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 (Forbes, 2006; Maynard *et al*., 2010; Gearheard *et al*., 2011). 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 communications and education (Galloway McLean, 2010; Bongo *et al*., 2012). 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, whereas, flexible institutions responsive to indigenous and local knowledge in real time can enhance resilience (Meek *et al*., 2008; Sydneysmith *et al*., 2010; Kumpula *et al*., 2012)

28.2.6.2. Reindeer, Climate Change, Development, and Adaptation

Reindeer husbandry has had a long important history in the Arctic, especially for the many indigenous people in Norway, Sweden, Finland, Russia, Mongolia, China, US, Canada, and Greenland. (Magga et al, 2011) Reindeer husbandry as a livelihood now involves about 100,000 herders and approximately 2.5 million semi-domesticated reindeer. (Oskal, 2008) Interactions between reindeer (*Rangifer tarandus* L.) and humans date from the late Pleistocene onward and wild and semi-domestic animals continue to be essential to indigenous peoples throughout the Arctic for a diversity of purposes. (Oskal, 2008; Forbes and Kumpula, 2009) 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 (Vuojala-Magga *et al*., 2011;Forbes, 2006). 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, economic base, way of life, clothing, mythologies, and worldviews, but is facing increasing challenges from unprecedented changes in their climate and weather as well as accelerating changes in land use, (Stammler, 2005; Forbes, 2006; Oskal, 2008; Paine, 2009; Vuojala-Magga *et al*., 2011),

Such changes in the climate are 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 (Bulygina *et*. *al*., 2009; Bulygina *et*. *al*., 2010; Callaghan *et al*., 2011b) –

very critical environmental variables for reindeer sustainability (Eira *et al*., 2012). Reindeer must forage continually and any significant impediment to their ability to access forage under the snow cover each day during winter can threaten their survival (Vuojala-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) 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 (Vuojala-Magga *et al*., 2011). Warmer Arctic temperatures have increased insect harassment causing major interference with foraging (Kitti *et al*., 2006). Other climate change impacts are also occurring, which have similarly important implications for reindeer pasture availability and migration routes. (Maynard et al, 2010) 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 (Kitti *et al*., 2006; Forbes and Stammler, 2009; Bongo *et al*., 2012).

Over the millennia, wild and semi-domestic reindeer populations 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). However, in recent years, these successful adaptation strategies which have guided their survival have been challenged by unprecedented rates of climate change and 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. (Forbes, 2006; Bongo *et al*., 2012). 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 (Forbes and Stammler, 2009; Kumpula *et al*., 2012). 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; Kumpula *et al*., 2011; Kumpula *et al*., 2012; 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 (Vuojala-Magga *et al*., 2011).

Of particular concern today, it is estimated that the Arctic may contain approximately 25 % of the world's remaining undeveloped petroleum resources and climate warming is accelerating access to northern lands for development. (Forbes, 2009). For example, Yamal in Western Siberia has approximately 90 % of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klokov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). 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 (Forbes et al. 2009; Nuttal et al, 2005). 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. (Derome and Lukina, 2010). Together with the symptoms of ongoing climate warming cited above, the combination of these factors presents 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 to adapt to future changes (Forbes *et al*., 2009; Kumpula *et al*., 2011; Vuojala-Magga *et al*., 2011; Kumpula *et al*., 2012).

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 Chapter 3) is a shift to earlier timing of spring runoff (Dankers and Middelkoop, 2008; Pohl *et al*., 2009; Hay and McCabe, 2010) 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.

Projected increases in permafrost thaw (see WGI Chapter 4) will also continue to affect the dynamics of thermokarst lakes (e.g., appearance of new lakes and drainage of some existing ones) and related ecological effects as outlined in Section 28.2.1.1. Similarly, the loss of glacier ice masses will alter spatial and temporal dynamics in runoff accompanied by changes to sediment loads, water chemistry and thermal regimes, and related channel stability, habitat and biodiversity (Milner *et al*., 2009; Moore *et al*., 2009).

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)

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 (Prowse et al., 2010). Such a conclusion is based on GCM-ensemble projections of air temperatures (SRES A2 scenario; 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 modelling 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 (SRES A2 scenario; 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 (Dibike *et al*., 2011). 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 can affect a number of aquatic processes (Prowse and Brown, 2010a). 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 can also 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 (Metje and Frenzel, 2007; Laurion *et al*., 2010). 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 (Walter *et al*., 2007; Walter *et al*., 2008; Laurion *et al*., 2010).

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 (IPCC, 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 as compared to rates for the approximately last half-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 tends not 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 can 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) (Outridge *et al*., 2007; Carrie *et al*., 2010;AMAP, 2011).

28.3.1.2. Antarctic

Previous assessments have been reinforced in this assessment. The most vulnerable region for change in Antarctic freshwater systems are the northern Antarctic Peninsula and maritime Antarctic islands in the southern Scotia Arc, which 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 (Smith *et al*., 2006; Hodgson, 2011), 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.*, 2006). 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.*, 2005). 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).

Under a warming climate an increase in catchment microbial biomass is likely because of the increased water supply from glacial melt 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, Laybourn-Parry et al. 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.

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 (Hodgson *et al.*, 2006b) and on subantarctic islands (Smith Jr *et al.*, 2012). 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, 2007b).

Studies have also shown that once cold freshwater habitats in Antarctica can be colonised by biota from northern refuges in maritime and sub-Antarctic areas (Barnes *et al.*, 2006). There is *medium confidence* that future elevated temperatures will allow the sub- and maritime Antarctic taxa to re-invade and establish self-maintaining populations on the Antarctic continent (Hodgson *et al.*, 2006b).

For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman *et al.*, 2010) whichhave evolved on the continent over multiple glacial interglacial cycles (Vyverman *et al.*, 2007; Vyverman *et al.*, 2010; Fernandez-Carazo *et al.*, 2011) 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.

As in previous assessments, expanding fur seal populations in some breeding areas will increase nutrient enrichment of the freshwater habitats. As well, alien species may be more easily introduced into these environments through human activities and poses a greater threat than colonisation across the natural barriers of the Southern Ocean. increase, even though no reports of alien freshwater species have been reported to date (Frenot *et al.*, 2005).

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Arctic

Arctic marine ecosystems are complex and thus predicting their future under climate change is challenging. In the Bering Sea and Barents Seas, there is *high confidence* based on a long history of observed responses of species to interannual and decadal variability in climate that climate change will impact marine ecosystems. While there is abundant evidence that climate induced shifts in ocean conditions impact marine ecosystems, predictions of the magnitude and spatial extent of ecosystem change are uncertain. Regions at lower latitudes have a rich basis of scientific literature and long time series from which to 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.

In the Arctic Ocean, a coupled bio-physical model was used to simulate changes in lower trophic levels under changing climate conditions for the period 1988 – 2007 (Zhang *et al*., 2010). This model projected increased marine primary productivity consistent with satellite observations.

There is *medium confidence* that in the deep basins of the Arctic Ocean changes in stratification and the number of ice free days will lead to a greater drawdown of nutrients and higher pelagic primary production. It is unclear whether the large-bodied copepods (*Calanus* spp.) may have the capacity to graze this down phytoplankton levels in summer (Olli *et al*., 2007).

28.3.2.1.1. Projected impacts on phenology (timing of spawning, timing of settlement, duration of growing season, age at maturity)

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 (Ormseth, 2007; Sundby and Nakken, 2008;Vikebo et al., 2007). Efforts to project how these physiological and behavioral responses will impact marine ecosystems are the focus of a large interdisciplinary ecosystem modeling effort in the Bering Sea (Wiese *et al*., 2012).

28.3.2.1.2. Projected spatial shifts in response to climate

In the northern Bering Sea, reduced sea-ice and warmer temperatures in the late 1990s and early 2000s led to a northward movement of benthic feeders (e.g. walrus, grey whales). This is thought to have been related to a reduced flux of particulate organic material to the benthos, because of increased pelagic grazing (Grebmeier *et al*., 2006). Further climate warming may lead to an extension of these conditions farther north (e.g. into the Chukchi Sea). If this occurred this would provide higher levels of prey for pelagic planktivores and baleen whales, but could have a negative impact on the benthic planktivores. In addition, some planktonic predators may suffer if the large lipid-rich Arctic Calanus species (*C. glacialis, C. hyperboreus*) are displaced by the smaller boreal forms (*C. finmarchicus, C. marshallae*) (Karnovsky *et al*., 2010).

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). Qualitative data synthesis and modeling shows that the response of fish stocks to changes in bio-climatic envelopes may be more complicated.

There is *medium confidence* that the waters off the coasts of Europe will provide the 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. In the Barents Sea, Huse and Ellingsen (2008) used a spatially explicit coupled bio-physical model forced with future climate scenarios to project the implications of climate change on the spawning distribution of capelin in the Barents Sea. Projections show that the spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey.

In the Bering Sea, there is *medium confidence* based on observations that planktivorous species like walleye pollock in the eastern Bering Sea will shift their distribution in response to shifts in ocean temperature (Kotwicki *et al*. In Press). However, in the northern Bering Sea the persistence of cold winter conditions in the Arctic coupled with the life history factors will restrict or retard the movement of several sub-arctic fish and shellfish species into the Arctic (Sigler *et al*., 2011; Stabeno *et al*., 2012; Hunt Jr. *et al*., 2013; Hollowed *et al*., In Press). There is *medium confidence* based on qualitative data synthesis that 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.

28.3.2.1.3. Projected impacts on fish and shellfish production in response to climate

In the Bering Sea there is *medium confidence* based on observations, that increased summer sea surface temperatures will cause a decrease in 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) incorporated this relationship between ocean zooplankton into a single species stock projection model to assess the implications of future climate scenarios on the future production of Bering Sea walleye pollock. Results showed that walleye pollock stocks were projected to decline by 2050 due to reduced survival in the first year of life although there is considerable uncertainty in the projections. Efforts to extend these models for use in projecting annual production in the Arctic are under development.

28.3.2.1.4. Cumulative effects

The cumulative effects of climate change on the phenology, spatial distribution and production of fish and shellfish are uncertain and the projected outcomes will differ 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.

28.3.2.2. Antarctica and the Southern Ocean

Continued increasing temperatures in the Southern Ocean are likely to result in increased metabolic costs in many pelagic species and movement south of the northern distribution of polar species and southern distribution of temperature and subantarctic species. 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 subantarctic breeding sites (Péron *et al*., 2012; Weimerskirch *et al*., 2012).

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). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections are highly uncertain (Murphy *et al*., 2012b). Recruitment success of krill may also decline in the long term as a result of impacts of ocean acidification on larval development (Kawaguchi *et al*., 2011). Overall, regional variation of factors that could impact directly on krill both positively and negatively will likely result in region-specific responses and depend on 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 and might provide avenues to escape further warming (Schmidt *et al*., 2011) but may make them less accessible to predators (Constable *et al*., submitted). These factors could lead to the marine food webs around the

South Atlantic islands with their current krill-based systems becoming more like the fish-based ecosystems of the Indian Ocean sector (Trathan *et al*., 2012; Murphy *et al*., 2012a; Murphy *et al*., 2012b).

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.

Coastal environments will be impacted by the dynamics of fast ice, ice shelf and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck *et al*., 2009) but negatively affect benthic communities (Barnes and Souster, 2011). Projections of the response of Emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature indicates that general declines in these populations are to be expected if sea ice habitats decline in the future (Barbraud *et al*., 2011; Jenouvrier *et al*., 2012) but these responses are also expected to be regionally specific because of the regionally different expectations of change in the ice habitats.

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 (Wramneby *et al*., 2010; Wolf 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. Antarctica

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 (Chown, Lee et al. 2012). However, human-assisted transfers of biota overcome several of the barriers facing natural colonists, including the speed of transfer and avoidance of extreme environments such as altitude or oceans (Barnes *et al*., 2006). Analyses for two remote Southern Ocean islands (Gough Island, Marion Island) have shown that human-assisted introductions may be more important by two orders of magnitude than natural introductions (Frenot, Chown et al. 2005). A broader regional analyses has shown that introduced species can alter native biodiversity through both homogenization and differentiation (Shaw *et al*., 2010).

Anthropogenic introductions of alien species are a major threat to Antarctic terrestrial ecosystems (Convey *et al*., 2009; Hughes and Convey, 2010; Convey, 2011). Climate change is expected to increase the potential for anthropogenic introduction of non-indigenous species to the Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity (Hughes and Convey, 2010; Braun *et al*., 2012). It is also expected to exacerbate the impacts on terrestrial habitats of increasing colonies of recovering whales and seabirds (Convey and Lebouvier 2009; Favero-Longo, Cannone et al. 2011). At present, the majority of non-indigenous species established in the sub- and maritime Antarctic are very restricted in their distributions (Frenot, Chown et al. 2005); however, several are invasive and widely distributed across the region. Climate change could result in increased rate of spread of invasive species through colonisation of areas exposed by glacial retreat, as has occurred at South Georgia (Cook *et al*., 2010) and in the maritime Antarctic (Olech and Chwedorzewska 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey *et al*., 2011). An important gap in understanding is the degree to which climate change (particularly relating to warming and water availability) may facilitate some established non-indigenous species switching to invasive status, (Frenot, Chown et al. 2005; Convey 2010; Hughes and Convey 2010; Cowan, Chown et al. 2011), which has been shown for the sub-Antarctic (Chown *et al*., 2012).

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 (Turner *et al*., 2009; Convey and Lebouvier, 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of the economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both economic benefits and costs (Forbes, 2011; 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).

Arctic 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. 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 (NorAcia 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 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). Thawing tundra can cause oil pipelines to buckle and break, causing spills (Epstein et al. 2008).Whether or not there will be these impacts, will depend on the design which may allow for these differential movements (Grosse et al.. 2010). 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 unlivable due to storm damage and coastal erosion in a number of years. The cost to re-locate these communities is estimated to be significant (Williams and Hanson, 2007).

28.3.4.1. 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) simulated 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).

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (medium certainty). There is strong evidence and considerable data showing links between climate driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Mueter and Litzow, 2008; Drinkwater, 2011;Section 28.2.2.2.1). 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 (Huse, 2008; Ianelli *et al*., 2011). 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, 2012). 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*., 2012; 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.

28.3.4.2. 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 diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten as a result of climate change (Xu et al. 2013), this would negatively affect access to logging sites. Access is best when frozen ground makes transportation possible in sensitive locations or areas that lack road. If the weather changes when logging has already taken place, sanding of the road may become necessary in order to ensure transportation within a specific timeframe, which carries significant economic costs (Keskitalo, 2008). Impact on the carrying capacity of the ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008). 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).

28.3.4.3. 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). 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).

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. Structures built on ice-rich soils will be more vulnerable to thawing and a changing climate than those built on ice-poor soils or bedrock and impacts are likely to be negligible. 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).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).

28.3.4.4. Inland Transportation, Communication, and Drinking Water

By adapting transportation models to integrate monthly climate model (CCSM3) predictions of air 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 ~$1x10^6$ 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). 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.

28.3.4.5. Terrestrial Resource Management (Oil and Gas, Mining, Forestry in the Arctic)

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

The most recent comprehensive 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 28-5 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 28-5 HERE
Figure 28-5: (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.]

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 on the level of resources in the Arctic.

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 28-6 Illustrates the dominant contribution of natural resource based industries to regional GDP in the Arctic (2005)

[INSERT FIGURE 28-6 HERE
Figure 28-6: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010.]

In Arctic Russia the extraction of energy alone contributes close to 60 per cent of regional GDP (see Figure 28-7). 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 28-7 HERE
Figure 28-7: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.]

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.

28.3.4.6. 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 *et 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 28-8). The models did not predict any noticeable changes of the ice conditions in the NWP until the early 2030s.

[INSERT FIGURE 28-8 HERE
Figure 28-8: 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 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.

Three active proposals for arctic submarine fiber optic cables connecting Eastern Asia with Europe - one through the NSR and two through the NWP and all planned to be in operation before 2015- illustrate the non-shipping uses for sea routes that are being made possible by seasonal ice free periods and which will require at least periodic access for maintenance. (Source: http://www.extremetech.com/extreme/122989-1-5-billion-the-cost-of-cutting-london-toyko-latency-by-60ms).

28.4. Adaptation in the Polar Regions

There is general agreement that both indigenous and non-indigenous people in the Arctic have a long history of adapting to natural variability in climate and the natural resource base, as well as in recent decades rapid socio-economic, cultural and technological change (Forbes and Stammler, 2009; Wenzel, 2009; West and Hovelsrud, 2010; Ford and Pearce, 2010; Bolton *et al.*, 2011). Climate change exacerbates the existing stresses faced by Arctic communities (Rybråten and Hovelsrud, 2010; Crate and Nuttall, 2009), and is only one of many important factors influencing adaptation (Berrang-Ford *et al.*, 2011). Climate adaptation needs to be seen in the context of these inter-connected and mutually reinforcing factors (Tyler *et al.*, 2007; Hovelsrud and Smit, 2010). The complex inter-linkages between societal, economic, political factors and climatic change represent unprecedented challenges for northern communities (Ford *et al.*, 2010; Hovelsrud *et al.*, 2011; Keskitalo, et al 2010; Abele et al., 2009).
There is considerable evidence that changing weather patterns, declining sea-ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for the wellbeing of communities in the Arctic (see 28.2.5.2 and 28.3.4). Sea-ice is particularly important for coastal communities which rely upon it for transportation between communities and hunting areas (Krupnik et al., 2010). Changing the duration and conditions of sea ice and the consequent changes to country food availability significantly impact the wellbeing of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford *et al.*, 2010), outdoor tourism (Dawson *et al.*, 2010) and hunting and fishing (Wiig *et al.*, 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where the impacts are often felt most acutely and the resources most readily available (Hovelsrud and Smit, 2010). Such adaptation is often taking place despite the lack of national guidelines (Dannevig *et al.*, 2012; Juhola et al., 2012; Glaas et al., 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (West and Hovelsrud, 2010; Hovelsrud and Smit, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events, such as floods, avalanches and mud slides, are found to be salient drivers of adaptation (Berrang-Ford *et al*., 2011; Dannevig *et al*., 2012; Amundsen et al., 2010).

National policies for adaptation are largely in their infancy in the Arctic (Keskitalo 2010a,b; Berrang-Ford et al., 2011; Yamineva 2012). The lack of local scale climate projections, combined with uncertainties in future economic, social and technological developments often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes towards risk may cause inaction (Adger *et al*., 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for the increasingly complex societies and governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Keskitalo et al., 2009; Hovelsrud and Smit 2010; Forbes et al. 2009; Ford and Goldhar, 2012). In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Berkes, 2009; Armitage et al., 2008).

28.4.1. Adaptation and Indigenous Peoples

The adaptive capacity of Arctic indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (see Chapter 12, section 12.3). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Tyler et al., 2007; Eira et al., 2012). The sharing of knowledge ensures rapid responses to crises (Ford et. al., 2007). In addition, cultural values such as patience, persistence, calmness, respect for elders and the environment are important for adaptation. Some studies suggest that traditional knowledge may not always be sufficient to meet rapid changes in climate and weather, or extreme events (see also Chapter 12), and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Valdivia et al., 2010; Hovelsrud et al., 2010a). This has in some cases created a sense of a “loss of order in the world” (Turner et al., 2008,) and less confidence in the reliability of knowledge keepers (Chapin III et al., 2006; Hovelsrud and Smit, 2010).

Over the last half-century, the adaptive capacity in some indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements (Ford et al, 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts. The establishment of permanent communities can also led to increasing employment opportunities and income diversification for indigenous peoples, which in turn may cause social inequalities (Ford et al, 2010). However, the current level of skilled labour and formal education may limit the abilities to take advantage of such opportunities (Furgal C., 2008). On the other hand the intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programmes may strengthen adaptive capacity (Bolton et al., 2011; Hovelsrud and Smit, 2010; Ford et. al., 2007; Forbes 2007).

Renewable resource harvesting remains a significant component of Arctic livelihoods and with climate change hunting and fishing has become a riskier undertaking, and many communities are already adapting in a reactive manner (Gearheard *et al*., 2011; Laidler *et al*., 2011). Adaptation includes taking more supplies when hunting; constructing more permanent shelters on land as refuges from storms; improved communications infrastructure; greater use of global positioning systems (GPS) for navigation; synthetic aperture radar (SAR) to provide estimates of sea-ice conditions (Laidler *et al*., 2011) and the use of larger or faster vehicles (Ford et al, 2010). 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).

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include: moving herds to better pastures (Bartsch *et al*., 2010); providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009); retaining a few castrated reindeer males to break through heavy ice-crust (Reinert et al., 2008); ensuring an optimal herd size (Forbes et al., 2009; Tyler et al., 2007); and creating multicultural initiatives combining traditional knowledge with scientific studies to create and distribute co-produced dataset (Vuojala-Magga *et al*., 2011; Bongo *et al*., 2012). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al., 2010b).

In some Arctic countries indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change, as well as other issues related to education, health-care and economic development (Abele et al., 2009). In some instances this has given rise to tensions over land/water use between traditional livelihoods (e.g. reindeer herding, marine mammal hunting) and new opportunities (e.g. tourism and natural resource development) (Forbes, 2006; Hovelsrud and Smit, 2010). Some territorial governments in Northern Canada promote adaptation by providing hunter support programs (Ford et al., 2006; Ford et. al., 2010).

The health of many indigenous peoples is being affected by the interactions of changes in the climate with ongoing changes in human, economic and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al, 2010). While wage employment may enhance the possibilities for adaptive capacity, greater involvement in full time jobs can threaten social and cultural social cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.4.2. Adaptation and Industrial Development

Increasing access to minerals and fossil fuels and increased shipping, due to reduced sea ice, will bring both opportunities and challenges. The extraction of off-shore fossil fuels in areas where icebergs are a significant threat will require design changes to drilling platforms (McClintock et al, 2007). Some of the resources that will be extracted are expected to be transported by ship to southern markets; other resources may be transported by pipelines whose design requirements will need to take climate change into account. On shore processing plants and particularly waste containment facilities must be able to maintain their structural integrity over the expected long lifetime of a project (Prowse et al, 2009). 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.

_____ START BOX 28-1 HERE _____

Box 28-1. Adapting Critical Infrastructure to Climate Change in Northern Canada

Climate change is increasingly 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 (Hayley and Horne, 2008). A risk-based project screening tool has been developed for considering climate change in northern engineered facilities (CEAA, 2003). 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 thawing permafrost will largely involve current solutions to reduce the impacts of ground disturbance (CSA, 2010). 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 with heat-pumps and thermosyphons to ensure that foundation soils remain frozen. Recently developed techniques, such as air-convection embankments may also be utilized. 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, a critical adaptive response will be monitoring infrastructure performance; determine if changes in permafrost conditions deviate from those predicted; and decide whether additional adaptation measures are required (Burgess, et al, 2010).

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. In addition, these ice-roads link communities and facilitate social and cultural activities, and provide access to hunting, fishing, or trapping areas (Furgal and Prowse, 2008; Ford et al., 2008).

_____ END BOX 28-1 HERE _____

28.5. Arctic Pollution and Climate Change

Recent studies suggest that transport pathways, intercompartmental distribution, bioaccumulation and transformation of environmental contaminants such as persistent organic pollutants (POPs), mercury (Hg) and radionuclides in the Arctic and the globe as such may be affected by climate change (AMAP 2011, UNEP/AMAP 2011). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice and rivers. Thus, the rate and efficacy of transport of these contaminants into the Arctic and their occurrence in the environment are expected to be significantly affected by climate change (Macdonald and Loseto, 2010; AMAP 2011).

An oxidized form of gaseous mercury in the Arctic atmosphere is deposited on ice and snow surfaces in episodic atmospheric mercury depletion events (AMDEs). The oxidation is enhanced by photochemical reactions involving halogens released from freezing sea ice. The extent of sea ice and changes in the timing of freezing will affect AMDE dynamics and the deposition of mercury in the Arctic (Steffen *et al.*, 2007).

The fate of POPs and mercury in the terrestrial environment is mainly controlled by temperature and biogeochemical processes (Teng *et al.*, 2012; AMAP 2011). Changes in the carbon cycle by thawing permafrost will affect the methylation of mercury and the bioaccumulation and release of POPs. Ma et al. (2011) and Hung et al. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

There is evidence that climate change will cause alterations in trophic structures, food sources and migratory patterns, which may influence bioaccumulation and biomagnification of some POPs. There is also concern about effects from multiple stressors, including exposure to POPs and climate change, in environments such as the Arctic where species are living at the edge of their physiological tolerance (Macdonald *et al.*, 2005; Borgå *et al.*, 2010; Teng *et al.*, 2012; UNEP/AMAP 2011).

There is *high confidence* that climate change will affect the fate and impacts of anthropogenic contaminants in the Arctic, but the extent to which this will occur is uncertain.

28.6. Research and Data Gaps

Our understanding of a region of the globe as large and heterogeneous as the Polar Regions and with multiple human and development stresses is still imperfect. For example, ice-sheets in Greenland and Antarctica and sea-ice in the Arctic are declining faster than models predict. Many of the physical and biological systems in the Polar Regions are sensitive to rapid change and could tip into new regimes as they cross critical thresholds. Systematic monitoring will be essential for the early detection of these changes and remote-sensing will be particularly valuable in providing geographically comprehensive coverage.

Increasing evidence indicates that changes in the Polar Regions are having impacts on global-scale physical and human systems. 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. Understanding these changes will require international and interdisciplinary collaboration.

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 such as new regulations governing infrastructure design and natural resource harvesting. Although there is a considerable body of traditional and western experience in adapting to changing climate and resource availability this may be inadequate if the magnitude and rate of the change is greater than in the past. Mechanisms will be required to develop, share and evaluate adaptation response options.

Frequently Asked Questions

FAQ 28.1: What will be the net socio-economic impacts of change in the Polar Regions?

Climate change will have cost and benefits for Polar Regions. In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, and forestry. Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts as well as effects on traditional livelihoods of northern residents are possible. Changing sea ice condition and permafrost thawing may cause damage to installations such as bridges, pipelines, drilling platforms, hydropower and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development. Since 1970s maximum ice thickness decreased up to 15 cm in rivers within Siberia. Statistically, a long-term mean increase of 2 to 3°C in autumn and spring air temperature produces an approximate 10 to 15 day delay in freeze-up and advance in break-up, respectively. As a result, many of the ice roads may become less viable option than the all-weather roads with implications for significantly increased costs. Particular concerns are associated with projected increase in the frequency (by 20-50% in the coming decade) and severity (with 35 to 60% increase in peak break-up water levels) ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk. Climatic, accecerbated by other large-scale changes can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices. Changing sea ice conditions will impact indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively. In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, and an increasing likelihood of introductions of alien species to terrestrial environments. Fishing for Antarctic krill near to the Antarctic continent is expected to become more common during winter months in areas where winter sea ice extent reduces.

FAQ 28.2: Why are changes in sea ice so important?

Sea ice is a dominant feature of Polar Oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude and species composition of primary and secondary production in the Polar Regions. With less sea ice many marine ecosystems will be experiencing shifts from light limitation to nutrient limitations as well as shifting balance between the primary production by ice algae and phytoplankton with implications for Arctic food webs. Sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. While the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc. Changes in sea ice will have bottom up consequences for marine foodwebs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g. Bearded seals in the Arctic and crabeater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50-70 years loss of hunting habitats may lead to extirpation of the polar bears from seasonally ice-covered areas, where currently two thirds of their world population live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, the sensitivity of the species to changing environmental conditions and adaptive capacity of each species. More open waters and longer ice-free period in the northern seas enhance the effect of wave action and coastral erosion with implications for coastal communities and infrastructure.

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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

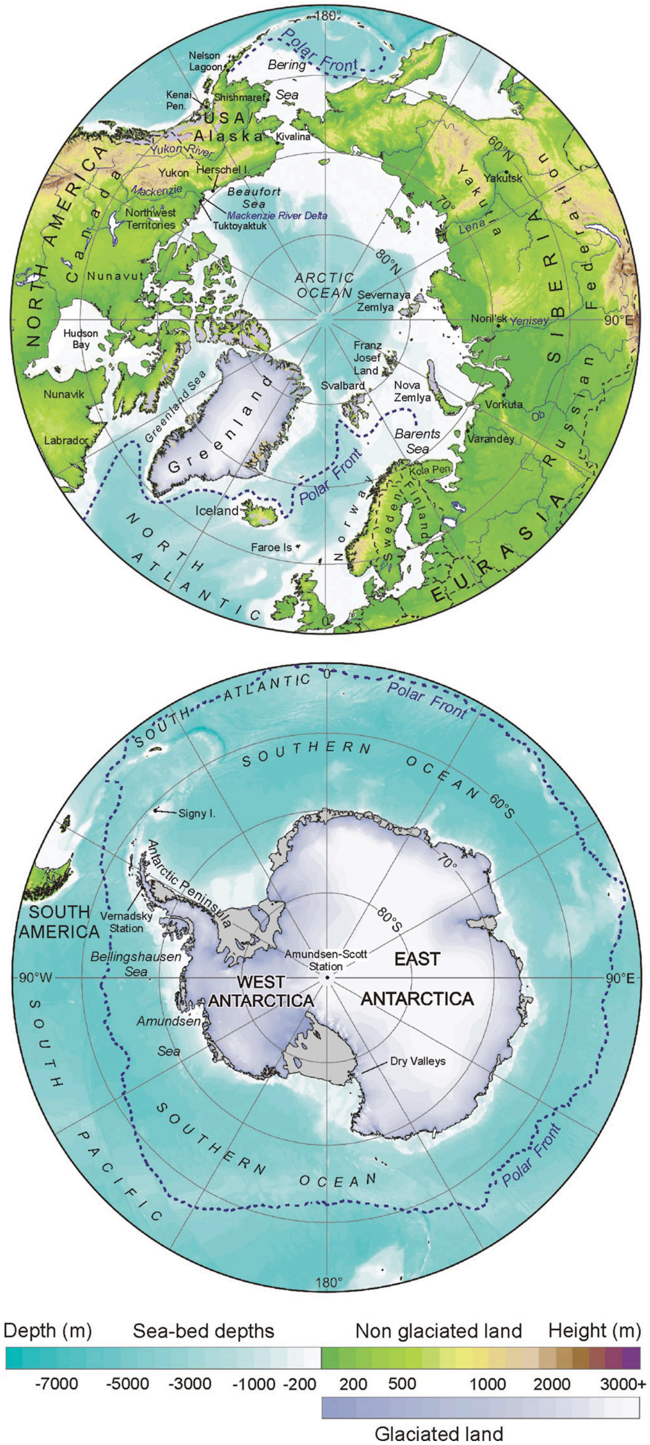


Figure 28-1: Location maps of the North and South polar regions. Source: IPCC, 2007.
[Note: WGII AR4 Figure 15.1 to be updated, including the addition of major currents.
Credit: P. Fretwell, British Antarctic Survey.]

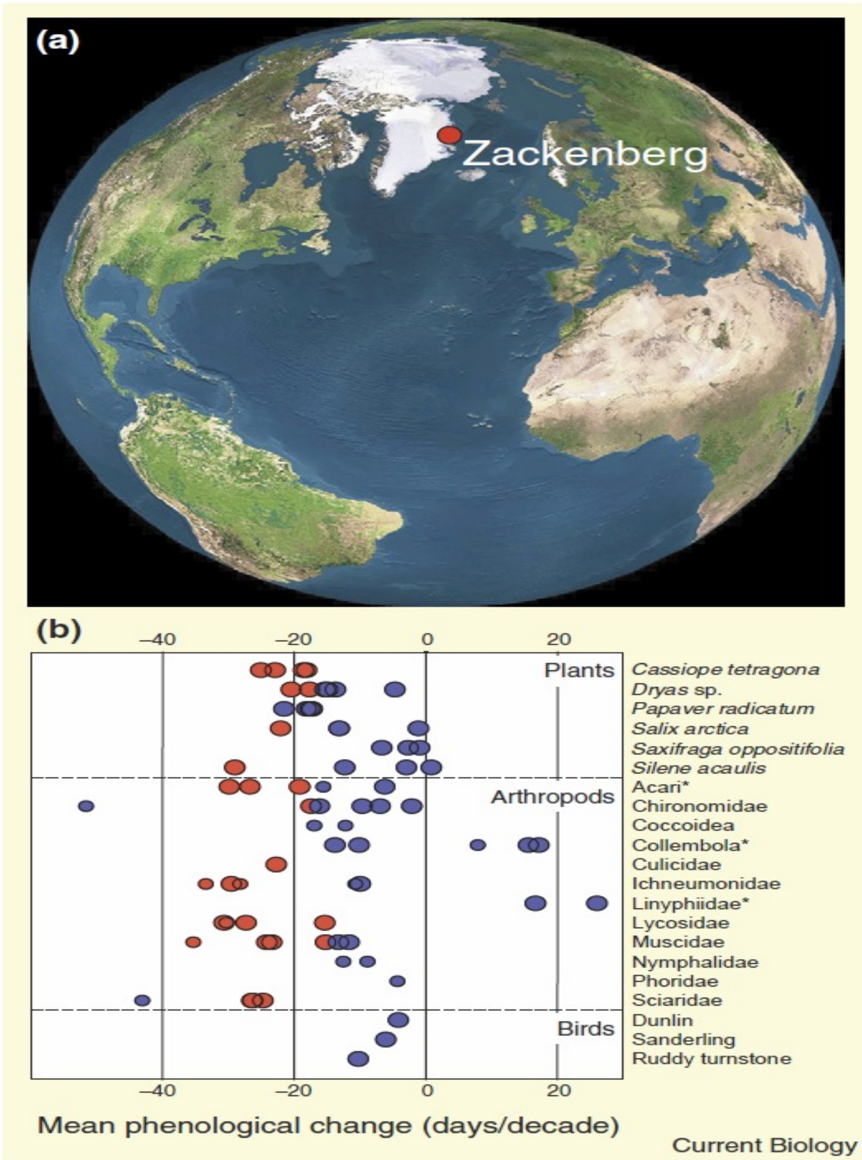


Figure 28-2: Advancement of phenological events in high-Arctic Greenland. a) location of the study area Zackenberg, North-east Greenland. b) Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initation dates (birds). Red dots are statistically significant,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

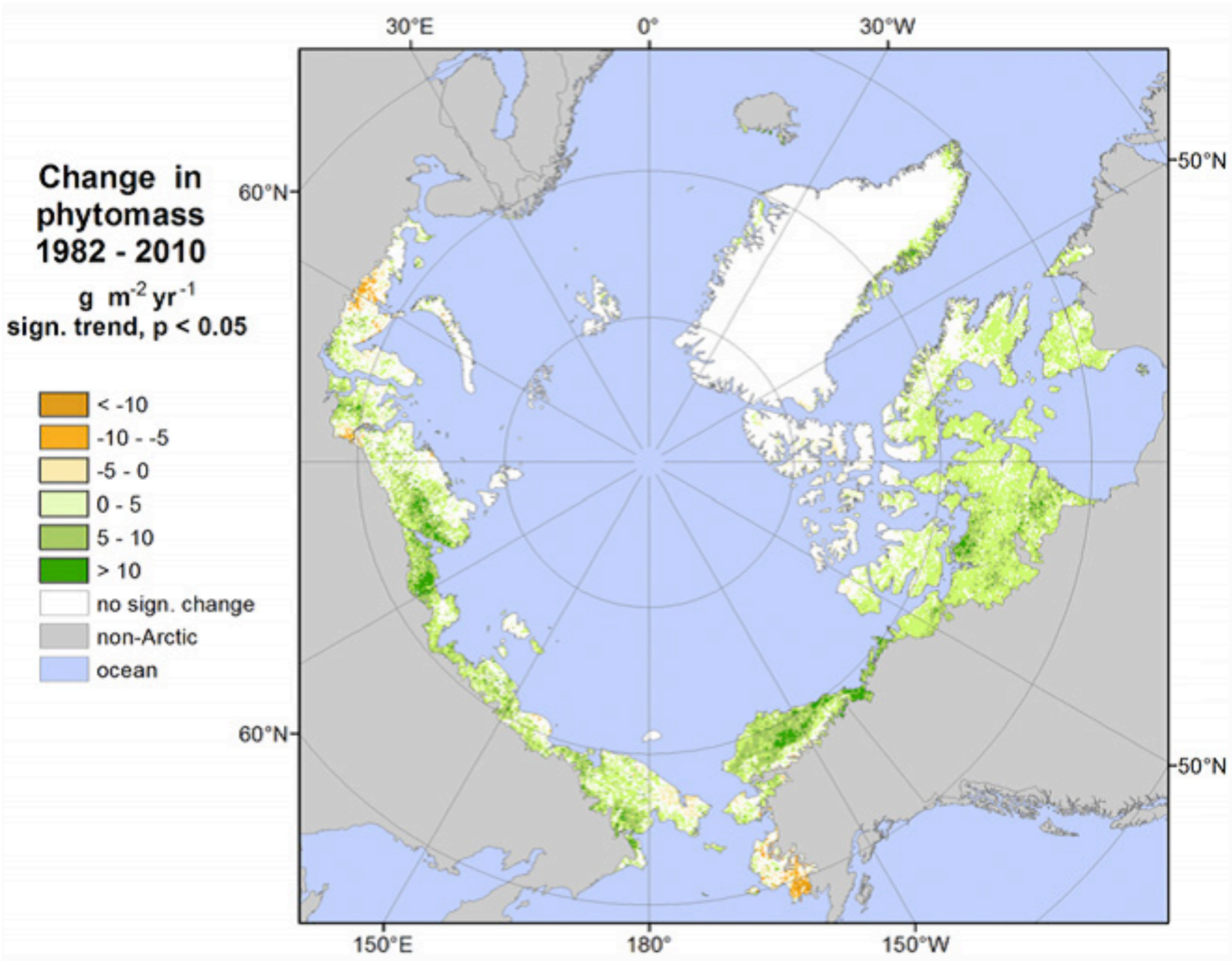


Figure 28-3: Significant changes (p < 0:05) in aboveground tundra phytomass from 1982 to 2010 (Epstein et al. 2012).

Figure 28-4: Fishing vessel activity. Source: AMSA, _____.

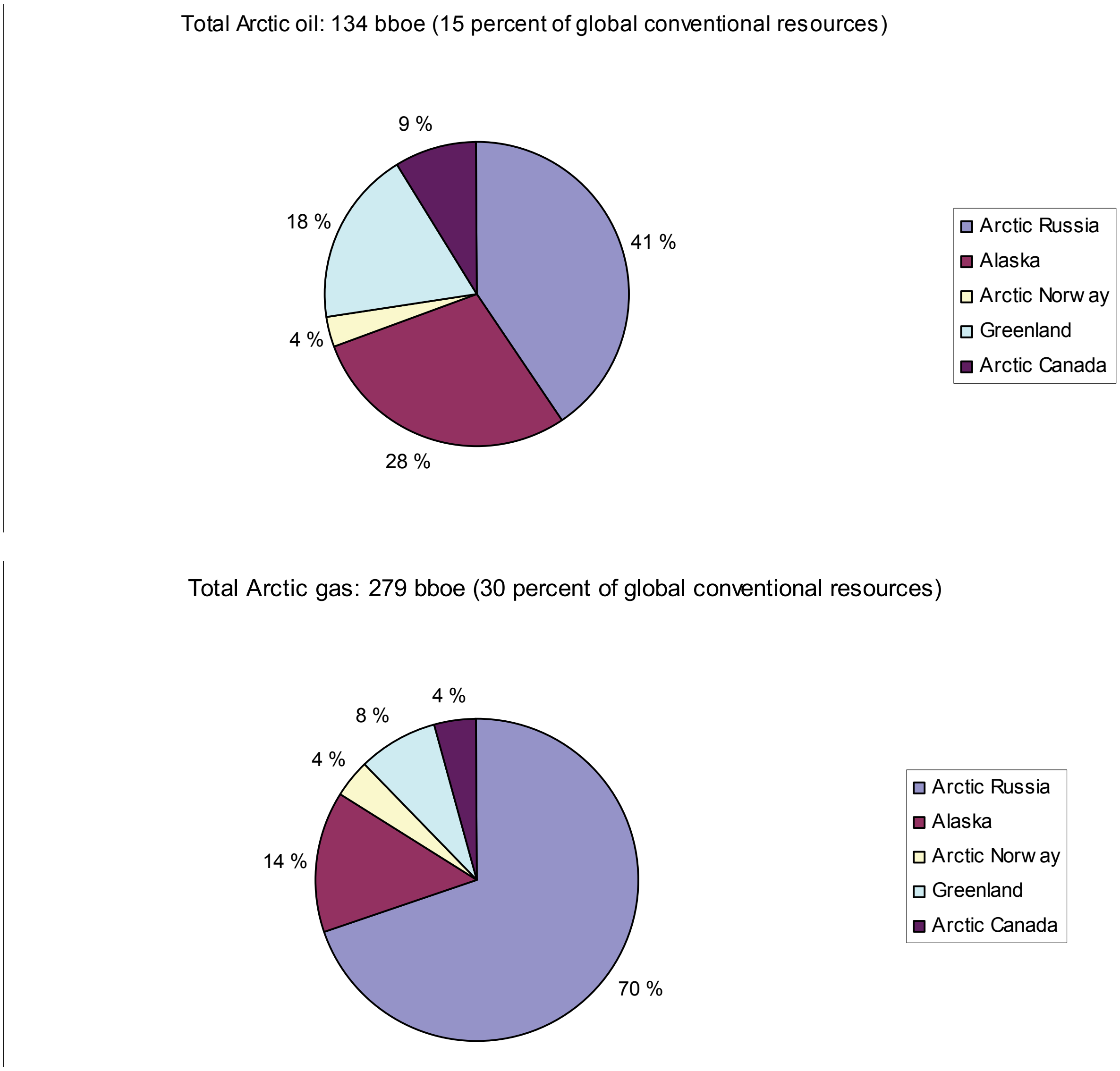


Figure 28-5: (top) Regional distribution of Arctic undiscovered oil resources (including NGL), and (bottom) regional distribution of Arctic undiscovered natural gas resources (including NGL). Source: Statistics Norway, 2010.

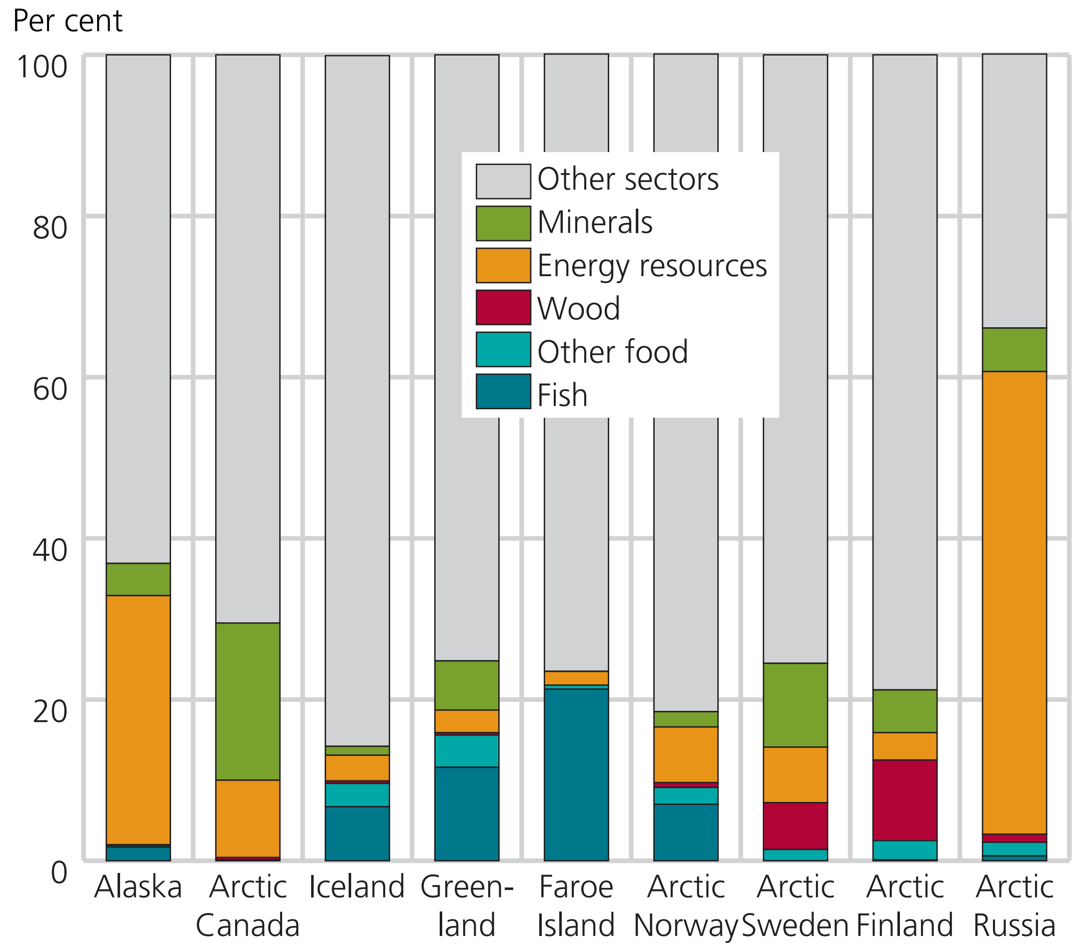
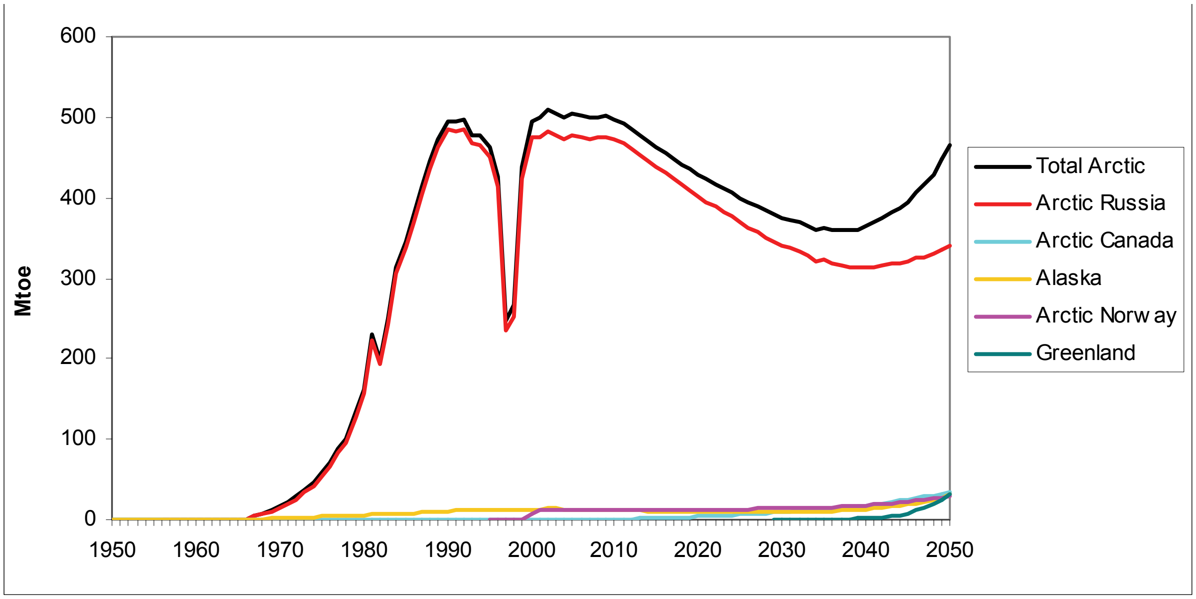


Figure 28-6: Value added in natural resource-based industries in Arctic regions, 2005 (% of regional GDP). Source: Statistics Norway, 2010. [TO BE UPDATED]

a)



b)

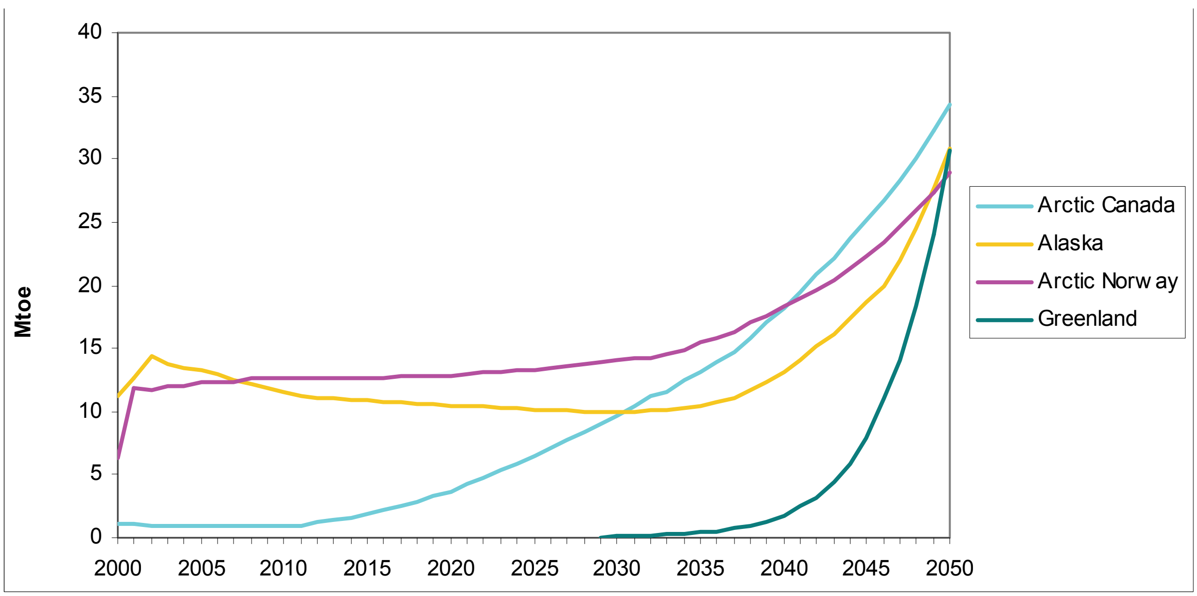


Figure 28-7: (a) Arctic gas production, reference scenario (Mtoe); and (b) regional distribution of West Arctic gas production, reference scenario (Mtoe). Source: Statistics Norway, 2010.

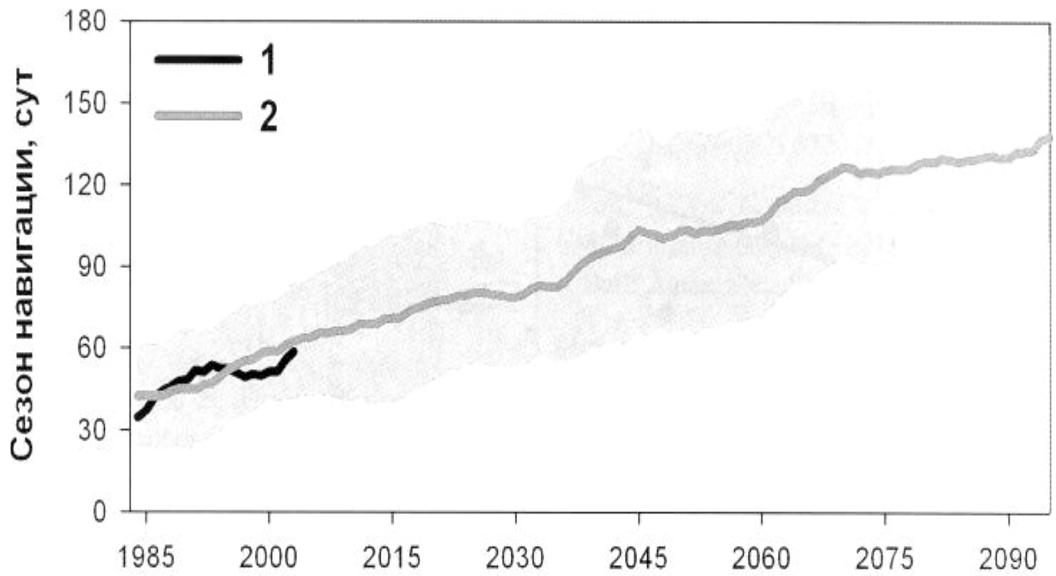


Figure 28-8: Projected duration of the navigation period (days) over the North-West passage (1) and Northern Sea route (2). Source: Mokhow and Khon, 2008.