Chapter 28. Polar Regions

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Executive Summary

[to be developed]

28.1. Introduction

Conventional definition of the Polar regions is based on geographic features. Previous IPCC reports define Arctic as the area within the Arctic Circle, and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58ºS (IPCC, 2001). There are other deifintions of the Polar regions based on the threeline, +10º C July temperature isotherm, zone of continuous permafrost on land and sea ice extent on the Ocean (Barcits, 2000). Within the territories of each of the eight Arctic countries the boundary is defined individually, while the marine boundary has been established by international agreements. For the purpose of this report we follow the approach adopted in the Arctic Climate Impact Assesment. In ACIA (2005) Arctic was defined as a region with loose boundaries, while the area was described in relation to a particular subject with its own boundary defined either implicitly or explicitly. In this report we expand the ACIA approach over the Antarctica while using the conventional IPCC definition of the Polar regions as a basis.

28.1.1. Summary of Knowledge Assessed in Previous Reports (including IPCC, ACIA, SWIPA, etc.)

Several international climate assessments, including the IPCC (2001, 2007), ACIA (2005), Snow, Water, Ice and Permafrost in the Arctic (SWIPA, 2011), and the State of the Arctic Coast (2011) reports and the Antarctic Climate and the Environment (Turner et al. 2009), 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.

28.1.1.1. Arctic

SWIPA (2011). There have been significant changes in the physical climate regime. Since 1980 Arctic has been warming at approximately twice the global rate. Sea ice reduced at unprecedented rate reaching the absolute minimum of 4.7 million km^2 in 2007 with 2008, 2010 and 2009 having the second, third and fourth rank since the beginning of satellite observations in 1979. Sea ice is getting thinner and younger, about 70% of it is 1-2 years old, and 95% is younger than 5 years. With less ice Arctic seas absorb more heat in the summer and release it to the lower atmosphere before freezing, which is why the warming is most pronounced in autumn close to the edge of the sea ice.

28.1.1.2. Antarctic

(summary of knowledge will be added later by Antarctic CAs)

28.1.1.3. Feedbacks to Global Climate

Polar regions contain important drivers of the global climate acting through albedo, oceanic thermohaline circulation, and greenhouse gas emissions. (Will be further detailed using the findings of SWIPA report, when it is published)

28.1.2. Two Contrasting Polar Regions

28.1.2.1. Arctic

The polar region of the northern hemisphere includes the marine ecosystems of the Arctic Ocean, its neighboring Seas including the northern Bering Sea shelf. The deep basins of the Arctic Ocean are surrounded by shallow shelf ecosystems (Figure 28-1). The physical oceanography of the Arctic Ocean is primarily influenced by sea ice, advection of Atlantic and Pacific water, freshwater runoff from land, and winds forced by the arctic oscillation. The declination of the earth insures that during winter months the Arctic Ocean and its neighboring seas will remain cold, dark and ice covered and summer growing seasons will continue to be shorter than at lower latitudes (Wang and Overland 2009). Topographic features, sea ice, the confluence of water masses and currents create salinity and temperature fronts that define the major marine ecosystems of the Arctic (Carmack and Wassmann, 2006, Stabeno et al. 2011, Stabeno 2010). Strong advection of warm saline Atlantic water enters the Arctic Ocean through Fram Strait (Drinkwater 2011). South of Spitsbergen, the northward flow bifurcates along the Polar Front and flows into the Barents Sea. In the Pacific, weak flow of lower salinity high nutrient waters enters the Arctic Ocean from the eastern Bering Sea across the Bering Strait (Figure 28-1; Drinkwater et al 2011). In the Arctic Ocean, water stratifies in response to temperature and salinity with cool low salinity deepwater along the bottom overlain by warm saline

Atlantic water, overlain by lower salinity cooler Pacific water topped with low salinity surface water (Carmack and Wassmann 2006). Water exits the region along the eastern coast of Greenland and through Baffin Bay.

[INSERT FIGURE 28-1 HERE
Figure 28-1: Map of the Arctic Ocean with shelves and basins. Blue arrows show areas of outflow of arctic water and red arrows show the places and strength of inflows of Pacific and Atlantic water. Source: Carmack and Wassman 2006.]

Earlier assessments have highlighted the importance of changing winter snow conditions (ACIA, 2005; IPCC, 2007; SWIPA, 2011). The latter include events resulting in ice crusts, raised as a potential threat to reindeer and caribou populations upon which many northern residents depend for their livelihood, both indigenous and non-indigenous (Grenfell and Putkonen, 2008; Helle and Jaakkola, 2008; Helle and Kojola, 2008; Moen, 2008; Roturier and Roué, 2009; Riseth et al., 2011). However, there are different perspectives on the extent to which climate change is actually driving trends in circumpolar reindeer and caribou populations (Vors and Boyce, 2009; Tyler, 2010; Tyler et al., 2007; Bartsch et al., 2010; Joly et al., 2011). To be certain, significant losses ≥25% can occur as the result of one or more successive events (Tyler, 2010; Bartsch et al., 2011). The available evidence does not support a synchronous circumpolar decline in wild and managed semi-domestic populations (Tyler, 2010; Joly et al., 2011). On the contrary, some of the largest caribou and reindeer populations experiencing both significant climate warming and accelerated industrial development in recent decades have actually been steadily increasing (Cameron et al., 2005; Forbes et al., 2009). For the largest semi-domestic populations in northern Fennoscandia and Russia, social and political factors and drivers can easily outweigh the ecological effects of environmental change (i.e. climate) (Nuttall et al., 2005; Forbes et al., 2006, 2009; Tyler, 2010). At the same time, even people who experience significant (≥25%) reindeer losses in association with extreme weather events may have other concerns besides climate change, in particular the flexibility and adaptive capacity of relevant institutions and rights to land that may be threatened by industrial development (Forbes and Stammler, 2009). The high degree of resilience noted in Nenets social-ecological systems depends upon the free use of space according to herders' own needs. However, as oil and gas infrastructure encroaches on their migration routes, this adaptive capacity will be greatly reduced (Forbes et al. 2009; Kumpula et al. 2011). While herders themselves tend to see development issues as more urgent than the symptoms of 'warming' (Forbes and Stammler, 2009), it is important that the potential synergies between warming and anthropogenic land change (*sensu* Turner et al., 2007).

Over recent decades, reductions in sea ice thickness and extent have been observed in the Arctic (Grebmeier et al. 2010, Wang and Overland, SWIPA 2011). These changes lengthened the summer open-water season and reduced the formation of thick multiyear sea ice. The pace of the loss of sea ice in the arctic exceeded that predicted in the AR4 report and the ACIA (2005). Model inspection revealed that models that incorporated seasonality in atmospheric forcing tracked the observed pattern of sea ice loss. Revised forecasts based on seasonally adjusted models indicate that the Arctic is likely to be ice-free in summer by mid century (Wang and Overland 2009).

28.1.2.2. Antarctic

In contrast to the Arctic, which is principally a polar ocean surrounded by continental land and islands, Antarctica comprises the Antarctic continent surrounded by the Southern Ocean, within which lie the subantarctic island archipelagos. The Southern Ocean links the major ocean basins in the Southern Hemisphere via the Antarctic Circumpolar Current (ACC). The ACC is the greatest current on earth, and parts of it are seasonally inundated by the extensive advance and retreat of sea ice. The seasonal pack is one of the important drivers of the physical environment in the Southern Ocean playing a pivotal role in modulating the dynamics of ecosystems in the region.

Terrestrially, the Antarctic continent is almost entirely covered in land ice, leaving only the continental margins and subantarctic islands to sustain substantial terrestrial life and human habitation. The Southern Ocean is divided meridionally by a number of fronts and has three major regions of productivity - the Antarctic Peninsula, Weddell Sea and Scotia Arc in the Atlantic sector, the Ross Sea in the Pacific sector and Prydz Bay and the Kerguelen Plateau in the Indian sector. The complexity of interactions between seasonality in light and sea ice, the Antarctic

Circumpolar Current, the continental system, atmospheric dynamics and the latitudinal variation in these interactions results in substantial differences in climate change impacts in different parts of the region.

Governance in the region is primarily through the Antarctic Treaty System (1959) and the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR; 1982). Sovereign claims to the continent and surrounding waters and islands have been set aside under The Antarctic Treaty which regulates activities south of 60ºS. CCAMLR regulates marine activities related to conservation and rational use, north from the continental margin to the Polar Front, one of the major fronts within the ACC. Most, but not all, of the subantarctic islands maintain undisputed sovereignty over their surrounding Exclusive Economic Zones, and where these fall within the area regulated by CCAMLR, nations have the right to exempt themselves from CCAMLR regulatory measures if they so choose.

The large scale of the region, the lack of indigenous populations, and the distance from important markets and research economies has meant that much less is known about the ecology of the region compared to other oceans. Historical fisheries statistics prior to CCAMLR are of poor quality, except for whaling records. Statistics related to the harvesting and removal of living resources have improved since CCAMLR came into force in 1982. Ecological research has included a number of short periods of intense coordinated activity throughout the region, starting with the International Geophysical Year (1957/8). Long-term ecological research has been undertaken in the Atlantic sector and in the west Antarctic Peninsula region for a number of decades, providing a solid foundation for understanding the ecology of the ecosystems in those areas, but leaving a large part of coastal Antarctica and the Southern Ocean with only sparse long-term data (although seals, penguins and some flying birds have been monitored regularly at some locations). Regionally-organised research (e.g. through past, SO-GLOBEC, and present, SCAR, CCAMLR, SOOS, Sentinel and ICED, initiatives) is becoming better coordinated, particularly given its importance in understanding global climate systems.

[INSERT FIGURE 28-2 HERE
Figure 28-2: Title?]

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 changes has been an increase in river flow. An earlier analysis indicated a 7% increase inflow of the six largest Eurasian rivers from 1936 to 1999 (Peterson *et al.*, 2002). Subsequent analysis for the period 1951-2000 showed that increases for these basins could not be attributed with certainty to precipitation changes (Milliman *et al.*, 2008). By contrast, the annual flow of major high-latitude Canadian rivers over the period 1964-2000 experienced an opposite trend with discharge decreasing an average 10%, but this decreasing trend was found to match that for precipitation (Dery and Wood, 2005). An analysis of more recent records, 1977-2007, for 19 large rivers encompassing the entire Arctic region indicates that an increasing trend of an average +9.8% has occurred for 19 rivers that comprise the majority of flow around the entire circumpolar Arctic; with some rivers such as the Lena and Yenisei exhibiting accelerating increases in more recent years (Overeem and Syvitski, 2010). Moreover, there were also shifts in timing of flow with the main month of snowmelt (May) increasing by an average 66% but flow in the subsequent month of peak discharge decreasing by ~6.8%. Such a shift was attributed to earlier snowmelt. Earlier timing of the maximum spring flood has also been noted for a suite of Russian Rivers; the shift in timing averaging 5 days for the period 1960-2001 and being most pronounced in eastern sectors with a colder more continental climate that has experienced rises in air temperature (Shiklomanov *et al.*, 2007).

While flow regulation has been raised as a factor that might obscure the true nature of such timing shifts, a recent study by Tan *et al.* (2011) of unregulated streams in Eurasia over the last half-century (1958-1999) also documented a modest change in the spring pulse onset and a strong change in the centroid of spring flow volumes for a majority of the studied streams. Again such temporal changes were attributed to upward trends in air temperature, particularly in the coldest of the major Eurasian Arctic river basins.

Although the timing of spring freshet has shifted on Eurasian rivers, it does not appear to be accompanied by an increase in flow maxima (Shiklomanov *et al*., 2007). There has, however, been a documented rise in the winter minimum flows for many Eurasian and North American rivers (Smith *et al*., 2007; St. Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007; Ye *et al*., 2009), the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm *et al*., 2010). Most such studies have hypothesized that the winter flow increases are due to larger groundwater inputs due to permafrost thawing and have been supported in part by some satellite-gravity measurements (Muskett and Romanovsky, 2009). Others argue that while permafrost thaw might be a contributing factor, the primary agent of increasing winter flows is an increase in net winter precipitation minus evapotranspiration (Rawlins *et al*. 2009a,b; Landerer *et al*., 2010). An insufficient spatial coverage of precipitation stations across the Arctic remains an obstacle to deciphering the relative roles of these two primary factors of change in explaining the observed trends in arctic river flow that has occurred over the approximately last half-century.

Information about the changes to the hydrology and water budget of lakes is scarcer than that for rivers, largely because of the lack of national observation and archiving programs. Information from satellite thermal imagery, however, indicates that lake, surface water temperatures have been warming for the period 1985-2009 as measured at large inland water bodies (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. In areas where water bodies warmed more rapidly than the surrounding air temperature, decreasing winter ice cover was suggested as playing a key role in producing enhanced radiative warming. Increasing lake-water temperatures has likely also played an important role in the storage of carbon in lakes. Based on results from Swedish boreal lakes, lake water temperature has been shown to exhibit a strongly positive relationship with the mineralization of organic carbon in lake sediments (Gudasz *et al*. 2010). This suggests that warmer water temperatures lead to more mineralization and less organ carbon burial. Extended ice-free conditions, accompanied by higher air temperatures and resulting evaporation, have also been identified as the reason for the recent summer drying out of some Canadian High Arctic ponds, which had been permanent water bodies for millennia (Smol and Douglas, 2007).

Despite the importance of ice-cover on northern hydrologic regimes, the last two decades has experienced a steep decline in freshwater-ice observations (Prowse *et al*., 2011). In the case of long-term lake and river sites in the Northern Hemisphere with ice-phenology records longer than 100 yr, Magnusson *et al*. (2000) reported that 38 of the 39 time series (1846-1995; only one site north of the Arctic Circle) showed either later freeze-up (15 sites averaging +6.3 d/100 y) or earlier break-up (24 sites averaging -5.8 d/100 y), thus resulting in an average reduction in ice duration of 12.1 d/100 y. A subsequent analysis (by B.J. Benson and J.J. Magnuson, reported by Koç *et al*., 2009) of a smaller set of only Northern-Hemisphere lakes (9 sites for freeze-up and 17 for break-up) for the winters 1855/56 to 2004/05, the rate of change in both events is noted to increase: from +6.3 to +10.7 d/100 y for freeze-up and -5.8 to -8.8 d/100 y for break-up, thereby further reducing average ice duration by 12.1 to 19.5 d/100 y. It is unknown how much of this increased rate of change results from different sample sizes or periods of record. However, some is certainly due to the strong and consistent changes in timing that are evident after the mid-1990s, which is also the end of the previous period of analysis by Magnuson *et al*. (2000). Analyses of shorter term phonological records shows that the timing of ice break-up (and freeze-up) tends to be more sensitive to variations in air temperature at lower latitudes where mean annual air temperatures are higher, than at higher latitudes where mean annual air temperatures are lower (Livingstone *et al*., 2010).

Despite this, however, data obtained by remote-sensing of Canadian lakes (Latifovic and Pouliot, 2007) indicates that very high-latitude lakes appear to be experiencing more rapid reductions in ice cover than those at more southerly, temperate latitudes. Specifically, while the majority of all sites showed earlier break-up and delayed freeze-up (averaging -0.18 and +0.12 d/y, respectively) for the period 1950s to 2004, as well as increases (to averages of -0.23 d/y and +0.16 d/y, respectively) for a more recent 1970-2004 period, the most rapid rates of change (-0.99 d/y and +0.76 d/y, respectively) occurred in six high-latitude lakes (primarily on the Canadian Archipelago) for the even more recent period of 1985 to 2004. This translates into an ice-cover reduction rate of

1.75 d/y, or about 4.5 times that found for the more southern parts of Canada for the most rapid depletion period of 1970 to 2004. The degree to which this reflects the effects of either more recent or higher-latitude warming, or potential differences in observational techniques, is unclear (Prowse and Brown, 2010).

River ice, another significant component of northern hydrologic regimes, has also been the focus of numerous phenological trend studies but the data and time intervals are highly disparate. In summarizing most available information for northern rivers, Beltaos and Prowse (2009) note an almost universal trend towards earlier breakup dates but considerable spatial variability in those for freeze-up. Although the data originate from studies of varying lengths, ranging from multi-decade to over two centuries, they conclude that changes are often more pronounced during the last few decades of the twentieth century. They further approximate a river-ice phenology response to 20th Century mean warming of 2–3°C in spring and autumn air temperatures has produced in many areas an approximate 10- to 15-day advance in break-up and delay in freeze-up, respectively. While this concurs with phenological rates of change in lakes and rivers previously estimated by Magnuson *et al*. (2000), they note the strong complicating role that changes in snow accumulation and spring runoff can have on such a relationship.

The above noted changes to hydrologic and associated ice regimes have also been observed to have produced a number of effects on the physical, geochemical and ecological components and processes of some arctic lake, wetland and river systems. It has been recognized for some time that the water budget and nutrient-sediment supply of delta riparian zones are heavily dependent on ice-jam floodwaters. Studies of the Mackenzie River Delta riparian lake system (approximately 45000 in number), whose highest flood stages are dependent on ice jams (Goulding *et al*., 2009), indicates that decreases in the severity of river-ice break-up has lessened the flooding of the high-closure lakes and the biogeochemical processing of river water on which the ecological health of this extensive, floodplain ecosystem depends (Lesack and Marsh, 2007).

Furthermore, such a trend in river levels combined with rising arctic sea level and sea ice recession have been proposed as the proximal drivers of biodiversity loss in this system, primarily related to the decline of lakes with short and variable connection times plus low and variable river water renewal (Lesack and Marsh 2010). Such circumpolar deltas located at the terminus of major arctic rivers also act as biogeochemical processing regions for river water before its discharge to the sea (Emmerton *et al*., 2008). Hence, changes in the delta flooding regime are likely to affect not only the ecology of the floodplain delta, but also biogeochemical characteristics, primary production and food web processes in the coastal marine ecosystem, although these remain to be assessed.

Changes in near-coastal freshwater environments have also been documented for the case of epishelf lakes, such as on northern Ellesmere Island (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 completely as a result of their melting and collapse (Mueller *et al*., 2008).

Thermokarst lakes, a common feature of terrestrial permafrost landscapes, has been the focus of ongoing research to determine whether the warming air temperatures observed in northern regions are affecting patterns of their formation, areal extent and drainage. A previous generally held assumption was that, under enhanced warming, zones of continuous permafrost should experience an overall increase in lake number and size, but a decrease in areas of discontinuous permafrost where lakes are more likely to drain with the loss of permafrost aquatards. While additional studies have documented changes in the size and number of permafrost lakes in various parts of the Arctic (Hinkel *et al*. 2007; Marsh *et al*. 2009; Riordan *et al*. 2006), spatial patterns and rates of change are not consistent and may be related to differing states/condition of the permafrost (Prowse and Brown, 2010).

Changes in thawing permafrost have also been identified as causing major alterations to the biogeochemistry of water entering high-latitude lakes and rivers (Frey and McClelland, 2009). Such changes have been found in certain Arctic lakes, having implications on their current and future ecological structure and function. A comparative study of permafrost thaw slump-affected and unaffected lakes in upland tundra near the Mackenzie Delta found high concentrations of major ions in slump-affected lakes and, counter intuitively, that slump-affected lakes have less pelagic brown water and less water colour than unaffected lakes (Lantz and Kokelj, 2008). Because brown water (humic) conditions can lead to light limitation of phytoplankton productivity, lower light levels in lakes unaffected by slumping were noted to further limit phytoplankton growth (Thompson *et al*., 2008). Macrophyte biomass was significantly higher in thaw slump-affected lakes compared to unaffected lakes, and was attributed to enhanced benthic light regimes produced by the change water transparency related to thaw-slump activity and/or enhanced benthic nutrient availability (Mesquita *et al*., 2010). The higher macrophyte biomass in slump lakes has been related to enhanced lake eutrophication through an ecological shift from pelagic-dominated to benthic-dominated production (Thompson *et al*., in Submission).

28.2.1.2. Antarctic

With only 0.32% of its area being ice free, the majority of the Antarctic continent's hydrology and freshwater ecosystems occur as a vast network of lakes and rivers underneath the ice sheet. Nevertheless in supraglacial habitats, ice free coastlines, glacial forelands, sub-Antarctic islands, on nunataks and other ice free areas, the presence of liquid water in lakes, ponds, streams and in terrestrial habitats is essential to all forms of life. Antarctica also differs from the Arctic in not having any major river systems. Surface streams and flowing waters are mostly fed by seasonal glacial meltwater and restricted to the coastal oases. The largest river, the Onyx River in the McMurdo Dry Valleys, is just 32 km long with recorded flows of 0.01 m^3S^{-1} to a single flood event of 30 m^3S^{-1}(McKnight et al 2008). The rivers often flow for just a few weeks each year, but in this time supply lakes with freshwater and provide seasonal wetted areas that support a diversity of microbial communities. However, in comparison with the Arctic, the rivers provide only very minor discharges of freshwater to the global ocean compared with the contribution from calving glaciers and subglacial meltwater.

The instrumental record of changes in Antarctic hydrology and freshwater ecosystems is relatively short with many datasets limited to individual field seasons in locations near to semi-permanent scientific facilities. Nevertheless, a number of national programmes have maintained long term monitoring stations for up to 15-18 years (Quayle et al 2002; Lyons et al 2001) and data mining of single year datasets has allowed other parameters to be compared over similar timescales (Verleyen et al., in press).

As with the Arctic systems, the focus in many of these field studies has been the response of Antarctic lakes and hydrology to the rapid warming recorded in some parts of Antarctia in recent decades (Turner et al. 2009). The response in lakes partly depends on their thermal proximity to freezing, which applies critical limits to environmental responses including ice extent, snow cover, light availability, and albedo. Monitoring of Signy Island lakes (maritime Antarctic) from 1980 to 1995 indicates that the local climate increase of 2°C over the past 40 to 50 years has reduced both permanent terrestrial ice cover and albedo and extended open-water periods by up to 63 days allowing the water and sediments to absorb more solar energy which has further warmed the lakes during winter (Quayle et al 2002). As a result chlorophyll a concentrations show summer phytoplankton levels significantly increased in seven of nine oligotrophic lakes measured, and means rose from 1.4 mg/litre in 1981 to 3.5 mg/litre in the mid-1990s (maximum 6.8 mg/litre in 1995). More recently, streams have accumulated higher nutrient concentrations (especially dissolved reactive phosphorus (DRP) which increased 5 times and ammonium which increased 2.5 times) by draining exposed fell-field soils and thawed ground. Increased plant and microbial activity has also resulted in elevated autochthonous carbon production in lakes, much of which accumulates in the sediments. Thawing of permafrost in lake catchments has also been recorded elsewhere in Antarctica, increasing nutrient loads in subsurface waters and lake inflows (Burgess et al. 1994) and altering lake trophic status (e.g. Laybourn-Parry, 2003).

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

In the absence of long-term datasets it is necessary to rely on the palaeolimnological record to identify whether recent changes have occurred, and how these compare with long term natural variability (Hodgson et al. 2004). This involves studying the suite of physical, chemical and biological markers deposited in lake sediments which act as proxies of environmental changes over time. For example studies on Signy Island have shown that an increase in lake sediment accumulation rates since the 1950s corresponds with the measured increase in atmospheric temperature (Appleby et al. 1995). Similar increases in sediment accumulation rates have been recorded in some nearby high-resolution marine cores (Domack et al. (2003). In the Windmill Islands (East Antarctica) palaeolimnological records show that some lakes have recently become more saline (Hodgson et al., 2006), and a number of ancient moss banks in the same region have become desiccated (Wasley et al., 2006); possibly in response to the increased wind speeds observed in some East Antarctic coastal regions that would have increased evaporation and sublimation rates. A number of palaeolimnological studies have tracked past changes in the precipitation evaporation balance in detail through the Holocene (Roberts et al. 1999, 2004, Verleyen et al., 2004, Hodgson et al., 2005). From these studies the impact of these changes on other parts of the lake ecosystem can be interpreted through a range of proxies. Whilst the recent rapid warming has been recorded in some palaeolimnological proxies, few studies have focused on this period in the proxy records at sufficiently high resolution to determine if the changes are outside of the natural variability of the Holocene.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

Global warming affects marine ecosystems of the Arctic and its neighboring seas by: (1) altering the timing and extent of sea ice retreat, (2) changing sea water density through freshening from the melting of glaciers and increased runoff, (3) reducing sea ice thickness an multi-year ice formation which in turn changes the timing and duration of irradince in the water column (Stabeno 2010, Wassmann 2011a).

Recent observations and model predictions indicate that the Arctic Ocean is vulnerable to ocean acidification. The acidification of the Arctic means that some regions of the Arctic will be understaturated with respect to calcite and aragonite, the primary structural component of the shells of crustacean organism (Steinacher et al. 2009, Yamamoto-Kawai et al. 2009, Chierici and Fransson 2009). The freshening of the waters in the Canadian basin due to glacial runoff and thawing permafrost is likely to accelerate the decrease in pH and the appearance of understaturated waters in the arctic (Denmann et al 2011). These factors are expected to cause added stress to marine organisms of the Arctic.

Climate change impacts the timing and magnitude of primary production. Two sources of primary production include spring and fall ice algal blooms and pelagic blooms in response to the solar cycle and stratification (Wassmann 2011a). 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 (Reigstad et al. 2002; Wassmann et al. 2006). Pelagic grazers are less abundant in the Arctic Ocean due to the short growing season and much of the production is deposited on the sea floor (Zhang et al. 2010). Satellite derived estimates of primary production provide evidence of increased primary production in response to extended ice free periods during summer have been documented (Arrigo 2008). Factors that alter sea ice thickness, the date of ice breakup and stratification will alter the timing, duration and magnitude of summer production (Zhang et al. 2010).

Large copepods (pelagic crusteceans that are a major prey of fish) tend to dominate the Arctic with regional differences in species composition. These copepods occupy different regions of the Arctic and they exhibit different strategies for survival. *Calanus finmarchicus* are common in the Barents Sea, *Calanus glacialis* dominates the western shelf along the Canadian basin and the White Sea, and *Calanus hyperboreus* is a deep water species found in the Greenland Sea, Fram Strait, the Labrador Sea, the Baffin Sea and the Arctic Ocean Basin (Falk-Petersen 2009), and *Calanus marshallae* has been reported in the southeastern Bering Sea middle domain *(*Baier and Napp 2003*)*. *Metridia longa* has been observed in the Beaufort Sea. These large copepods use different strategies to overwinter. *M. longa* continues feeding and remains active through the winter (Suethe et al. 2007). It is hypothesized that Calanus is able to overwinter on the shelf of the southern Bering Sea and it is known to overwinter in deeper waters over the slope of the northeast Norwegian Sea (Gaarsted et al. 2011). *C. hyperboreus* undergoes diapause to save energy during winter (Suethe et al. 2007). Farther north, the initiation of spring primary production may be delayed due to the persistence of sea ice and the light cycle. Zooplankton blooms are also delayed until July and August (Falk-Petersen et al. 2009, Wassmann 2011a). The delay in the emergence of zooplankton results in underutilization of early spring production which in turn leads to deposition of carbon on the seafloor where it feeds a productive benthic ecosystem (Grebmier et al. 2006). Factors that alter the timing and duration of phytoplankton production could disrupt the match between copepod hatch dates and spring production which in-turn would impact the survival of zooplankton and timing of spring prey availability for their predators (Soreide et al. 2010).

Krill (*Thysanoessa sp*.) are an important component of marine ecosystems representing an important prey item of several dominant pelagic fishes in the region (Orlova et al. 2009, Ressler et al. In Press). In the Chukchi and Beaufort Seas, euphausiids (*T. inermis and T. raschii*) have been observed but are not considered endemic to the region (Berline et al. 2008). In the Barents Sea a variety of euphausiids have been observed including *T. inermis* and *T. longicaudata*. Examination of the size and life stage of krill revealed that euphausiids are probably advected into the Arctic from the Bering Sea and intrusions of Atlantic water (Berline et al 2008, Dalpadado et al. 2008). Factors that influence the water temperature and the speed and direction of currents through Bering and Fram Straits are likely to influence the availability of euphausiids in the Chukchi Sea and Beaufort Sea regions.

The broad shelf regions of the Barents and Bering Seas support abundant and diverse fish and shellfish populations. Farther north, fewer fish species are adapted to the short growing season, the delay in the emergence of copepods and the cold ocean conditions. In general, dominant pelagic species are smaller sized fish capable of rapid growth in the first year of life with an eclectic diet (e.g. capelin, *Mallotus villosus*) and in some cases antifreeze proteins to tolerate cold temperatures (e.g. polar cod, *Boreogadus saida*). Examination of the biogeography of species shows that potentially interacting species partition their habitat vertically and horizontally in response to competition, predation and environmental disturbance (Mueter and Litzow 2008, Spencer 2008). Habitats are bounded by topographic features, fronts, currents or river plumes, and oceanographic features left by sea ice including salinity fronts, and the cold water mass that forms in summer along the sea floor in the Bering Sea (the cold pool) (Logerwell et al. 2010, Norcross et al. 2010, Hollowed et al. in review). 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 (Hunt et al. 2011, Hollowed et al., In Review, Bouchard and Fortier 2011, Sundby and Nakken 2008). Examination of historical responses of fish to climate shifts and associated changes in ocean conditions suggests that climate change will impact the growth, spawning and feeding distribution and potentially will cause shifts in species dominance (Gjøaeter et al. 2009, Drinkwater 2011).

28.2.2.2. Antarctic

28.2.2.2.1. Southern Ocean

Most long-term integrated ecosystem research in the Southern Ocean has occurred since the 1980s. Novel analyses of pre-satellite-era data have revealed probable changes in ocean and sea ice habitats since the late 1940s, including an increase in mid-water ocean temperature (Gille 2008) and an overall 20%-30% reduction in the extent of sea ice (de la Mare 1997; Curran, Ommen et al. 2003; de la Mare 2009). Concomitant with these changes was the sequential industrial overexploitation of many whale species in the Southern Ocean and benthic finfish (Kock, Reid et al. 2007). Antarctic fur seals had been nearly extirpated in the 1800s and a number of other subantarctic seal species, such as elephant seals, had been heavily exploited. As a result, ecosystem change since that time might not only be because of change in the physical environment but also because of trophic changes due to over-exploitation of many top predators and the subsequent recovery of some of them (Ainley, Ballard et al. 2007; Nicol, Croxall et al. 2007; Trathan and Reid 2009).

Since the late 1970s, the advent of satellite remote sensing along with other intensive field and ship-based observations have enabled significant changes to be detected, including increased westerly winds (Turner, Comiso et al. 2009) as well as a southward shift in their location due to an increase in the Southern Annualar Mode toward positive values since the 1960s (Turner, Bindschadler et al. 2009), regional differences in sea ice extent, along with differences in the timing of its advance and retreat (Stammerjohn, Martinson et al. 2008; Turner, Comiso et al. 2009), abrupt loss of ice shelves (Cook, Fox et al. 2005; Cook and Vaughan 2010), freshening of the bottom water indicating a freshening of the surface waters near to the continent, a southward shift in the ACC fronts, along with a changed eddy field (Meredith and Hogg 2006; Sallee, Speer et al. 2009; Sokolov and Rintoul 2009), and an increase in ocean acidification (Turner, Bindschadler et al. 2009).

The most obvious change in habitat across the Southern Ocean has been in the seasonal distribution of sea ice. Sea ice is an integral part of Southern Ocean ecosystems because it structures the habitat, provides food resources and refugia, and affects reproductive cycles, recruitment, and foraging behavior for a wide range of species. There have been rapid changes in sea ice dynamics over the last 30 years, but there is also marked regional variation: for example, sea ice has declined in the Antarctic Peninsula region, but has increased in the Ross Sea. Overall, sea ice extent is thought to have actually increased since the 1970s, despite the reduction in the Antarctic Peninsula region (Turner, Comiso et al. 2009). These changes have been linked to regional warming and changes in the wind stress pattern associated with SAM and are already resulting in modifications to regional food webs (Montes-Hugo, Doney et al. 2009; Trathan, Fretwell et al. 2011; Trivelpiece, Hinke et al. 2011).

The west Antarctic Peninsula (wAP) is one of three areas of the globe experiencing rapid climate change. Sea ice seasons are now much shorter,winds, cloud cover as well as air and ocean temperatures, have increased (Clarke, Murphy et al. 2007; Ducklow, Baker et al. 2007), and aspects of biological activity have been observed to have shifted south, including for primary production, krill and Adélie penguins (Trivelpiece, Hinke et al. 2011). Indeed, emperor penguin are now thought to have abandonded one of their most northerly breeding sites (Trathan, Fretwell et al. 2011). (see box - wAP)

The Ross Sea generally has the greatest productivity in the Southern Ocean (Arrigo, Worthen et al. 1998; Arrigo, van Dijken et al. 2008). In the western margins and in the area towards the Balleny Islands the extent of sea ice has not changed appreciably over the last 70 years but may have been increasing since the late 1970s (Stammerjohn, Martinson et al. 2008; Turner, Comiso et al. 2009). This contrasts the other regions, perhaps making it a refuge for biota from climate change impacts.

In the vicinity of Prydz Bay and the Kerguelen Plateau, three main climate change signals have been observed – a significant reduction in the maximum sea ice extent bordering the continent, warming of the Polar Frontal Zone, and movement of the Polar Front to the south (Sokolov and Rintoul 2009). Despite these changes, there are few data available on time trends of abundance or dynamics of populations in the lower trophic levels for these regions.

Modifications to the depth of the upper ocean mixed layer impacts on the upwelling of micro- and macronutrients into the upper ocean and hence the availability of these to phytoplankton for primary production. It also influences the vertical flux of natural carbon and anthropogenic carbon, and vertical exchanges of marine organisms.

Across the Southern Ocean, waters are also becoming more acidic as anthropogenic carbon dioxide is absorbed. As CO_2 is more soluble in the cold polar waters, the Southern Ocean is likely to be one of the oceans where we will see the most rapid future changes in ocean acidification (Guinotte, Orr et al. 2006). Acidification of Southern Ocean waters will potentially impact nutrient and alkalinity cycles, formation of carbonate particles, and plankton community structures. Observed changes already include reduced thickness of shells in foraminifera (Moy, Howard et al. 2009). Acidification impacts on zooplankton are currently uncertain, but laboratory experiments suggest krill may be vulnerable (Kawaguchi, Kurihara et al. 2011).

Antarctic krill is the dominant consumer of phytoplankton in large parts of the Southern Ocean. Its importance varies throughout the Southern Ocean, dominating in the Atlantic sector (Nicol, Constable et al. 2000; Murphy, Watkins et al. 2007; Atkinson, Siegel et al. 2009). In this area, other invertebrates and mesopelagic fish are only important as prey for upper trophic levels following years when krill biomass is reduced (Murphy, Watkins et al. 2007; Waluda, Collins et al. 2010). In the soutwest Atlantic, Antarctic krill are found on the continental shelf, whereas in other areas is more oceanic (Atkinson, Siegel et al. 2009). In the Ross Sea, particularly along the western margins, crystal krill and the Antarctic silverfish are also important prey species over the shelf area (Smith Jr., Ainley et al. 2011). Antarctic krill is important in the north west of this area near to the Balleny Islands. In the area around Prydz Bay and the Kerguelen Plateau, Antarctic krill is important south of the Southern Boundary of the Antarctic Circumpolar Current (Nicol, Pauly et al. 2000) but copepods and myctophid fish dominate to the north of that on the Kerguelen Plateau (Pruvost, Duhamel et al. 2005). In Prydz Bay, the third largest embayment in Antarctica, crystal krill are important along with Antarctic silverfish (Hosie 1994). Notably, this area has a mix of the shelf, Antarctic krill and myctophid fish foodwebs.

Antarctic krill tend to consume larger diatoms whereas other herbivores, such as salps and copepods exploit smaller size classes. These larger diatoms are found throughout the Southern Ocean but restricted to areas where there are sufficient quantities of iron and silica, the latter of which is the foundation of their skeleton. The other main group to form blooms is *Phaeocystis*, which is found to dominate in the Ross Sea. Krill larvae are thought to be dependent on the sea ice communities in late winter (Marschall 1988).

The prognosis for Antarctic krill overall is ambigous because of the regional variation of factors that could impact directly on krill both positively and negatively and because of their ability to adapt physiologically and behaviourally. Recently, it has been shown that krill can exploit the full depth of the ocean, thus their potential habitat is far greater than once thought (Schmidt, Atkinson et al. 2011). The combined effects of changing sea ice conditions and its possible effects on productivity as well as on krill survivorship, reproduction and recruitment remain to be investigated. As well, new research is showing that the survival of larval krill may be negatively affected by increasing ocean acidity (Kawaguchi, Kurihara et al. 2011).

In the Scotia Sea, Antarctic krill are believed to have declined in abundance since the 1980s (Atkinson, Siegel et al. 2004). The sea ice extent and duration of cover are now shorter, with the area likely to have experienced the greatest reduction in winter sea ice extent of all areas in the Southern Ocean since the 1950s. The switch from a krill-based food web to a copepod- and fish-based food web in times of low abundance of krill suggests that the latter may become more dominant in the future (Trathan, Forcada et al. 2007; Shreeve, Collins et al. 2009). Also, salps have been postulated to be competitors with krill for phytoplankton when oceanic conditions displace shelf and near-shelf waters (Loeb, Siegel et al. 1997).

Organisms inhabiting the polar oceans differ from those in the rest of the world's oceans because they are adapted to colder conditions and many have a dependency on the annual advance and retreat of the sea ice. As the sea surface warms, pelagic species will naturally migrate southward, as expected, for example, from the close relationship of zooplankton assemblages with the different frontal zones (Hunt and Hosie 2005); however, given the complexity of land forms and ocean circulation in some regions, changes in distribution may be more complex, limited by both circulation and primary productivity (Trathan and Agnew 2010). Furthermore, benthic species may also be restricted in their capacity for such migration, particularly for those in the subantarctic. Bentho-pelagic species such as notothenid and channichthyd fish are cold-adapted and many are restricted to shallow (< 500 m) shelf areas around subantarctic islands. There is no evidence to date of impacts on these distributions.

Higher predators are considered to integrate across variation in population processes of lower trophic levels. Some key trends (in distribution and abundance) in bird populations (penguins and flying birds) have been linked to climate change impacts. Upper-trophic level responses to climate variability and climate change have been considered at a regional and circumpolar scale with population responses recorded for a variety of species, principally to indices of ENSO, SOI and the SAM (Trathan, Forcada et al. 2007). Individual studies show predators exhibit strong responses to these climate indices, with many, but not all, species showing a negative response to warmer conditions (Fraser, Trivelpiece et al. 1992; Barbraud and Weimerskirch 2001; Barbraud and Weimerskirch 2001; Barbraud and Weimerskirch 2003; Fraser and Hofmann 2003; Jenouvrier, Barbraud et al. 2003; Forcada, Trathan et al. 2005; Jenouvrier, Barbraud et al. 2005; Jenouvrier, Weimerskirch et al. 2005; Forcada, Trathan et al. 2006; Trathan, Murphy et al. 2006; Trathan, Forcada et al. 2007).

A number of studies have highlighted how ice-dependent marine mammals and seabirds, notably Adélie penguins, have declined in the West Antarctic Peninsula region and those that are not ice-adapted, e.g. the gentoo penguins, have increased (Trivelpiece, Hinke et al. 2011). In contrast, Adélie penguin populations are increasing in the Ross

Sea (Smith Jr., Ainley et al. 2011) and eastern Antarctica (Nicol and Raymond 2011) where sea ice conditions in summer are closer to their long term average.

Not all changes will be due to environmental change. For example, albatross and petrels have been declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall, Trathan et al. 2002). Also Antarctic fur seals have been recovering from their near extirpation since the early 1900s; their substantial recovery occurred from the 1950s onwards during the period of reduction in sea ice extent in the region. Baleen whale populations are also beginning to increase after near extinction in the 20th Century (Nicol, Worby et al. 2008).

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

Long term downward trends in the populations of marine mammals and birds in the subantarctic of the Indian sector of the Southern Ocean have been interpreted as a region-wide shift to a system with lower productivity (Weimerskirch, Inchausti et al. 2003; Jenouvrier, Weimerskirch et al. 2005; Lea, Guinet et al. 2006). Similarly, studies of bird populations on the coast of Adélie Land have shown declines in abundance and shifts in their breeding phenology, which have been assumed to be related to climate change impacts (Croxall, Trathan et al. 2002; Jenouvrier, Barbraud et al. 2005; Jenouvrier, Barbraud et al. 2005; Jenouvrier, Weimerskirch et al. 2005; Barbraud and Weimerskirch 2006; Jenouvrier, Caswell et al. 2009). While large seabirds, such as albatross and petrels, may have lesser constraints over the areas they forage within during the breeding season, they still show significant responses to climate variability (Pinaud and Weimerskirch 2002; Barbraud and Weimerskirch 2003; Inchausti, Guinet et al. 2003; Jenouvrier, Barbraud et al. 2005; Olivier, van Franeker et al. 2005; Barbraud and Weimerskirch 2006; Nevoux and Barbraud 2006; Barbraud, Marteau et al. 2008; Rolland, Barbraud et al. 2008; Rolland, Barbraud et al. 2009; Rolland, Nevoux et al. 2009; Nevoux, Forcada et al. 2010; Nevoux, Weimerskirch et al. 2010; Peron, Authier et al. 2010; Rivalan, Barbraud et al. 2010; Rolland, Weimerskirch et al. 2010; Barbraud, Rivalan et al. 2011).

Changes in the distribution and abundance of land-based marine predators in Antarctica will not be solely related to the locations of important prey. Breeding site availability can influence the locations of predator foraging areas, which need to be near to colonies in summer. While a number of areas in the Antarctic and peri-Antarctic islands have become ice-free during the breeding season of penguins, these areas have not been exploited as breeding habitat, possibly due to the philopatric breeding habits of some penguins. However, gentoos have increased their breeding range in many areas of the Antarctic (Forcada and Trathan 2009) possibly because they are more flexible in their breeding habits. Also, there may be density dependent impacts at breeding sites and these may mask other signals related to climate change (Reid and Forcada 2005).

Importantly, changes in distribution and range of land-based predators may not be linear. Ocean currents are limited by bathymetry, but changes to ocean structure may mean that oceanography could alter in unpredictable ways. Profitable foraging areas close to available breeding habitat may not be available or preferred prey species may not be accessible from existing breeding sites (Trathan, Forcada et al. 2007).

28.2.2.2.2. West Antarctic Peninsula

The Antarctic Peninsula region has warmed at a rate of 3.7 ± 1.6°C (century)$^{-1}$, which is several times the rate of global warming (Vaughan, Marshall et al. 2003). As a result, winter temperatures have warmed by almost 6°C since the mid-part of the 20th century (Stammerjohn, Martinson et al. 2008), which has resulted in reductions in seasonal sea ice extent and a shorter (by almost 3 months) winter sea ice season (Smith and Stammerjohn 2001; Stammerjohn, Martinson et al. 2008). In the adjacent surface ocean, summer temperatures have increased by more than 1°C and upper ocean salinity has increased. Coincident increased storm frequency and wind strength have deepened the upper ocean mixed layer and increased cloudiness has altered the amount of shortwave radiation reaching the ocean surface. These changes in the marine habitat now ongoing are having significant effects that are impacting all tophic levels of the western Antarctic Peninsula (wAP) marine food web (Massom, Stammerjohn et al. 2006).

The focal point of the present day wAP food web is Antarctic krill (*Euphausia superba*), which is dependent on sea ice for reproduction, survival and recruitment (Atkinson, Siegel et al. 2004; Atkinson, Siegel et al. 2008). This keystone species provides the linkage between lower and upper trophic levels and the flux of nutrients and carbon through Antarctic krill is an important regulator of biogeochemical cycling on the wAP continental shelf (Holm-Hansen, Naganobu et al. 2004). Thus, changes in the biomass or production of Antarctic krill are immediately felt throughout the food web, changes in the lower and upper trophic levels are transmitted through the food web via linkages with Antarctic krill, and rates of biogeochemical cycling are altered.

Analyses of satellite-derived ocean color and *in situ* measurements obtained for the wAP continental shelf waters between 1976-2006 suggested that the annually integrated chlorophyll concentration has declined by 12% and that the maxima in chlorophyll concentration has shifted to higher latitudes. The reduction in chlorophyll was attributed to increased mixed layer depth (producing lower mean light levels) resulting from longer exposure to stronger winds because of reduced sea ice. The chlorophyll maximum at higher latitude was in a region that still had substantial winter sea ice cover.

Reduced sea ice has been suggested as one of the causes that may be responsible for a decline in Antarctic krill biomass n the South Atlantic sector of the Southern Ocean in the past 40 years (estimated to be 30% decline by Atkinson et al. (2004)). This decline has been accompanied by an increase in gelatinous zooplankton (salps) which are known to dominate in regions of the wAP during times of low sea ice (Loeb, Siegel et al. 1997; Ducklow, Baker et al. 2007). Also, a reduction in krill biomass can potentially allow other copepod species and mid-trophic level organisms (small myctophid fish) to dominate and provide food for higher trophic levels (Waluda, Collins et al. 2010). However, the trophic efficiency of the longer food web is less (Murphy, Watkins et al. 2007) and the long-term implications of this for higher trophic levels are unknown.

The large and persistent populations of predators (e.g. Adélie penguins, crabeater seals) in the wAP region have life histories that are dependent on sea ice and exploit Antarctic krill as a primary prey item. The penguin populations of the wAP have shown a clear change in community composition over the past three decades, with the ice-dependent Adélie penguin being replaced by the ice-intolerant gentoo penguins (Trivelpiece, Hinke et al. 2011). These trends have been attributed to decreased winter sea ice (Fraser, Trivelpiece et al. 1992; Ducklow, Baker et al. 2007) and increased snow precipitation which accumulates in the breeding colonies (Patterson, Easter-Pilcher et al. 2003). Increased wetting of chicks in the colonies due to increase precipitation has been shown to significantly decrease survival, especially when accompanied by reduced food supply (Chapman et al., in press). The reduced winter sea ice has presumably reduced the supply of Antarctic krill within the foraging area of the Adélie penguin and also its alternate prey the Antarctic silverfish, also an ice-dependent species (cf. Forcada et al. (2006)).

The decrease in sea ice and sea ice extent along the wAP will limit the available breeding and foraging habitat for crabeater seals and possibly its primary prey (Ducklow, Baker et al. 2007; Costa, Huckstadt et al. 2010). Projections are that these seals will decline and be replaced by southern elephant seals and/or other seal species that are not dependent on sea ice (Costa, Huckstadt et al. 2010).

Baleen whales (humpback and minke) in the wAP feed primarily on Antarctic krill (Kawamura 1994) and some (minke whales) are found only in pack ice habitat (Kawamura 1994; Beekmans, Forcada et al. 2010). Recent analyses have indicated that there is little niche overlap between baleen whale species in this region (Friedlaender, Lawson et al. 2009). However, changes in habitat structure and the abundance of their primary prey will affect the distribution and abundance of these top predators. Thus, krill predators with historically little niche overlap may have increased potential for interspecific competition for shared prey resources (Friedlaender, Lawson et al. 2009).

The changes in the physical habitat of the wAP are believed to be resulting in a shift of the krill-dominate food web to higher latitudes and the replacement of this food web at lower latitudes with one composed of species that that do not depend on sea ice and are more able to exploit a range of prey items, for example gentoo penguins (Trivelpiece, Hinke et al. 2011). This shift may be accompanied by an overall decline in the productivity of the wAP shelf

(Montes-Hugo, Doney et al. 2009). However, a modeling study of the effect of increased winds and decreased sea ice on the circulation dynamics of the wAP continental shelf indicated that iron associated with increased inputs of oceanic waters to the shelf could significantly affect biological productivity of the region (Dinniman et al., submitted). Thus the effects on the wAP marine food are not likely to be simple responses to stronger winds, decreased sea ice or modified species assemblages. The ability to project these future changes remains as a significant challenge and an important area for future research.

28.2.2.2.3. East Antarctica and Kerguelen Plateau

The East Antarctic sector of the Southern Ocean (30-180^{o}E) has not been as intensively studied as the South West Atlantic consequently physical, chemical and biological changes are less well documented. In winter the region is covered by extensive sea ice and has not experienced the recent sea ice loss experienced by the Antarctic Peninsula region. There are suggestions that winter sea ice extent may well have increased over the last 30 years (Vaughan, Marshall et al. 2003; Parkinson 2004). There is evidence of changed conditions in the deep ocean with a freshening and warming of deep waters (Rintoul 2007). There is little documented evidence of changes in surface oceanographic conditions. Increased intensity of westerly winds is thought to have increased mixing and to have intensified some elements of the Southern Ocean Current systems as well as changes in frontal positions (Sokolov and Rintoul 2009).

Changes in the distribution, abundance and species composition of the primary producers have been documented in some areas of the Southern Ocean off East Antarctica but there are not the strong and persistent changes that have been observed in other areas.

Much as in the South Atlantic, the focal point of much of the East Antarctic food web south of the ACC is Antarctic krill (*Euphausia superba*), which is dependent on sea ice for reproduction, survival and recruitment (Atkinson, Siegel et al. 2004; Atkinson, Siegel et al. 2009). The populations of krill off East Antarctica are smaller than those in the South Atlantic (Atkinson, Siegel et al. 2009). In the East of this region the krill population is coastally constrained whereas in the 30E region krill extend much further northward into oceanic waters (Jarvis, Kelly et al. 2010). Other food webs exist in much of the oceanic areas, around the subantarctic islands and on the continental shelf. The relationship between krill population size and sea ice extent has been demonstrated on a regional scale (Nicol, Pauly et al. 2000) but there are no time-series data from East Antarctica that demonstrate a temporal link between annual sea ice extent and krill production and recruitment.

There have been a number of studies suggesting changes in the planktonic community over the last 50 years with suggestions of significant shifts in the zooplankton community (Takahashi, Tanimura et al. 1998).

The large and persistent populations of predators (e.g. Adélie penguins, crabeater seals) in the East Antarctic region have life histories that are dependent on sea ice and exploit Antarctic krill as a primary prey item. Numbers of some species of penguins and seals have declined whereas some have increased and there is no clear signal in the environment that can unambiguously linked to these population changes (Barbraud and Weimerskirch 2001; Weimerskirch, Inchausti et al. 2003). The subantarctic islands of the Eastern sector are not home to krill-based ecosystems and changes in the population sizes of seal species there appear more likely to be a result of recovery from past exploitation (Goldsworthy, McKenzie et al. 2009).

Baleen whales (humpback, fin, blue and minke) off East Antarctica feed primarily on krill (Kawamura 1994) and some (minke whales) are found only in pack ice habitat (Kawamura 1994; Beekmans, Forcada et al. 2010). Recent analyses have indicated that populations of humpbacks that breed off Australia and feed off East Antarctica, are increasing quite rapidly suggesting that food availability is currently not limiting (Zerbini, Clapham et al. 2010). However, changes in habitat structure and the abundance of their primary prey may well affect the distribution and abundance of these top predators. There is insufficient information on the changes in population sizes of any of the other species of whales off East Antarctica (Nicol, Worby et al. 2008).

Physical and chemical changes that are likely to affect ecosystems in the next few decades included ocean acidification, ocean warming and changes in sea ice distribution, extent, rates of advance and retreat and ice type (Nicol, Worby et al. 2008). The ecological ramifications of these changes are uncertain. Changes in winter sea ice extent in areas where there has always been little sea ice may have a more pronounced ecological effect than proportional declines in areas where there has historically been extensive sea ice in winter. The East Antarctic marine system has extensive sea ice in winter and large areas of open ocean in summer and these characteristics will influence how the ecosystems respond to future changes. Additionally, the subantarctic islands in this region are known to be getting warmer with associated glacial melt and these ecosystems will change somewhat differently from others around the Southern Ocean. It may well be that with warming, the South Atlantic islands with their krill-based systems may come to resemble more the ecosystems of the Indian Ocean sector (Trathan, Forcada et al. 2007).

28.2.2.2.4. Ross Sea

to be done later

28.2.3. Terrestrial Environment and Related Ecosystems

28.2.3.1. Disappearance of Tundra

Remote sensing data reveal that tundra vegetation in North America may be responding to the recent warming via enhanced photosynthetic activity (Verbyla, 2008). At a circumpolar scale, the highest photosynthetic activity and strongest growth trends are reported in locations characterized by erect shrub tundra (Raynolds et al., 2006, 2008). In the Russian Arctic, ground-level quantification of increasing deciduous shrub growth comes from the abundant and nearly circumpolar erect 'woolly willow' (*Salix lanata* L.). Analysis of annual growth in this shrub reveals remarkably high correlations with summer temperature at long distances (>1600 km) across the tundra and taiga zones of West Siberia and Eastern Europe (Forbes et al., 2010). Such correlations are extremely useful as proxies for reconstructing past climates, particularly since the loss of a reliable temperature signal in northern boreal forests (D'Arrigo et al. 2008). The growth of woolly willow also demonstrates a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981–2005 (Forbes et al., 2010), confirming a parallel ‘greening’ trend reported for similarly warming North American portions of the tundra biome (Tape et al. 2006; Verbyla, 2008; Walker et al. 2009). The data strongly indicate that low shrub thickets can transform *in situ* to erect shrub/forest. This process has the potential to contribute substantially to the disappearance of tundra without the northward migration of coniferous forest projected by ACIA (2005), IPCC (2007) and SWIPA (2011). Edwards et al. (2005) similarly argue, based on pollen and macro fossil data from E Siberia and NW Canada, that *deciduous* boreal forest should be included in the range of future scenarios used to assess the probable feedbacks of vegetation to the climatic system that result from warming at northern high latitudes. There is evidence from Fennoscandia that heavy grazing by reindeer may significantly check deciduous low erect shrub growth (Kitti et al., 2009; Olofsson et al., 2009), and so help prevent the disappearance of tundra. However, in cases where high erect shrubs are already above the reindeer browse line of ≈1.8 m, their transformation into tree size individuals is likely to track warming temperatures rather than grazing intensity (Forbes et al., 2010).

28.2.3.2. Status and Current Changes in Arctic Seabird Populations

More than 40 species of seabirds breed regularly in the Arctic and some of the worlds largest seabird populations are found in the region (Murray, 2008). An assessment of the trends and status of 37 species in 214 different populations of Arctic marine birds over a 34 year period, showed overall a relatively stable pattern (McRae *et al*., 2010). Some species’ like the common eider (*Sommateria mollisima*) and guillemots (*Uria sp*) have been declining substantially in recent decades (McRae *et al*., 2010). The ivory gull (*Pagophila eburnea)* (Gilchrist and Mallory, 2005) and the spectacled eider (*Sommateria fischeri*) populations have declined to such an extent that they have been classified as threatened according to the IUCN Red List.

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. Temporal or spatial variability in these oceanographic conditions or SST caused by interannual changes in weather or oscillations in climate on decadal scales like the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO), are common in the Arctic and strongly affect the dynamics of seabird populations (i.e.(Irons *et al*., 2008)). Life history characteristics as longevity, maturation at a late age, low annual fecundity, heavy investment in few offspring, high adult annual survival rates, and generalist feeding behavior, are all considered adaptation by arctic seabirds to a highly spatiotemporal variable prey base.

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). Seabirds are highly mobile outside the breeding season and are able to exploit concentrations of prey where they are found. During the breeding season, however, they must forage within 200 km of their colonies and are, consequently, much more vulnerable to spatial changes in prey availability.

Such spatial mismatch between prey base and breeding has been documented for only a few seabird populations. The percentage of Arctic Cod in the diet of a declining black guillemot (*Cepphus grylle*) population on Cooper Island in the western Beaufort Sea was highly negatively correlated with the distance to the ice edge which is the habitat of arctic cods (Moline *et al*., 2008). In this area the sea ice extent decreased by 50% since the 1979ties.

Even though timing of breeding advanced for Brünnichs guillemots (*Uria lomvia*) in a colony in the southernmost part of its range in Arctic Canada over a 25 years period, it did not advance sufficiently to match the advance in break up of sea ice which is associated with high prey availability (Gaston *et al*., 2005). Decreasing proportion of breeding females and a mismatch with the chick rearing period was the result of later spawning of capelin (Gaston *et al*., 2009). Lower 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. In a colony of the species' northernmost range sea ice cover did not change and the breeding population was stable. Gaston et al. (2005 and 2009) concluded that current trends suggest that continued warming should benefit birds breeding on the northern limit of the species range, while adversely affecting reproduction for those on the southern margin.

In contrast, Byrd et al (Byrd *et al*., 2008) could not document any significant correlation between productivity of brünnichs guillemots and common guillemots (Uria aalgae) breeding on the Pribilof islands in the Bering Sea and changes in sea ice extent over a 30 year period. Kittiwakes (*Rissa tridactyla and Rissa brevirostris*), however, breeding in colonies on the same islands, advanced their timing of breeding by half to almost one day per year and reduced their productivity in correlation with less sea ice and higher 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).

General cooling or warming of sea surface temperatures affects the prey base of Arctic sea birds, and, consequently, has the potential to influence the populations. 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). They suggested that the reaction to climate change by guillemots is caused because guillemots are sensitive to abrupt change in the environment throughout their ranges. A major ecosystem shift in the Northern Bering Sea ten years ago caused by increased temperatures and reduced seaice cover had a negative impact on benthic prey for diving birds like eiders and these populations in the area have declined (Grebmeier *et al*., 2006).

The little auk (*Alle alle*) is one of the most abundant seabird species in the Arctic. It is endemic to the region. As a specialist on *Calanus* copepods, little auks are one of few Arctic seabird species that are not an apex predator and generalistic feeder. During the breeding season they prefer large fat-rich copepod species'(small crustaceans) that are found in cold or ice-covered Arctic waters (Karnovsky *et al*., 2010). By using a coupled atmosphere–ocean global climate model (AOGCM), 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 breeding colonies in the North Atlantic may be negatively impacted as temperatures exceed the thermal preferenda of large *Calanus*. Little auks in Svalbard also responded by advancing the date for egg-laying when SSTs increased and seaice cover was reduced (Moe *et al*., 2009).

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

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

A general increase in SSTs and retreat of the ice cover will likely improve the environmental conditions and food abundance for sea bird species that have their range in the southern part of the Arctic or south of the Arctic. A poleward expansion of the range of these species is expected during a continued warming (ACIA 2005). Several other factors than climate influence on the dynamics of sea bird populations (Regular *et al*., 2010), however, and projections of future changes during a continued Arctic warming are therefore 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

28.2.3.3. Polar Bears

The understanding, documentation, and projection of the impacts of climate change on polar bears (*Ursus maritimus*) has developed extensively in recent years with both empirical and modelling studies (Laidre et al. 2008, Durner et al. 2009, Hunter et al. 2010, Amstrup et al. 2010, Molnár et al. 2011). While empirical studies provide the most direct insight into the mechanisms of change, modelling studies based on empirical observations allow a more complete understanding of conservation status into the future.

Sea ice is the primary habitat of polar bears and is used as the surface for migration, mating, some maternity denning, and for access to their prey (DeMaster and Stirling 1981). The annual sea ice over the continental shelves is the preferred habitat of polar bears due to higher density of prey than offshore areas (Stirling et al. 1993, Frost et al. 2004, Durner et al. 2009). Changes to annual ice over continental shelves is the primary concern for the conservation status of polar bears (Stirling and Derocher 1993, Derocher et al. 2004, Stirling and Parkinson 2006, Hunter et al. 2010). There is high agreement and robust evidence that the primary issue for polar bears is the recent and projected loss of annual sea ice over continental shelf areas, decreased sea ice duration, and decreased sea ice thickness (Derocher et al. 2004, Durner et al. 2009, Amstrup et al. 2010).

Of the nineteen subpopulations of polar bears in the circumpolar Arctic, long-term data series adequate for clear identification of subpopulation-level effects related to climate change are restricted to only two. Indicators of subpopulation stress vary across the distribution of polar bears reflecting differences in the rate of sea ice change and with the intensity of research and monitoring. Generally, studies indicating subpopulation stress are in the most intensively studied areas in the Western Hudson Bay subpopulation in Canada (Stirling et al. 1999, Regehr et al.

2007) and the Southern Beaufort Sea subpopulation shared between the USA and Canada (Stirling 2002, Regehr et al. 2010, Rode et al. 2010a). The remaining subpopulations have inadequate time series of data for abundance trend detection or lack adequate monitoring. There is high confidence with moderate evidence and high agreement that the primary conservation concern for polar bears is based on sea ice projections that result in habitat loss that results in reduced food intake, increased energy expenditure, and increased fasting period (Stirling and Derocher 1993, Stirling et al. 1999, Mauritzen et al. 2003, Derocher et al. 2004, Regehr et al. 2007, Amstrup et al. 2010). Only moderate evidence exists for the effect of loss of annual ice over continental shelves on polar bears because the effects of climate change on polar bears are complex and are currently documented in only some subpopulations in the early stages of predicted effects. There is robust evidence and high agreement for declining sea ice (i.e., habitat loss) resulting in altered energy status (i.e., body condition) for polar bears that can reduce growth rates of individuals and lower body condition (Stirling et al. 1999, Rode et al. 2010a). There is very high confidence that reduced body condition associated with sea ice loss is a precursor to demographic change. There is robust evidence that reduced body mass linked to either longer ice-free period reduced ice cover over continental shelf areas results in lower fasting endurance, lower reproductive rates, and lower survival (Regehr et al. 2007, Regehr et al. 2010; Molnár et al. 2011). There is robust evidence and high agreement that reduced body condition can result in lower reproduction and decreased survival rates, both of which result in lower subpopulation growth rates or subpopulations declines (Derocher and Stirling 1996, Derocher and Stirling 1998, Stirling et al. 1999, Regehr et al. 2010, Hunter et al. 2010, Rode et al. 2010a). Several additional studies in the Southern Beaufort Sea subpopulation have tentatively linked changing environmental conditions and include observations of cannibalism (Amstrup et al. 2006), reduced feeding (Cherry et al. 2009), and unusual hunting behaviour (Stirling et al. 2008b). There are suggestions of polar bear diet change linked to changing ecosystem conditions in Hudson Bay (Iverson et al. 2006, Thiemann et al. 2008). There is medium confidence that these observations of polar bear behaviour and ecology are related to changing sea ice conditions.

Ultimately, declines in survival and reproduction are manifest in subpopulation declines. There is robust evidence and high agreement for downward projected trends for polar bear abundance in the foreseeable future and such trends are linked to changes in sea ice (Stirling and Derocher 1993, Derocher et al. 2004, Amstrup et al. 2010, Stirling Parkinson Stirling and Parkinson 2006, Wiig et al. 2008, Durner et al. 2009, Molnár et al. 2010, Molnár et al. 2011). There is a very high level of confidence in lower reproductive rates and reduced survival rates caused by climate change. There is robust evidence for subpopulation decline over 21% between 1987 and 2004 in the Western Hudson Bay subpopulation that was related to climate change (Regehr et al. 2007). There is moderate evidence for recent decline and longer-term drastic decline by the end of the 21st century in the Southern Beaufort Sea based on demographic projection models related to sea ice conditions (Regehr et al. 2010, Hunter et al. 2010). A Bayesian network model used to forecast the future subpopulation status of polar bears projected extirpation of approximately two thirds (2/3) of the world's polar bears by the middle of this century (Amstrup et al. 2008). Aspects of this Bayesian study were criticized (Armstrong et al. 2008) but these criticisms were refuted (Amstrup et al. 2009). The conclusion of Amstrup et al. (2008) that approximately 2/3 of the world's polar bears will be extirpated by mid-century is consistent with other studies and has robust evidence with medium agreement. While extinction of polar bears has limited evidence, there is a very high level of confidence that subpopulation extirpation will occur over a broad geographic area with climate change.

Multiyear ice is used by polar bears in some subpopulations in summer and autumn at the maximal melt of annual ice (Ferguson et al. 2000). Decreases in multiyear ice could result in increased polar bear habitat as multiyear ice is replaced by an annual ice ecosystem (Derocher et al. 2004) but there is limited evidence of such habitat improvement. Loss of multiyear ice as a refuge may pose difficulties for some subpopulations although there is limited evidence. Increasing the distance to terrestrial refugia and multiyear ice at maximal melt may have negative consequences such as drowning and cub mortality (Monnett and Gleason 2006, Durner et al. 2011).

There is robust evidence for changes in sea ice conditions linked to shifts in distribution of polar bears (Derocher et al. 2004, Fischbach et al. 2007, Schliebe et al. 2008, Gleason and Rode 2009, Towns et al. 2010). Increases in the number of problem bears around communities have been associated with distribution shifts and declines in body condition (Towns et al. 2009). There is high agreement that the number of human-bear interactions may increase as sea ice conditions continue to change (Stirling and Derocher 1993, Derocher et al. 2004, Stirling and Parkinson 2006, Towns et al. 2009).

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

28.2.3.4. Arctic and Subarctic Marine Mammals

Unlike research on polar bears, Arctic and subarctic marine mammals lack the depth of empirical studies on species responses to climate change (Kelly 2001, Ragen et al. 2008, Laidre et al. 2008) and modelling studies are lacking. Our understanding of the possible effects of climate change on Arctic marine mammals varies widely reflecting differing levels of insight into their habitat requirements and trophic relationships. Many Arctic and subarctic marine mammals are highly specialized, have long-life spans, and are poorly adapted to rapid and directional environmental change (Moore and Huntington 2008). Many of the predicted changes, however, will likely not be evident until significant sea ice loss has occurred (Laidre et al. 2008). There are two arctic ice-dependent seals (ringed seals, *Pusa hispida*, and bearded seals, *Erignathus barbatus*). In addition, there are four ice-associated subarctic species that live on the edge of Arctic pack ice (spotted seal, *Phoca largha*, ribbon seal, *P. fasciata*, harp seal, *Pagophilus groenlandicus*, and hooded seal, *Cystophora cristata*). None of the seals rely on sea ice year-round and the species vary in their association with sea ice (Lydersen and Kovacs 1999). Similarly, walrus (*Odobenus rosmarus*) rely on sea ice for part of their life cycle but commonly retreat to coastal habitats when ice is unavailable. Three species of whales remain in the Arctic year round (bowhead whale, *Balaena mysticetus*, narwhal, *Monodon monoceros*, and beluga, *Delphinapterus leucas*) with narwhal being the most ice-associated species.

Most studies of climate change and Arctic marine mammals provide a qualitative assessment of concerns and risks associated with climate change (Tynan and DeMaster 1997). None of the northern marine mammals have adequate demographic time series data to currently assess population level effects of climate change (Laidre et al. 2008). There is high agreement that the effects of climate change on Arctic and subarctic marine mammals will vary. Depending largely on life history characteristics, distribution, and habitat specificity, climate change will improve conditions for a few species while others will have minor negative effects and some species will suffer major negative effects (Tynan and DeMaster 1997, Ragen et al. 2008, Laidre et al. 2008). Resilience to climate change in Arctic and subarctic marine mammals will vary and some ice-obligate species should survive in regions with sufficient sea ice and some possibly adapting to ice-free coastal areas (Moore and Huntington 2008). Moore and Huntington (2008) also suggest that less ice-dependent species may be more adaptable and could benefit from a longer feeding period in areas formerly covered by ice but an increase in seasonally migrant species could increase competition for resources.

An analysis of the sensitivity of eleven Arctic and subarctic marine mammals to climate change suggested that feeding specialization, dependence on sea ice, and reliance on sea ice for access to prey and predator avoidance were key features of vulnerability (Laidre et al. 2008). There is medium agreement on which species are most at risk from climate change. Hooded seals and narwhal were identified as most at risk and ringed seals and bearded seals as least sensitive by Laidre et al. (2008). In contrast, Kovacs et al. (2010) stated there were serious concerns for the future of ringed seals and bearded seals although they shared concern for hooded seals and narwhal. Higher vulnerability of narwhal to climate change has robust agreement although only limited evidence. Physiological specialization by narwhal suggests they may have limited ability to change swimming and diving behaviour in response to climate change induced habitat alteration (Laidre and Heide-Jorgensen 2005, Williams et al. 2011). Some species that spend only part of the year in the Arctic, such as the gray whale (*Eschrichtius robustus*) and killer whale (*Orcinus orca*) may benefit from reduced sea ice cover due to increases in prey availability (Moore 2008, Laidre et al. 2008, Higdon and Ferguson 2009). Expansion of killer whales into the Arctic was postulated as a possible cause of a trophic cascade (Higdon and Ferguson 2009) although there is limited evidence of such change at this time.

There is limited evidence although moderate agreement that generalists and pelagic feeding species may benefit from increased Arctic marine productivity resulting from reduced sea ice while benthic feeding ice-dependent species that rely on continental shelf habitats may fair poorly (Bluhm and Gradinger 2008). There is limited evidence but high agreement that species such as walrus that have a specialized diet (primarily benthic invertebrates, Born et al. 2003) are expected to fair poorly with reduced Arctic ice (Kelly 2001, Laidre et al. 2008, Kovacs et al. 2010). Walrus rely on either ice or land near to foraging areas for resting and loss of sea ice may affect access to food. Field observations provide some insight into possible mechanisms of impact. For example, walrus calves were separated from their mothers during an episode of rapid ice retreat and such events may effect recruitment (Cooper et al. 2006). Kelly (2001) suggested that continued warming might reduce access to continental shelf habitat and negatively affect access to forage for lactating female walrus in summer and autumn. While there is limited evidence, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, and development) (Burek et al. 2008).

There is high agreement that the effects on Arctic and subarctic marine mammals will vary spatially and temporally with some populations affected earlier than others and this variation will make 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 negatively affected by sea ice loss but there is limited evidence of changes to most species at this time.

28.2.3.5. Observed Terrestrial Biological Response to Climate Change in Antarctica

28.2.3.5.1. Environmental change responses

Despite the considerable attention drawn by rapid trends of physical environmental change (climate and cryosphere) over recent decades, particularly along the Antarctic Peninsula and some sub-Antarctic islands, few robust studies of biological responses to these changes in non-manipulated terrestrial ecosystems are available. The clearest report is of rapid population expansion and local-scale colonisation by the two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in the maritime Antarctic (Fowbert and Smith, 1994; Parnikoza et al., 2009; Smith, 1994), which remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. The reports are interpreted as warming and increased water availability in terrestrial habitats encouraging the growth and spreading of established plants, increased frequency of successful seed set, and increased germination and establishment of seedlings. Similar changes are reported anecdotally in the local distribution and development of typical cryptogamic vegetation of this region, includeing the rapid colonisation of ice free ground made available through glacial retreat and reduction in extent or previously permanent snow cover. As these vegetation changes creates new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonises them. However, robust baseline survey data and monitoring studies capable of documenting these changes remain critically lacking (Convey, 2006, 2010), and their establishment must now form an urgent priority (Wall et al., 2011).

While recent macroclimatic trends are well documented in this region (Convey et al., 2009a; Turner et al. 2009), their relationship in detail with conditions ('microclimate') experienced by biota at a relevant physical scale is much less clear and has yet to receive sufficient research attention. Prompted by this difficulty, Block and Convey (2001) and Convey et al. (2003) analysed a long term study of the water relations of the terrestrial arthropod fauna on Signy Island (maritime Antarctic), proposing this as a proxy means of measuring water availability and changes therein. They concluded that systematic changes in patterns of water availability were consistent with local climate warming trends – in particular with water being available earlier in the spring and later in the autumn, and there being increased water stress in mid-summer.

A number of field manipulation studies attempting to mimic aspects of climate change predictions have been completed at sub, maritime (the majority) and continental Antarctic sites. Even use of the simple and imperfect methodologies demonstrated that the soil microbial flora, bryophytes and invertebrate fauna respond rapidly and positively to improved environmental conditions (Convey and Wynn-Williams, 2002; Kennedy, 1994; Smith, 1990, 1993, 2001; Wynn-Williams, 1996). The use of more robust methodologies, with better replication and in some cases multivariate approaches to the manipulation of temperature, water and radiation regimes has shifted the emphasis from the simple description of rapid responses to a higher level of integrated and improved understanding. Biological responses have been quantified in terms of plant biochemistry, morphology, life history and ecology, invertebrate population density and diversity, and and at different trophic levels, including the decomposition cycle, across the food web (e.g. Bokhorst et al., 2007a,b, 2008; Convey et al., 2002; Day et al., 1999, 2001; Sinclair 2002). It is clear that biological responses to environmental change are often subtle, but that they may integrate to give far greater impacts for the community or ecosystem (Convey, 2003, 2006; Day, 2001; Searles *et al*., 2001). There is also a clear need to continue such field experiments for periods long enough to permit responses to the initial perturbation to stabilise, highlighting the critical need for commitment to long term studies.

28.2.3.5.2. Direct human impacts on the Antarctic terrestrial environment

Athough climate change is having measureable effects on terrestrial ecosystems, they are also subject to multiple stressors including direct human impacts, anthropogenic assistance in the colonisation of non-indigenous species, and knock-on effects from the recovery of marine megafauna populations (in particular the Antarctic fur seal) from massive human over-exploitation during the Eighteenth and Nineteenth Centuries. However, few studies have quantified human disturbance to Antarctic terrestrial and freshwater ecosystems (Poland et al., 2003; Tejedo et al., 2009; Kennicutt et al., 2010; Hughes, 2010).

The presence of stations, vehicles and their operations clearly leads to local pollution through dispersal of chemical pollutants, dust, and direct damage to vegetation, soil surfaces and freshwater systems (Bargagli, 2005; Kaup and Burgess, 2002; Tin et al., 2009). Soil and freshwater ecosystems may experience eutrophication through human activities (Ohtani et al., 2000). Specific studies of human-formed tracks have documented considerable impact on plant species and soils on various sub-Antarctic islands (Gremmen et al., 2003; Scott and Kirkpatrick, 1994), and likewise on soil properties and invertebrates in the maritime Antarctic South Shetland Islands (Beyer and Bölter, 2002; Tejedo et al., 2009), and soils in the continental Antarctic (Campbell et al., 1998). Even formally protected areas ('Antarctic Specially Protected Areas') are not immune from these impacts (Hughes & Convey, 2010; Braun et al., 2010). A common feature of these studies is recognition that recovery from these types of disturbance to vegetation and soils may take decades, at least.

28.2.3.5.3. Anthropogenic transfer of non-indigenous species

Antarctica's terrestrial ecosystems are typically very isolated, within the continent by the island-like nature of areas of ice-free ground and inter-continentally by the atmospheric and oceanic circulations surrounding the continent, combined with the vast distances and inhospitable conditions that must be survived while in transit and on arrival. Nevertheless, natural colonisation events have taken place and continue to do so (Barnes et al., 2006; Clarke et al., 2005), utilising a range of dispersal mechanisms and routes (e.g. Hughes et al., 2006).

Human-assisted transfers of biota overcome several of the barriers facing natural colonists, in particular being much more rapid than the natural processes, and in avoiding exposure to the extreme environmental stresses inherent in transfer at altitude in the atmosphere, or on the ocean surface. It remains difficult to estimate the relative importance of natural and human-assisted colonisation routes into the Antarctic, although at two remote Southern Ocean islands (Gough Island, Marion Island) it has been estimated that the latter has outweighed the former by at least two orders of magnitude since their discovery (Gaston et al., 2003; Gremmen and Smith, 2004). Overall, the presence of all non-indigenous biota known to date can be most plausibly be linked with 'national' operations and their preceding industrial exploitation industries with, despite expressed concerns, none yet explicitly linked with the rapid expansion of the tourism industry within Antarctica over the last few decades (Convey and Lebouvier, 2009; Frenot et al., 2005; Tin et al., 2009).

Even though a wide range of non-indigenous species are already known to be established on various sub-Antarctic islands (in some cases with islands now hosting more non-indigenous than indigenous species in certain higher taxonomic groups, such as flowering plants), the majority are currently very restricted in their distributions (Frenot et al. 2005). In some cases this results from their persistent rather than invasive status, while in others expansion of distributions is limited by physical barriers, in particular that presented by tidewater glaciers. Where environmental changes result in alteration of the physical environment within which terrestrial ecosystems exist – such as glacial retreat forming new beach-heads connecting previously isolated systems – there is potential for unrestricted spread of established non-indigenous species into new non-impacted areas, as has been documented on South Georgia (see Cook et al., 2010). Direct anthropogenic assistance in local transfer, through poor or non-existent application of biosecurity measures, is also strongly implicated in the subsequent dispersal of established non-indigenous species to new locations (see Frenot et al. 2008 and Convey et al., 2011 for examples and discussion from sub-Antarctic South Georgia and Iles Kerguelen).

Across most sub-Antarctic islands, in the centuries since human discovery there have been major impacts on terrestrial ecosystems from the deliberate and accidental introduction of many plants and animals (Bergstrom et al., 2009; Bonner, 1984; Chapuis et al., 1994; Convey et al., 2006; Convey and Lebouvier, 2009; Frenot et al., 2005, 2008; Leader-Williams, 1988), providing an urgent warning of the potential consequences should invasive species become established on the Antarctic continent (Convey, 2008). Although very few establishment events have yet been recorded in this latter region, it is already known that accidental transfers of biota do occur, particularly associated with cargo, vehicles, food and personal clothing (Sjoling and Cowan 2000; Frenot et al., 2005; Hughes et al., 2009; Whinam et al., 2004). Several botanical transplant experiments took place during the 1960s and 1970s (Smith, 1996). While such experiments are no longer permitted under the Antarctic Treaty System, it was realised in the 1980s that an unintended consequence at one location had been the introduction and establishment of sub-Antarctic terrestrial invertebrates (Block et al., 1984) which remain to the current day (Hughes and Worland, 2010).

The eradication of non-indigenous vertebrates, in particular predatory cats, has been achieved on Sub-Antarctic Marion and Macquarie Islands where they had had considerable negative impacts on burrow nesting marine birds (reviewed by Frenot et al., 2005). However, such eradication programmes can lead or contribute to considerable or unexpected collateral impacts (e.g. Bergstrom et al., 2009). Currently the world's most ambitious rat eradication programme is underway on South Georgia, with plans to follow this with eradication of reindeer from the island. However, there is no realistic possibility of remedial extermination of most established invertebrate or plant species, which raises the possibility that such species, the majority currently of 'persistent' status with apparently low impact, may soon switch (possibly facilitated by regional climate amelioration) to 'invasive' status, with unknown consequences for native species and ecosystems.

There are currently far fewer non-indigenous species known to be established on the Antarctic continent (five confirmed, at least three others unconfirmed) than on the sub-Antarctic islands (~200) (Convey, 2008; Frenot et al., 2005, 2008; Hughes & Convey, in press; Smith and Richardson, 2010). While several vertebrates, invertebrates and plants on various sub-Antarctic islands clearly have 'invasive' status (*sensu* Frenot et al., 2005), and others are identified as having high potential to switch from their current 'persistent' status under current regional environmental change scenarios, there is at present no evidence of any of the persistent non-indigenous species established on the continent becoming invasive (but see Hughes & Worland, 2010). A common feature of many of the non-indigenous species already known to be established in the sub-Antarctic is that they belong to ecological functional groups, or introduce trophic or ecological functions, that are poorly or not represented in the native communities (Frenot et al., 2005; Convey et al., 2010). To an extent this is obvious in the case of vertebrates, as no terrestrial vertebrate herbivores or predators are present in any Antarctic region. However, a large number of terrestrial invertebrates has also been introduced to ecosystems within the Antarctic, and their impacts are less widely known, yet still potentially fundamental to ecosystem functioning (Convey, 2010). Additionally, anecdotal and a few published reports are available of yet further non-indigenous biota existing synanthropically for shorter or longer periods (i.e. directly in association with human activity, such as within station buildings, associated with foodstuffs, etc.) (Greenslade, 2006; Hughes et al., 2005).

In reality, knowledge of the presence, distribution and impacts of non-indigenous species in the Antarctic is poor, and the available data on numbers of such species are likely to be a considerable underestimate, other than for the vertebrates. At the majority of locations baseline survey and monitoring data are simply unavailable for most invertebrate and lower plant groups while, even for locations and groups where data are available, there are no ongoing programmes monitoring distribution and abundance changes or impacts. The presence of non-indigenous microbiota is particularly poorly known (Convey, 2008; Cowan et al., in review; Frenot et al., 2005). In recent years, the use of molecular biological methodologies has started to improve the potential of identifying non-indigenous microbes (e.g. Baker et al., 2003).

28.2.3.5.4. Impacts from the recovery of marine ecosystems after human over-exploitation

The largely uncontrolled over-exploitation of marine vertebrate resources of the Southern Ocean during the Eighteenth, Nineteenth and first half of the Twentieth Centuries (reviewed by Trathan & Reid, 2009) caused major perturbation to these marine ecosystems, such that it is both unclear what their original state was, and whether ecosystem trajectories will result in recovery towards a state similar to the original. In the context of terrestrial ecosystems, the marine exploitation industries had three main impacts, those of (i) habitat destruction through onshore infrastructure construction, (ii) the associated first phase of introduction of non-indigenous species, and (iii) a potentially massive spike in the quantity of marine biomass and nutrients input to the terrestrial environment (primarily through the dumping of seal and whale carcasses), followed by a longer term alteration to this transfer mediated by changes in the populations of both the target species and carrion feeders (Convey & Lebouvier, 2009). The first two have already been considered briefly above while the latter, although potentially fundamentally important for terrestrial ecosystems often believed to be strongly nutrient limited, has not been a subject of specific study in the Antarctic.

However, one element of post-exploitation recovery that has particular importance for Antarctic terrestrial ecosystems is that of the very rapid increase in populations of Antarctic fur seals (*Arctocephalus gazella*) to levels that are currently thought to be at least equal to if not greater than those that existed pre-exploitation. The speed and magnitude of this recovery is thought to be linked to lack of competition from the krill feeding great whales, also largely exterminated through uncontrolled human over-exploitation, but with longer life cycles and hence much slower rates of population increase. This population recovery has been centred on South Georgia. Both here, and throughout the Scotia arc South Orkney and South Shetland archipelagos, as well as increasingly further south along the Antarctic Peninsula, the presence of large numbers of fur seals on land has led to the rapid destruction of or large scale changes in the previously dominant and typical cryptogam-dominated terrestrial floras (and their associated faunas) over large areas of ground accessible from the coast where the majority of well-developed terrestrial ecosystems are found (Smith 1988; Favero-Longo et al., 2011). It has also led to the rapid eutrophication of lake ecosystems accessible to the seals (Butler 1999; Quayle & Convey 2006). While South Georgia and parts of the South Shetland Islands hosted breeding populations of these seals before the exploitation era, palaeolimnological studies (Hodgson & Johnston, 1997; Hodgson et al., 1998) confirm that many of the areas now being occupied in summer by large non-breeding concentrations of animals have not previously suffered this impact, at least in the current interglacial period. This provides an example of a secondary impact of human exploitation of the Southern Ocean marine ecosystem, whose direct consequences for large areas of sub- and maritime Antarctic terrestrial ecosystems already likely far outweighs those of response to regional climate change.

28.2.4. Human Populations

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. (Hild and Stordahl, 2004; 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 interconnected factors including not only additional stressors such as contaminants like POPs (persistent organic pollutants), radioactivity, and mercury, but also the complicated social, cultural, political, and economic forces operating in these communities. (AMAP, 2009; UNEP/AMAP, 2011; Larsen and Huskey, 2010) In fact, 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. (Anisimov et al, 2007; Hovelsrud and Smit, 2010) In addition, the impacts of these factors influencing community vulnerability vary significantly among the highly varied communities in the Arctic which range from small, remote, predominantly indigenous to large northern, industrial settlements. (Chapin et al, 2005) A significant amount of research has been carried out on the health and well-being of Arctic indigenous populations and, therefore, this section emphasizes both the direct and indirect impacts of climate changes on these more vulnerable segments of the population.

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

Direct impacts of climate changes on the health of Arctic residents include extreme weather events (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts). (Berner et al, 2005) Precipitation increases are expected to impact the magnitude and frequency of natural disasters such as rock falls, debris flow, and avalanches. (Koshida and Avis, 1998) Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration and/or rapid onset of extreme weather events and storms, which, in turn, may create risks to safe travel or subsistence activities, risks to rural and isolated communities, and risk of being trapped outside one's own community. (Berner et al, 2005; Laidler et al, 2009; 2010) Indigenous people have reported that the weather has become less predictable and, in some cases, that storm events progress more quickly today than in previous memory. (Huntington et al, 2005; Ford et al, 2006; Laidler et al, 2009; 2010) In fact, changing river and sea ice conditions impact the safety of travel and inhibit access to critical hunting, herding and fishing areas. (Hovelsrud et al, 2011) 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; Hovelsrud et al, 2011)

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. (Khasnullin et al., 2000). 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). (Anisimov et al, 2007; Hassi et al., 2005). High humidity and thunderstorms can be associated with short-term increases in cardiovascular and respiratory diseases (Kovats et al., 2000; Anisimov et al, 2007). It is estimated that 2,000 to 3,000 deaths/yr occur from cold-related injury and diseases during the cold season in Finland. These winter-related mortality rates are higher than the number of deaths related to other standard causes in the country during the year (e.g., there are 400/yr from traffic accidents, and 100-200/yr from heat). (Anisimov et al, 2007) Respiratory diseases among children in Northern Russia is 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 (Nayha, 2005). It is also believed that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, some Arctic residents are reporting respiratory stress associated with extreme warm summer days which has not previously experienced (Furgal et al., 2002), and it is well-known that exposure to extreme high temperatures can include heat stroke, dehydration, heat exhaustion, and respiratory problems. (Epstein and Ferber, 2011)

28.2.4.2. Indirect Impacts of Climate on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), the built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion). (Berner et al, 2005; Maynard and Conway, 2007) Local and traditional knowledge in communities across the Arctic are observing extremes not previously experienced and increasingly unusual environmental conditions (e.g., Krupnik and Jolly, 2002). 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. (Lafortune et al., 2004).

Underlying all climate change impacts and processes, are the complicated stresses from contaminants such as POPs (persistent organic pollutants), radioactivity, and mercury which create additional and/or synergistic impacts on the overall health and well-being of the communities. (UNEP/AMAP, 2011; Maynard, 2006) 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, and 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) AMAP studies have shown that long-range transport of environmental contaminants from both anthropogenic and natural pollutants to the Arctic from both external and local industrialized sources, plus their accumulation in animals and plants, pose a significant health hazard to Arctic residents and, especially, indigenous peoples -- primarily due to biomagnification up the food chain. (AMAP, 2009; Maynard and Conway, 2007) The consumption of traditional foods by indigenous peoples places these populations at the top of the Arctic food chain and, therefore, they may receive some of the highest exposures in the world to certain contaminants. (UNEP/AMAP, 2011) Natural pollutants being transported to the Arctic are dust, volcanic ash, smoke from boreal fires, and pathogens (primarily wind-borne); anthropogenic pollutants include persistent organic pollutants (POPs), radionuclides, heavy metals, pesticides, polycholorinated biphenyls (PCBs), acid aerosols, smoke, dust, ash, and oil (UNEP/AMAP, 2011). Contaminants must be a major consideration in the climate impact analyses 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; Macdonald et al, 2003).

Contaminant transport mechanisms fall into four major categories all of which are effected by climate change: the atmosphere with strong south-to-north air flows and strong westerlies; Arctic rivers and strong south-to-north water flows into the Arctic; ocean waters as a major storage reservoir and transport mechanism; and sea ice, transporting and redistributing contaminants on or in the ice during formation, movement, and melt (Maynard and Conway, 2007; UNEP/AMAP, 2011). In addition, rain and snow can release contaminants carried to the Arctic from lower latitudes, which then end up in melt water on land, on rivers, and in surface layers of the ocean – all areas of high biological productivity. This is particularly important during springtime when spring growth bursts can accelerate uptake by young plants and animals, which in turn, may be favored traditional food resources. (UNEP/AMAP, 2011)

There are additional concerns regarding radioactivity 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 radionuclide sources in some parts of the Arctic and the risk for accidents is a cause for concern. Russia has plans to build floating nuclear power plants, and issues exist regarding how waste will be handled and the increased marine transport of spent fuel across the Arctic. (AMAP, 2010) In addition, there are potential new sources (e.g., the power plants dealing with Technologically Enhanced Naturally Occurring Radioactive Material (Tenorm) in the context of uranium mining and oil and gas and other minerals) which could increase the risk of radioactive contamination. (AMAP, 2010) There continue to be concerns about existing sources such as poorly-maintained nuclear powered vessels or those being decommissioned, radioactive wastes which has been dumped or stored, radioactive thermoelectric generators (RTGs) which are used as energy sources in the North, reprocessing facilities and nuclear power plants close to the Arctic - among other issues. (AMAP, 2010)

Warming temperatures are enabling increased overwintering survival and distribution of 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, 2008; Parkinson and Butler, 2005). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Sweden (Lindgren and Gustafson, 2001), *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean. (Hughes-Hanks et al., 2005). it is also likely that temperature increases will increase the incidence of zoonotic diseases (that can be transmitted to humans) (Bradley et al., 2005). Many Arctic zoonotic diseases which currently exist in local host species (e.g., tularemia in rabbits, muskrats and beaver, and rabies in foxes can spread through climate-related mechanisms (such as relocation of animal populations) (Dietrich, 1981). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, Vibrio parahaemolyticusin, in Alaskan oysters (McLaughlin et al. 2005). Warmer temperatures have also resulted in an increase in the range and longevity of insects, including those that sting and bite. The Allergy Asthma and Immunology Center of Alaska reports a three-fold increase in patients suffering allergies from stinging insects from 1999-2002 to 2003-2007 (Demain et al. 2008; Epstein and Ferber, 2011). Statistically significant increases in patients seeking medical care for insect bite and sting related events are being observed throughout the state (Demain et al. 2008; Epstein and Ferber, 2011). The first known cases of fatal anaphylaxis (severe allergic reactions)—from Hymenoptera genus (e.g., yellow jacket) stings—occurred in Fairbanks Alaska in the summer 2006. (Demain et al. 2008)

Food security is critical 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 (e.g., Blanchet et al., 2000; Asiminov et al, 2007). Indigenous peoples continue to maintain a strong connection to their environment and local area through the harvest of local country foods, which also helps provide a sense of overall well-being. (Gray, 1995; Nuttall et al., 2005). However, climate change is already posing a serious threat to food security and safety for indigenous peoples and the availability of country food because of the impacts on traditional subsistence hunting, fishing and herding. (Dartmouth, 2011) 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. (Nuttal et al, 2005) Populations of marine and land mammals, fish and water fowl are also being reduced or displaced by changing temperatures, ice state, habitats and migration patterns reducing the traditional food supply. (Dartmouth, 2011)

Furthermore, traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by a warming again reducing food available to the community. (Dartmouth, 2011) For example, food contamination problems are becoming important wherever thawing of permafrost "ice houses" is occurring for communities and families. (Hovelsrud et al, 2011; Parkinson and Evengard, 2009) Additionally, the knowledge of how to preserve food in the traditional way is being lost. These reductions in the availability of traditional foods will force indigenous communities to increasingly depend upon 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. (Dartmouth, 2011; Van Oostdam et al, 2003) A complicating factor in evaluating trade-offs between traditional and market food is that wild foods represent the most significant source of exposure to environmental contaminants. As the uptake, transport and deposition activities of many of these contaminants are influenced by temperature, climate warming may also indirectly influence human exposure. (Kraemer et al, 2005; Anisimov et al, 2007)

Other factors affecting food insecurity are exemplified by conditions in some Canadian regions. Food insecurity in Canada is highest in the three territories, where there are significantly higher numbers of female single parent households and the cost of a standard list of grocery items can be up to three times higher than in southern Canada. (Bolton et al, 2011; Berrang-Ford, 2011) In communities not accessible by road, access to market food items is reliant upon shipment via air or sea, which significantly increases the price. Data from Canada for 2001 show that 68% of households in Nunavut, 49% of those in the NW Territories and 30% of those in the Yukon had at least one occasion in the previous year when they did not have the financial resources for sufficient food.

Climate change is beginning to threaten community and public health infrastructure, most seriously in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada through increased river and coastal flooding and erosion, increased drought and thawing of permafrost, resulting in loss of reservoirs or sewage contamination. Salt-water intrusion and bacterial contamination may be threatening community water sources. (Anisimov et al, 2007; Dartmouth, 2011) Quantities of water available for drinking, basic hygiene and cooking are becoming limited due to damaged infrastructure and drought. (Anisimov et al, 2001; Dartmouth, 2011) Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure such as sewage lagoons or inadequate hygiene, spreads sewage. Studies in Alaska have shown a 2-4 times higher hospitalization rates among children less than 3 years of age for pneumonia, influenza, and childhood respiratory syncytial virus infections, and higher rates of skin infections in persons of all ages in villages where the majority of homes had lower water availability because of no in-house piped water source, compared to homes that had higher water availability because of in-home piped water service. (Dartmouth, 2011) 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. (Dartmouth 2011; Berner et al, 2005)

These combined physical, medical, economic, political, socio-cultural, and environmental forces operating on and within Arctic communities today have a important implications for human health and well-being (Curtis et al, 2005; Hamilton et al, 2010) The changes in the physical environment which threaten certain communities (e.g., through thawing permafrost and erosion) and which lead to forced relocation of residents or changes or declines in resources resulting in reduced access to subsistence species (e.g., Inuit hunting of polar bear) can be a pathway to rapid and long-term cultural change including loss of traditions. (Anisimov et al, 2007) These losses can, in turn, create psychological distress and anxiety among individuals. (Hamilton et al, 2003; Curtis et al, 2005) Additional attention needs to be focused on solutions for the high suicide rates among impacted peoples of the North, particularly, the indigenous populations who are losing the means to practice their traditional customs and maintain their culture, and, therefore, their traditional role in that society. (Coyle and Susteren, 2011)

28.2.5. Economic Systems

28.2.5.1. Arctic

There are multiple stressors on Arctic economies of which global climate change is just one (Hovelsrud G. K. et al, 2011; Forbes, D.L. 2011; Larsen et al. 2010; AHDR 2004). Arctic livelihoods are impacted by local to global influences, and local community living is no longer characterized by the kind of isolation that characterized earlier times (Huntington et al. 2007, 183). Coastal erosion, thawing permafrost, and changing sea-ice conditions, when combined with non-cryospheric drivers of change such as increased economic activity, socio-economic development, demography, governance, health and well-being will result in multifaceted and cascading effects (Hovelsrud G. K. et al, 2011). Traditional livelihood activities, which historically have been closely connected to the natural resource base, are also influenced by globalization (e.g. Keskitalo 2008). In the face of unprecedented changes in the local environment on which traditional livelihoods and cultures depend, Arctic coastal communities are coping with rapid population growth, technological change, economic transformation, confounding social and health challenges and, in much of the Arctic, rapid political and institutional change (Forbes, D.L. 2011; ASI, 2010). Although climate change and other processes affecting natural resources and environmental conditions impose large impacts on quality of life and economic activity for communities, 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 (e.g. Forbes, D.L., 2011).

The Arctic economy consists of a combination of formal and informal sectors, all of which are sensitive to climate change. The formal, market based, Arctic economy is characterized by the dominance of the primary sector, with significant large-scale natural resource exploitation activities. Outside of the urban areas indigenous people often mix activities of the formal sector (e.g., commercial fish harvesting, oil and mineral resource extraction, forestry, and tourism) with traditional or subsistence activities, which include harvesting a variety of natural renewable resources to provide for human consumption. Hunting and herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall et al. 2005; Rasmussen 2005; Poppel 2006; Aslaksen et al 2009; Poppel and Kruse 2009; Larsen and Huskey 2010; Crate et al., 2010). Renewable harvesting is linked both to the subsistence-based informal economy and to the market economy (Lindholt 2006; Glomsrød and Aslaksen 2006). It is projected that there will be significant impacts on the availability of key subsistence marine and terrestrial species as climate continues to change, and the ability to maintain one's economic well-being may be affected. Adjustments in harvest strategies and reallocations of labour and resources are likely to occur.

While large-scale resource extraction is a central characteristic of the Arctic formal economy, subsistence in the form of customary harvesting continues to play an important role. The extent of this informal activity varies between and within regions of the Arctic (ASI 2010). A significant number of indigenous people throughout the Arctic continue to depend largely on harvesting and the use of living terrestrial, marine, and freshwater resources. Many of these resources are used as food and for clothing and other products. They also figure prominently in the cash economy of local households and communities. The SLiCA survey, covering Greenland, Chukotka, Alaska, and Canada, has shown that subsistence harvest is important to a large segment of the indigenous population. Half the households in the survey reported they harvested half or more of their family's meat consumption, and that for two-thirds of the households traditional food accounted for half or more of their household's consumption (Poppel and Kruse 2009). Conservative estimates made with data from the recent Nunavut Wildlife Harvest Study (Priest and Usher, 2004) reveal that total harvest of the four staple species (ringed seal, caribou, narwhal and arctic char) provided each of approximately 125 households with between 850-900 kg of edible foods in the late 1990s and early 2000s in Kangiqtugaapik in Nunavut. Sharing and consumption of wild foods are seen as important components of modern Inuit identity (Wenzel, 1991, 2005 cited in Crate et al., 2010). In the early 1990s – initially in western Canada, and later elsewhere - indigenous communities started reporting climate change impacts (Berkes and Armitage 2010, 117). According to herders, non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes et al. 2009, 22043). The ability of Inuit in regions of Nunavut to pursue subsistence activities are already impacted by environmental changes. This raises the question of what effect this might have e.g. for the future of East Kitikmeot Inuit polar bear hunting, and sharing and consumption of polarbear meat (Keith 2009, 123).

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

28.2.5.2. Antarctic

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28.2.6. Economic Sectors

28.2.6.1. Arctic

28.2.6.1.1. Agriculture

Climate change is expected to have positive impacts for agriculture, including extended growing season, although variations across regions are expected (Hovelsrud et al, 2011). At the same time, rain-on-snow events and melting and refreezing of snow may result in frost damage; increased precipitation and run-off combined with episodes of freezing and thawing which could considerably increase soil erosion in agricultural fields (Ibid.). Regional differences exist and a changing cryosphere is expected to have predominantly positive impacts on agriculture in the Arctic. In areas with a reduction in snow cover, the growing season may be extended (Torvanger et al., 2003; Falloon and Betts, 2009; Grønlund, 2009; Tholstrup and Rasmussen 2009 – in SWIPA). Agricultural opportunities 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, 84).

28.2.6.1.2. Forestry

Climate change is likely to have economic costs and benefits for forestry. 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, 227). Economic profits may be affected by the damage to forest and timber caused by increased freeze-thaw events, and the increased fungal or insect attacks which may destroy drying timber and reduce economic returns (Aaheim et al. 2009), while on the other hand costs related to snow damage could be reduced (e.g. Hovelsrud et al, 2011).

28.2.6.1.3. Fisheries

Fisheries are important throughout the Arctic. Along the Arctic coast a significant share of Arctic residents make a living from marine resources. The coast is a region exposed to natural hazards and is particularly sensitive to climate change (Forbes, D.L., 2011). Reduced sea ice has impacts on the abundance, migration, seasonal distribution and composition of key commercial fish stocks (Glomsrød and Aslaksen 2009).

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 and the Barents Seas and low volume subsistence fisheries in the coastal regions of the Arctic Ocean (Figure 28-3, Table 28-1). 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. There is considerable interest in whether global warming will alter conditions to commercial fisheries and how extraction of natural resources would be governed internationally (Berkman and Young 2009, Proelss 2009). In the United States, the Secretary of Commerce approved a fishery management plan for all federal waters north of Bering Strait that closed U.S. portions of the Arctic to commercial fishing (Wilson and Ormseth 2009).

[INSERT FIGURE 28-3 HERE
Figure 28-3: Fishing vessel activity. Source: AMSA.]

[INSERT TABLE 28-1 HERE
Table 28-1: Commercial fishery areas, catches, and market products.

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 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*) (Wilson and Ormseth 2009). Some evidence of range extensions of commercial species including Pacific cod and walleye pollock were observed in the Beaufort Sea (Rand and Logerwell 2011).

It is unclear whether environmental changes in the Arctic Ocean will be conducive to the establishment of fish stocks of sufficient abundance and value to support commercial activity. Advection pathways are favorable to drift from the Atlantic into the Arctic, and the presence of a deep trench lining the Atlantic and the Arctic (Fram Strait) may provide an opportunity for commercial concentrations of fish to colonize the Arctic under ice free summer conditions and increased prey availability. Some evidence of range extensions and dominance shifts have been recorded (Wassmann 2011b), however the absence of a historical baseline for the region makes it difficult to resolve whether these shifts are the result of fishing, natural variability, or global warming.

28.2.6.1.4. 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 quality of catch estimates are reliable for many regions in the southern shelf seas of the Arctic (e.g. eastern Bering Sea, Barents Sea and eastern Canada), however, estimates from the Arctic Ocean are uncertain. Zeller et al (2011) estimated that the amount and trend in subsistence catches in the Arctic could have been as high as 950,000 t of which 770,000 t, 89,000t and 94, 000t was landed in Russia, the USA, and Canada respectively. Fisheries for these species are prized food for native peoples in the Arctic. The survival of Arctic coastal fishes in the polar regions 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 and Evenson 2011). Climate change related factors that influence the water level and freshening of rivers will likely influence run size of these species (Fechhelm et al 2007). These impacts could be exacerbated by increased industrialization of the Arctic river systems. Reist et al (2006) hypothesized that climate impacts will expand the availability of suitable habitat for species that typically reside in the margins of the Polar region which could result in colonization of regions to the north, however when or if, this will occur depends on several uncertain processes.

28.2.6.1.5. Infrastructure, fishing, and hunting

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 *(Martin et al. 2009; Huntington et al. 2007, 174*; Sherman et al., 2009; Sundby and Nakken, 2008; West and Hovelsrud, 2010; Forbes, 2011). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower also poses major economic costs and risks, which are more closely linked to the design lifetime of the structure than with melting permafrost. Still, current engineering practices are designed to help minimize the impacts (Prowse et al, 2009, 274). 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 (Berkes et al 2003: National Round Table on the Environment and the Economy 2009, 48-50; *Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford et al 2010a; Anisimov et al. 2007;* D. Forbes, 2011).

According to Prowse et al. (2009) in Northern Canada climate warming presents an additional challenge for northern development and infrastructure design. However, 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, 274)

28.2.6.1.6. Tourism

Tourism in the Arctic will be impacted in many ways by changing climate, with impact assessments indicating substantial uncertainty (Eskeland and Follorp, 2006, 86). ”Climate change” tourism is a growing attraction (viewing glaciers). The decreasing or disappearing glaciers are found to have a negative impact on the attractiveness for visitors in glaciated natural parks (Scott et al. 2007; Wolf and Orlove 2008). Loss of sea ice may open up waterways and opportunities for increased cruise traffic (e.g. Glomsrød and Aslaksen, 2009), and add to an already rapid increase in cruise tourism. Spills on Svalbard have increased due to the growth in activities related to tourism and research. Dangers of cruise or cargo ships running a ground and with subsequent oil spillage are the biggest environmental risk connected to marine transportation at Svalbard (NorAcia 2010, 113).

[Eco-tourism missing]
[Publications specifically on eco-tourism needed. Bruce?]
[Tourism already well covered in other recent assessments (e.g. SWIPA and State of Arctic Coasts 2010)]
[Include Prowse et al. 2009; Furgal et al. 2008]

28.2.6.1.7. Marine transportation in the Arctic Ocean

As the extent of multi-year sea ice in the Arctic continues to contract in coming decades (SWIPA, 2011), the opening of new commercial shipping lanes presents socio-economic opportunities as well as social and ecological threats. 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). 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 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 черная книга, стр. 22).The increased shipping associated with the opening of the Northern Sea Route (NSR) will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific (Østreng 2006, 75). The frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season of natural resources, which is the late spring/summer. In this period, vulnerable natural resources are spread all over the NSR area in the Arctic (Østreng 2006, 74). Northern Sea Route in Russia *de facto* has already been re-opened, at least for the western portion encompassing the Barents Sea (Johannessen et al., 2007; Mikkelsen and Langhelle, 2008). An active Northern Sea Route is likely to be immensely profitable for Russia, in addition to having geopolitical importance as the United States and Canada seek more stable sources of hydrocarbons than the Middle East (Mikkelsen and Langhelle, 2008). Even if the extraction takes place offshore, there are still important social impacts to be accounted for onshore. Local residents are concerned about the future status of marine, terrestrial and freshwater biota since there will be substantial coastal infrastructure to facilitate offshore developments (Meschtyb et al., 2005). 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 (Forbes et al. 2009; Kumpula et al. 2011). Thus, the combined actual and potential socio-economic and social-ecological footprint of commercial shipping is likely to be significant (Mikkelsen and Langhelle, 2008). Given the high capacity of Russia’s marine shipping infrastructure to handle traffic in ice-choked waters, the NSR can be expected to operate effectively even without a warming climate. However, rapid sea ice contraction would certainly increase access and, therefore, the amount of traffic (Østreng, 2006; Mikkelsen and Langhelle, 2008; Forbes, 2011; SWIPA 2011).

Increased economic opportunities along with challenges associated with culture, security and environment, are expected in Northern Canada with the increased navigability of Arctic marine waters together with expansion of land- and fresh water-based transportation networks (Furgal and Prowse 2008, 60). 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 Arctic Ocean is predicted to become increasingly open to transportation, tourism and mineral exploration. The positive sides in the development of the marine transportation sector include not only a shorter way to travel between Tokyo and London than the Panama Canal, but also the advantage of allowing passage of ships that cannot fit through the existing canal systems, as well as a shelter from storms provided by the Northwest passage archipelago. 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 and Prowse 2008, 84, 98). Additionally, near-total darkness and bitter cold make winter navigation exceedingly hazardous in the Circumpolar Arctic, not to mention the ice conditions in most areas of the Arctic, which are highly variable from year to year and will likely remain that way (Furgal and Prowse 83-84).

28.2.6.1.8. Ice roads

As the transportation in the Arctic Ocean might benefit from global warming, other common ice-dependent forms of transportation in the Arctic will suffer from the changing climate. The seasonal private and public lake, river and snow road network provides transportation platforms throughout the Arctic forming critical travel routes that link communities and facilitate their ability to continue social and cultural activities during winter months. The rapidly expanding mining sector also relies heavily on ice roads to move heavy equipment, minerals and fuel for the remainder of the year (Furgal and Prowse 2008, 86). The Diavik Diamond Mine in Canada i.e. had to take expensive measures to compensate for ice roads that failed to freeze thick enough to allow resupply (National Round Table on the Environment and the Economy 2009). There have been indicators of possible climate induced changes in ice road serviceability in conjunction with the reduction in commercial shipping within northern Manitoba, Canada which has resulted in the relocation of winter road systems from ice to land. This in turn has led to higher maintenance costs, and dwindling construction supplies, rising food and fuel prices, and a related rise in unemployment in the area (Prowse et al. 2011). In addition, many northerners depend on the natural ice-road network for access to hunting, fishing, and reindeer herding or trapping areas, often in support of traditional subsistence-based lifestyles (e.g. Ford *et al*., 2008; Furgal and Prowse, 2008)

28.2.6.1.9. Resource exploration on the Arctic shelf

Resource exploration in the Arctic is climate sensitive. Climate change is likely to impact accessibility and cost of exploration and extraction of a range of commercial resources. In the oil and gas industry exploration activities are likely to be most affected by climate change (Prowse et al. 2009, 272). The Arctic has large reserves of minerals (Lindholt, 2006) and potentially large reserves of undiscovered sources of raw materials, oil and gas. The socio-economic impacts on the Arctic region and local communities of oil and gas exploration activity can be positive or negative (Huntington, 2007; Duhaime, 2004, 2006; Forbes, 2008; Forbes et al. 2009; Kumpula et al. 2011). 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).

[Awaiting contribution from CA]

28.2.6.1.10. Terrestrial resource management (oil and gas, mining, forestry in the Arctic) [to be developed]

In non-developed deposits located in the Arctic regions, the proven resources of oil and gas make up 5.3% and 21.7% of the world resources, respectively. Almost all of the explored gas deposits and 90% of the explored oil deposits are located in the Russian part of the Arctic regions. Among them, the greatest one is the Shtokman Deposit in the Barents Sea, discovered in 1988 but not developed until now. It contains about 3,200 billions m^3 of gas (Lindholt, 2006). Projected declines in sea-ice covers leading to development of integrated land and marine transportation networks in Northern Canada, is likely to stimulate further mine exploration and development (Prowse et al. 2009, 273).

[B. Forbes to contribute text on terrestrial resource management]
[S. Glomsrød to contribute text on oil and gas sector]

28.2.6.2. Antarctica and the Southern Ocean

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

28.2.6.2.1. Fisheries

The Southern Ocean has experienced two centuries of exploitation of marine species. Harvesting of seals began in the late 18th century, which almost totally wiped out the populations of Antarctic fur seals, with only a few remaining by the middle of the last century. The early 20th century also saw the industrial scale removal of the great whales, while the second half of the century saw removal of substantial amounts of fin fish before the start of a fishery for Antarctic krill in the late 1970's.

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

Patagonian toothfish fisheries, with a current region-wide catch limit of approximately 9,000 tonnes, occurs in waters shallower than 2000m on the subantarctic island shelves, plateaux and banks. Antarctic toothfish occurs in higher latitudes around the Antarctic continent and has a regional total allowable catch of approximately 4,000 tonnes. Both species can migrate over large distances. The fisheries for toothfish occur primarily on the Kerguelen Plateau, in the Ross Sea, and around islands in the northern Scotia Arc. Mackerel icefish occur in shelf areas less than 500m in depth and are very localised in their distribution. Its regional annual allowable catch varies from very small to a few thousand tonnes. Stocks around the Antarctic Peninsula were depleted in the 1970s and are yet to recover. Given their limited distribution, fisheries for icefish could be vulnerable to climate change impacts in the region.

Exploitation of Antarctic krill was first reported in 1973 and has occurred at various levels since that time, peaking during the 1980's at a level of about 500,000 tonnes and since that time until just a few years ago catch levels have been lower at about 110,000 tonnes. Catches are now again increasing because of the development of technologies to empty the codend using air-driven pumps, allowing catch rates to be more efficient, and the development of suitable markets for krill oil in both aquaculture and human dietary supplements (Nicol, Foster et al. 2011). The cumulative catch of krill so far is 7 million tonnes.

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, Nicol et al. 2009). This changing pattern in the krill fishery will need to be accounted for by CCAMLR in the management strategy for the fishery.

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

At present, CCAMLR takes a precautionary approach in its implementation of the ecosystem approach stipulated within its Convention text (Constable, de la Mare et al. 2000). It sets annual catch limits for each of its fisheries. The catch limits aim to maintain stocks at or above target levels while taking into account uncertainties over stock status and the parameters used to assess current and future dynamics. The target levels for toothfish are set according to targets for top predators – the median status of the spawning stock is aimed to be 50% of the median prior to fishing. The target levels for icefish and Antarctic krill are set according to targets for prey species, which at present is for the median status of the spawning stock to be 75% of the pre-exploitation median.

For established toothfish and icefish fisheries, annual monitoring is undertaken to provide data on the status of the stocks to include in assessments. Decision rules are used to determine catch limits to achieve the target status of the spawning stock. For Antarctic krill, synoptic surveys have been undertaken to estimate pre-exploitation abundance. The decision rules are used to establish precautionary catch limits until such time as improved monitoring can provide regular updates on stock status. For Area 48 (the southwest Atlantic sector), there is also a trigger level of 620,000 tonnes, with smaller scale limits in each of the statistical subareas in the region, to limit the expansion of the fishery until a method for taking account of the spatial requirements of predators is developed.

CCAMLR aims to develop a feedback management procedure for krill fisheries based on indicators of the status of krill and its predators (Nicol and de la Mare 1993; Croxall and Nicol 2004; Kock, Reid et al. 2007; Constable 2011). Monitoring is being undertaken through the CCAMLR Ecosystem Monitoring Programme (Agnew 1997). However, at present this work does not factor in measures to account for climate change impacts on the ecosystem (Trathan and Agnew 2010; Constable 2011). Importantly, CCAMLR is yet to adopt an approach that can differentiate between climate change and fishery impacts on the food webs. Such an approach will be needed to ensure that fisheries do not impact on the marine ecosystems capacity to be resilient to the effects of climate change.

28.2.6.2.2. Tourism

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

28.2.7. State-Level Governance, Sovereignty, Military Presence

28.2.7.1. Climate Change and Conflict

There are studies showing that climate change can lead to migration and migration can result in conflict, although the complete chain is not proven. (Richardson et al, 2011) Ciccone (2008) studied the relationship between rainfall and income with a focus on conflict risk and he found lagged income changes (rainfall-driven) increase the risk of conflict. This is only one of several possible pathways for climate change to increase conflict risk with migration usually placed as an intermediary variable. (Gleditsch et al 2007)

28.2.7.2. Arctic Governance

The profound transformation driven by the forces of climate change and globalization is creating a heightened interest in the Arctic on the part of global actors motivated by economic opportunities involving commercial shipping, oil and gas development, mining, fishing, and tourism. The tightening of the economic and geopolitical links between the Arctic and the rest of the world are stimulating reassessment of the adequacy of governance systems. A major initiative - The Arctic Governance Project (AGP) –is bringing together preeminent researchers, members of the policy community, and representatives of indigenous peoples and exploring ways to achieve a sustainable and just future for the Arctic. (www.arcticgovernance.org)

28.2.7.2.1. Indigenous peoples, climate change, and traditional knowledge

[Note: This is focused on Eurasian Indigenous Reindeer Herders – need to add other indigenous populations, (e.g. Inuit) Also. Detailed references for these next few paragraphs needed.]

Reindeer herding is a human-coupled ecosystem which has developed a high resilience to climate variability and change. The explanation to this is that reindeer herding is a system based, as a rule, on continuous change due to the practice of seasonal migrations and day-to-day changes. The core survival strategy of reindeer communities is based on knowledge about how to live in a changing environment. The concept of "stability" is foreign in the languages of reindeer herders. Their search for adaptation strategies is not connected to "stability" in the normal meaning of this word, but instead is focused on constant adaptation to changing conditions. The basic needs for the animals are access to food and water, space for rest and shelter and space for physical activity. (Magga et al, 2011)

Reindeer husbandry is a traditional livelihood in Eurasia, carried out by more than 20 different ethnic indigenous Arctic peoples in Norway, Sweden, Finland, Russia, Mongolia and China, (e.g. the Sámi, Nenets, Komi, Khanty, Dolgan, Nganasan, Yukagir, Even, Evenk, Sakha (Yakut), Chukchi, Koryak, and Chuvan), involving some 100,000 herders, 2.5 million semi-domesticated reindeer, and covering some four million square kilometers. (Magga et al, 2011) As climate change affects the Sami regions of Norway, Sweden, Finland, and Russia with greater variability in temperature, precipitation and wind, and higher winter temperatures, these factors in turn strongly affect snow quality and quantity, with snow quality as a crucial factor for reindeer herding. Considering their experience obtained through time and their traditional ecological knowledge, the pastoral practices of Sami herders are inherently well suited to handle huge variations in climatic conditions. Reindeer herding and its natural environment have always been subject to large variability in weather patterns, and skillful adaptation to these past variations offers important insights on adaptation to climate change. In a particular, it is crucial to recognize the importance of traditional ecological knowledge. (Berkes, 2008; Reinert et al, 2009

Traditional ecological knowledge is defined as the knowledge, practice, and beliefs about dynamic relationships of living beings and the environment, a knowledge which has evolved in adaptive processes and been handed down from generation to generation. (Reinert et al, 2009; Berkes, 2008) Combining traditional and scientific knowledge about ecological systems and their interrelationships with cultural and economic systems, is crucial for understanding the resilience capacity of ecological and social systems and for identifying factors that can enhance the potential for sustainable development and self-sufficiency. (Berkes et al, 2008; Reinert et al, 2009)

The adaptation of Sami reindeer herding to climate change is conditioned by its political and socio-economic environment (Nuttal et al, 2005; Tyler et al, 2007) Important parts of the traditional adaptive strategies – the composition of the herds and the flexibility to move reindeer herds between summer and winter pastures – are challenged by nation-state policies restricting herd diversity and mobility and by rigid regulations. Governmental management of Sami reindeer herding in Norway is strongly conditioned by models of agricultural husbandry not suitable for reindeer herding. (Nuttal et al, 2005; Reinert, 2006; Tyler et al,, 2007) On the other hand, the reindeer husbandry communities of the Circumpolar north are guided by three cultural constructs within which they seek to: (1) Control their own destiny, (2) Maintaining their cultural identity, and (3) Be able to live close to and rely on nature for their livelihood and well-being. (Magga et al, 2011)

With a changing climate and increased industrial development, the ability to adapt the fine-tuned survival skills of reindeer herding in an Arctic landscape has become jeopardized as development can terminate, blocks or delay critical migrations between winter and summer ranges. Infrastructure designed to extract oil, gas, hydropower and minerals may appear insignificant in a seemingly vast undeveloped landscape, but may remove or compete for the few (or even only) migration routes possible across the land, leaving remaining herders highly vulnerable in a changing climate (Degteva and Nellemann, *in preparation*, Maynard et al., 2010; Oskal et al., 2009, Vistnes et al. 2009). Both in Yamal Peninsula and in Finnmark, Norway, two industrial development projects - gas and copper mining respectively - may block the migration routes of tens of thousands of reindeer with negative impacts on the herders. Such developments can alter the use of pasture areas through avoidance effects of reindeer to such development, infrastructure and human activity (Nellemann et al 2002).

Thus, a multi-faceted, long-term adaptation and mitigation strategy must be developed to increase the resilience of reindeer husbandry to these many challenges from land use changes as well as climate change. For example, unless a no-net loss of reindeer grazing ranges is implemented, continued piecemeal development, mainly as a result of activities indirectly associated with petroleum activity, will seriously threaten reindeer herding. Identifying alternative ranges, restoration of current ranges, or the development of mitigation schemes to reduce impacts of current and new activity will be required in order to ensure long-term sustainability and survival of reindeer husbandry. (Magga et al, 2011)

28.2.7.2.2. Reindeer, climate change, adaptation, and development

Climate change is happening faster in the Arctic than in any other regions of the world and the changes in ice cover and increases in temperature have already impacted reindeer husbandry and will continue to do so both directly, for example through changes in food availability, and indirectly such as through changes in human land use. (Oskal, 2008) Temperature changes have begun to cause some rivers to freeze later in the autumn and melt earlier in the spring, resulting in challenges for the annual migration of reindeer between different seasonal pastures. Warming-induced changes in freeze-thaw cycles are also creating problems. For example, as river and lake ice thaws earlier in the spring along migration routes, newborn calves can no longer cross the ice surface, but have to attempt crossing open waters, and large numbers of calves have been swept away by currents (Klein et al, 2005; Nuttal et al, 2005). Another change that has already been observed is increasing climate variability at a local level. This is especially true during the critical wintertime, where increasingly periods of mild weather accompanied by rain will be followed by colder periods, form ice layers in the snow and block the reindeers' access to food on the ground. As reindeer live only on natural pastures, this often represents a "worst-case scenario" from the reindeer herders' perspective. Increasing precipitation in the form of snow can add to these challenges, while warming would shorten the period of snow cover in any particular year. (Oskal, 2008; Maynard et al, 2010)

A deeper snow pack in winter can also make the reindeer more vulnerable to predator attacks (e.g., wolves) because the lighter wolves can travel on thinner snow crusts that reindeer sink through (Brotton and Wall, 1997). Increased insect harassment, accompanying warmer temperatures, is a second major factor shown to interfere with foraging. (Kitti et al, 2006) The outcome of this harassment is increased energy requirements, and results in a significant decline in body fat and lactation and decrease in calving success (Walsh et al 1992; Brotton and Wall, 1997; Gunn and Skogland, 1997). One example of recent climate impact is the unusually warm winter of 1996-1997, which was associated with a deep snow pack and icing, and which caused about 10,000 reindeer to die of starvation on Russia's far northeast Chukotsk Peninsula. (Malcolm, 1996; Nuttal et al, 2005)

Reindeer herders have also observed major changes in biodiversity. A significant example of this is repeated occurrences of certain species replacing others, such as the spreading of shrubs into the barren tundra-areas (Jia et al, 2003; Hinzman et al, 2005; Tape et al, 2006). Shrubs contribute to a hard packing of snow during the tough winter months, thus making access to food a challenge for reindeer. In addition, important food resources for the reindeer, such as lichens and reindeer preferred species of grasses, in time may disappear partially if not fully due to this shrub encroachment. Changes and/or increases in insect populations could also change reindeer behaviour during the summer by not allowing them to feed long enough in summer pastures due to increased harassment. (Oskal, 2008; Kitti et al, 2006)

Indirect effects of climate change are also being observed, with major implications for reindeer pasture availability and migration routes. (Kitti et al, 2006) Due to the sea ice melting and longer summers, increased accessibility of the Arctic regions for human activities is a growing threat to reindeer herders. Human development and activities represent disturbances with negative effects for the semi-domesticated reindeer herds (Kitti et al, 2006) and irreversible loss of marginal pasture resources – a serious challenge for reindeer husbandry. In particular, female reindeer and calves will stay away from humans, physical installations and general human activity. In the last 50 years, for example, approximately 25 % of the reindeer pastures of the Euro-Arctic Barents Region have in effect been lost due to human development (Tyler et al, 2007).

Of particular relevance today is the fact that the Arctic is estimated to contain approximately 25 % of the world's remaining undeveloped petroleum resources (Forbes, 2000). For instance, Yamal in Western Siberia holds about 90 % of Russia's gas reserves, while also being the largest reindeer herding area of the world. Activities to access these resources would reduce the grazing lands, and are viewed as another human activity in the Arctic contributing to the reduction of the "available room for adaptation" for reindeer husbandry (Forbes, 2000; Nuttal et al, 2005). In fact, industrial development (e.g., pipelines and oil and gas infrastructure) has increased across reindeer migration routes in Northern Russia, blocking pathways to summer pasturelands (Forbes et al, 2006).

It is also expected that there will be a sharp increase in the near future in oil and gas development, mining, and other forms of development in the Russian North – accompanied by infrastructure, pollution, and other manifestations of human presence – which will increase future pressure on available pasturelands for the reindeer and the indigenous communities associated with them. (Forbes, 2000; Forbes et al, 2006; Jernsletten and Klokov, 2002; Derome and Lukina, this volume) Furthermore, future reductions in sea ice from global warming recently projected are very likely to increase the amount of marine traffic and general access to the Arctic and, as a result, significantly increase development as well as serious problems related to sovereignty, social, cultural and other environmental issues, which will directly impact the indigenous reindeer herding community. (McCarthy et al, 2005). Finally, it is important to establish agreements between indigenous reindeer herders, industry and governments to ensure flexible access to historical pastures and migration routes which can co-exist with increasing development in a changing climate. There is no question that the protection of grazing lands used by reindeer stands out as one of the most important adaptation strategies that can be implemented to ensure long term sustainable reindeer pastoralism as well as to secure flexibility and robustness when facing climate change. (Magga et al, 2011)

_____ START BOX 28-1 HERE _____

2 suggestions for a box: (1) Focus on Sami reindeer herders and land use conflict with oil and gas and (2) broader impact of energy development on indigenous peoples

Suggestion #1: *a box to describe adaptation challenges of Sami indigenous reindeer herders as they address issues associated with climate change as well as land use change (oil and gas development and mining)*

Recent EALÁT-NASA studies in Eurasia, which combine remote sensing data with indigenous observations of changes over the past 30 years illustrate the magnitude of large-scale development of oil and gas related infrastructure which has taken place in the area (Degteva and Nellemann, *in preparation*, Kumpula *et al*. 2011, Maynard *et al*, 2010; Oskal *et al*, 2010). A series of cloud-free Landsat scenes between 1972 and 2010 combined with reindeer herder maps and photos provide both space-based and land-based observations of the growth of pipelines, roads, drill pads, buildings and other structures across the grazing areas and migration routes. (Oskal *et al*, 2010). These reindeer herders migrating through Bovanenkovo area are already experiencing negative impacts, but as long as they are able to migrate through the industrial developed areas to the nutrient rich summer pastures on the other sides of the petroleum field, they are willing to accept the development so far. The ability to migrate though these heavily developed pastures might be explained by the close coupling between herders and reindeer, which still is maintained in the YNAO. However, if the development becomes so dense that it is physically impossible to pass through the industrial complex or if migration through the industrial facilities becomes forbidden like for instance in the Hammerfest zone in Norway, it may seriously threaten reindeer pastoralism in the entire Yamal Peninsula (EALÁT workshop report 2009). Significant indirect effects of hydrocarbon development on reindeer herders include herders' lack of access to fish, the introduction of wild dogs, pollution, and an increased number of people visiting the region who have little knowledge about reindeer pastoralism (Forbes *et al* 2009).

Suggestion #2: *a possible box or paragraph on the broader impact of energy development in the Arctic and its impact on peoples and governments and include things like:*
-Resolution of disputed lands (offshore) between Russia and Norway – oil and gas potential is huge
-Yamal: an example of the conflict between oil and gas development and indigenous people
  Could highlight projects from reindeer herders (Anna Degteva, Maynard and EALAT team have completed study here; Bruce Forbes and Florian Stammler also have separate project here)
-Exploration of Greenland
-Exploration of US and Canada
-Impacts on Indigenous peoples and other locals is significant

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_____ START BOX 28-2 HERE _____

Box 28-2. Well-Being – Definition for the Arctic

(to be further developed)

There is some general agreement among researchers about what constitutes the key elements of overall well-being, namely physical well-being, material well-being, social well-being, development and activity, and emotional well-being. These elements may also be referred to as physical health, income and wealth, relationships, meaningful work and leisure, and personal stability (McAllister, 2005). Easterlin (2001) takes the terms "happiness, utility, well-being, life satisfaction, and welfare to be interchangeable," and according to McAllister (in Venn, 2007), the many different definitions of well-being can be summarized as something that "…comprises objective descriptors and subjective evaluations of physical, material, social and emotional well-being, together with the extent of personal development and purposeful activity, all weighted by a set of values. For the Arctic region research suggests that prominent features of human development and well-being include closeness to nature, cultural wellbeing, fate control, material wellbeing, education, and good health (ASI, 2010).

In the case of tundra nomads in the Nenets and Yamal-Nenets Autonomous Okrugs (NAO and YNAO), well-being has been directly and indirectly affected during the Soviet and post-Soviet eras. The key drivers have been misguided policies, institutional rigidity, socio-economic upheaval and extensive hydrocarbon extraction (Forbes, submitted). There have been both positive and negative consequences over the past half century and the most important of these are worth highlighting here since other regions may learn from the lessons drawn.

The displacement of children from the tundra in NAO in the 1960s and 70s was a painful process for many nomadic families (Tuisku 2001). This contrasts with the situation on Yamal, where large, nuclear families remain the norm (Ulvevadet and Klokov 2004; Stammler 2005). In NAO many obstacles remain preventing the return of family members to the tundra. This is a legacy of Soviet attitudes, which prevailed during the program of sedentarization. Relative to other regions within Russia (Krupnik 2000; Stammler 2005), and their counterparts in Fennoscandia (Forbes et al. 2006), the institutions governing reindeer herding have remained benign concerning day-to-day and month-to-month herd management. Even though administrators tend to see herding mainly as the "production of meat and antlers" (Tuisku 2002, p. 193), decisions can still be made quickly and efficiently and herds are not micro-managed for meat production to a degree that would reduce herders' ability to adapt to change. This is especially true on Yamal Peninsula compared to NAO, where the modern institutional arrangement accommodates decision-making that is sensitive to herders' needs and timetables.

Nenets nomads whose territories lie within the pathways of ongoing and planned developments understandably tend to rank hydrocarbon extraction as the issue of greatest concern for the future (Forbes and Stammler 2009; Kumpula et al. 2011). Key factors include the incremental loss of pastures and fishing resources to industry and changes in subsidies (Rees et al. 2008; Forbes et al. 2009). Yet industrial development is still only one among the various issues facing reindeer herders and administrators. For most herders the biggest concern is their basic economic survival and well-being from day to day, year to year (Tuisku 2003; Stammler 2005; Forbes and Stammler 2009).

_____ END BOX 28-2 HERE _____

28.2.7.3. Antarctica and the Southern Ocean

Human activities in Antarctica and the subantarctic islands are very limited in comparison to other parts of the world. There are no permanent populations living in this region and neither industrial nor intensive agricultural activities occur there. However, although the human presence is quite small compared to the overall size of the continent, human activities are concentrated on small ice-free areas adjacent to the coast because they are relatively easy to access by ship and they provide a stable surface for building. These ice-free areas are also home for the majority of the land-living plants and animals of Antarctica. The environmental impacts of human activities are concentrated in these areas, and impacts include disturbance to the landscape and contamination with pollutants.

Even though they are smaller in size, the areas where human activity occurs face many of the same threats as those areas occupied by or adjacent tohuman settlements in the Arctic.

There are four main types of human activities that take place in the Antarctic region, these are: marine capture fisheries, national scientific research programmes, commercial tourism, and private expeditions.

Governance in the region is primarily through the Antarctic Treaty System (1959) and the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR; 1982). Sovereign claims to the continent and surrounding waters and islands have been set aside under The Antarctic Treaty which regulates activities south of 60oS. CCAMLR regulates marine activities related to conservation and rational use, north from the continental margin to the Polar Front, one of the major fronts within the ACC. Most, but not all, of the subantarctic islands maintain undisputed sovereignty over their surrounding Exclusive Economic Zones, and where these fall within the area regulated by CCAMLR, nations have the right to exempt themselves from CCAMLR regulatory measures if they so choose. Each of the instruments places on Members and Parties obligations regarding environmental management and governance. Decisions are taken by a consensus.

Other key bodies governing specific activities in the region include the International Whaling Commission (IWC), the Agreement on the Conservation of Albatross and Petrels (ACAP), the Convention on the Conservation of Antarctic Seals (CCAS), the International Maritime Organisation (IMO), and the *International Convention for the Prevention of Pollution from Ships* (MARPOL).

Within Antarctica the impacts of climate change would be considered by the Committee on Environmental Protection (CEP) and the Council of Managers of National Antarctic Programs (COMNAP), both of which advise the Antarctic Treaty Consultative Meeting (ATCM). They would also be evaluated by the Scientific Committee of CAMLR (SC-CAMLR), which advises the Commission of CAMLR. The Scientific Committee of the IWC would advise the IWC Commission. The Scientific Committee on Antarctic Research may also provide advice to both forums, including through periodic reports such as the SCAR report on 'Antarctic Climate Change and the Environment' (Turner, Bindschadler et al. 2009).

28.3. Key Projected Impacts and Vulnerabilities under Different Climate Pathways

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Results of research conducted from various basins around the Arctic and at a broader full circumpolar scale using projections from global and regional climate models for varying scenarios of increasing greenhouse-gas concentrations continue to point to an intensification of the hydrologic cycle within the Arctic (Kattsov *et al*., 2007; Holland *et al*., 2007; Lewis and Lamoureux, 2010; Pohl *et al*., 2007; Dankers and Middlekoop, 2008; Hay and McCabe, 2010). Although there is regional heterogeneity in specific hydrologic responses, such intensification is characterized by enhanced evaporation and evapotranspiration, particularly during the summer months, but a proportionally larger increase in precipitation, particularly during winter and fall, which results in greater, annual river discharge (Kattsov *et al*., 2007). Although the driving AOGCMs employed in many analyses of future hydrologic regimes still tend to overestimate precipitation and P-E at higher latitudes, such biases are considered small relative to the overall magnitude of the increases (2080-99 vs 1980-1999) in terrestrial freshwater flux to the Arctic Ocean, which range from 14 to 25% (for the mean B1 and A2 scenarios of 17 models) by the end of the 21st Century (Kattsov *et al*., 2007). *[Note: this section to be updated if new material is published about the hydrologic output of the new AR5 suite of IPCC models, prior to AR5 WGII publication deadlines].*

Also evident in the results of studies that have coupled AOGCMs with hydrologic models is a shift to earlier timing of spring runoff (Pohl *et al*., 2007; Dankers and Middlekoop, 2008; Hay and McCabe, 2010). In some cases, an increase in the magnitude of spring runoff has also been projected, which has also been forecast to produce increases in sediment flux. A hydrologic modelling study in permafrost regions of the Canadian Archipelago (Cape Bounty) indicate a 100 to 600% increase (based on CGCM3 A1b and A2 scenarios, respectively) in sediment yields by the end of the 21st, but these were considered minimum estimates because the possibility of future, enhanced permafrost disturbance was not factored into the modelling approach (Lewis and Lamoureux, 2010). Although snow, freshwater ice and permafrost control the driving and resisting forces that ultimately transform the overall form of arctic alluvial channels, their combined synergistic effect under projected future changes remains unclear (McNamara and Kane, 2009). In the case of small streams, even if the thickness of the hyporheic zone in Alaskan streams might not deepen substantially in the future, the period of flowing water is expected to lengthen substantially, thus modifying nutrient and organic matter processing in this important habitat area (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 from erosion or thaw of the landscape (Bowden *et al.*, 2008).

Projected changes in spring flood regimes of northern rivers have also been addressed by considering changes to river-ice regimes. A future reduction in thermal gradients along northward flowing and ice-covered arctic rivers has been suggested to decrease spring flooding because of lessening in the severity of ice jamming (Prowse *et al.*, 2010). Such a conclusion is based on GCM-ensemble predictions of air temperatures for mid and late-21st Century (2041–2070 and 2071–2100) along the lengths of the 4 largest arctic rivers, Lena, Ob, Yenisei and Mackenzie; the results of which indicate earlier timing and lower dynamics in ice breakup conditions compared to current (1979–2008) conditions. [*Potential Figure: average projected changes in 0 °C conditions on the four largest Arctic rivers based on average values of four GCMs*] One caveat made on such a projection is the complicating role of changes in the magnitude of spring snowmelt, which has also been projected to increase, particularly in areas with winter temperatures <-30ºC (Adam *et al.*, 2009). The net result of these two factors (magnitude of spring melt and severity of ice jams) remains to be quantified but will vary by river basin according to spatial and temporal variability in future precipitation accumulation and snowmelt regimes around the circumpolar north, including in the headwaters of the large basins located in more southerly latitudes.

As noted for current conditions, any reductions in river ice-jam flooding would have major positive benefits for communities and infrastructure located along the river margins but 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 (freshwater water impounded behind near-shore pressure ridges or grounded sea ice) 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 in terrestrial lake-ice regimes have been identified in previous arctic assessments to be of concern for a variety of ecological and socio-economic systems, but only recently have projections been made of future regimes. The most spatially comprehensive modelling of lake-ice regimes was conducted by Dibike *et al.* (2011), who compared current (1960–1999) and future (2040–2079) ice-cover phenologies for hypothetical 20-m deep lakes positioned at a resolution of 2.5° latitude and longitude for all Northern Hemisphere land masses between 40° and 75°N. Results from using a one-dimensional lake simulation model driven by output from the Canadian Global Climate Model (CGCM3) indicate that future warming will result in an overall increase in lake-water temperature, with summer stratification starting earlier and extending later into the year and, hence, the timing of freeze-up being delayed by 5 to 20 days. Break-up was projected to occur 10 to 30 days earlier, resulting in an overall decrease in lake-ice duration of about 15 to 50 days. Maximum lake-ice thickness was also modelled to decrease by 10 to 50 cm. Changes in snow loads and related ice-cover composition were also modelled. In general, maximum snow depth changed by -20 to +10 cm and white ice by -20 to +5 cm, depending on the geographical location and other climate parameters – the high latitudes being an area of projected increases in winter snowfall that can promote white-ice formation particularly with thinner ice cover.

Dibike *et al.* (2011) also examined some of the broad patterns in lake thermal structure that would accompany the above noted changes in ice cover. Two longitudinal transects at 105°W and 90°E, representing cross-sections through central continental areas of North America and Asia, respectively, were examined in detail. [*Potential Figure to be inserted here]*. Of particular note was that higher-latitude lakes along the 105°W transect exhibited less change in future summer stratification than those along 90° E; the differences possibly due to regional differences in warming and/or differences in relative coldness and/or elevation of the two regions.

The loss or reduction in duration of ice cover on lakes and corresponding changes in pelagic water thermal regimes have been identified as creating a number of cascading effects. For example, Flanagan *et al.* (2006) showed experimentally that sedimentation, pelagic food web structure and nutrients are co-factors directly controlling CO_2 flux in freshwaters. Projected changes in aquatic food web structure arising from decreasing ice-cover along with altered thermal and related stratification regimes can affect carbon cycling and dynamics in arctic freshwater lakes via alterations in herbivore control of algal populations and changes in algal species composition. Changes in lake morphology (e.g., via increased drying or drainage), alterations in thermal stratification patterns, and effects of sediment decomposition arising from increased warming will collectively affect carbon dynamics. In a warming Arctic, shallower lakes that are not thermally stratified will have greater opportunity for mixing surface waters with sediments, resulting in greater carbon recycling back into the water column. Alternatively, in thermally stratified lakes carbon sinking below the thermocline may not return to surface waters until fall turnover, decreasing the likelihood of carbon lost to sedimentation being recycled back into the water column (Flanagan *et al.*, 2006).

Lake ice duration also has a controlling influence on pelagic water-column oxygen conditions (e.g., Laurion *et al.*, 2010). The projected shift of lakes from cold monomictic (continuous mixing in summer) or polymictic (multiple episodes of mixing in summer, favored by cold temperatures) to dimictic (stratified in summer) will increase the possibility of oxygen depletion and even anoxia in the bottom waters during their periods of summer stratification. For some lakes, the loss of ice will result in the loss of suitable habitat, both in availability and quality (Vincent *et al.*, 2008a). Habitat availability for high oxygen-demanding biota such as Arctic char (*Salvelinus alpinus*) will be reduced under increasing incidence of water column stratification arising from warming. Severe oxygen depletion under ice often leads to the 'winter kill' of resident fish. The occurrence of such events are expected to be reduced in a warmer climate with shortening ice duration, with potential cascading effects on lower trophic levels (Balayla *et al.*, 2010).

In addition to habitat alterations, geochemical responses of Arctic lakes will be altered. As already observed for certain Arctic thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production from the vast wetland-lake regimes of northern latitudes (Metje and Frenzel, 2007; Laurion *et al.*, 2010). Short-term sediment warming experiments in a set of Swedish lakes has shown temperature sensitivity was a stronger control over methane production than oxidation, which was governed by substrate availability (Duc *et al.*, 2010). This suggests that elevated temperatures from climate warming will enhance methanogenesis, causing increased methane release from sediments until methane oxidation increases in response to higher methane levels. However, still significant uncertainty still remains regarding what changes in environmental factors that alone or in combination can affect the relative balance of methanogensis and methanotrophy (Walter *et al.* 2007a,b, 2008; Laurion *et al.* 2010). In addition to methane, enhanced water temperatures are projected to lead to reduced organic carbon (OC) burial. Based on a broad range of six climate warming scenarios from the IPCC (Solomon *et al.* 2007), it is projected that there will be a 4-27% decrease (0.9-6.4 $TgC\ yr^{-1}$) in OC burial in lake sediments across the entire northern boreal zone by the end of the 21st Century (Gudasz *et al.*, 2010). These estimates are based on an assumption that future organic carbon delivery to lake sediments will be similar to present-day conditions. Even with enhanced delivery, as might be expected with thawing permafrost, rising temperatures is noted to increase organic carbon mineralization thereby lowering burial efficiency.

Changes in the duration of ice cover and the associated alterations in thermal regimes and stratification patterns will also affect the fate of contaminants to northern lakes. *[It is anticipated that more material will be inserted on this issue after the release of the upcoming AMAP report on mercury]*. Greater methylation of mercury, for example, is likely to result from higher temperatures, particularly in shallow zones. In addition, higher water temperature is likely to increase pelagic production and thereby enhance algal scavenging of mercury, which is a foodweb entry pathway for mercury (Outridge *et al.*, 2007). Higher water temperatures associated with a decrease in ice cover, and related changes in food and energy pathways and/or productivity (benthic to pelagic) will likely modify the movement of contaminants through such lakes (Carrie *et al.*, 2010).

Changes in lake-ice regimes will have significant impacts and cascading effects on aquatic ecosystem structure and function through alterations in species distribution patterns, foodweb complexity and trophic coupling. Effects are projected to occur at the individual level (e.g., displacement from preferred habitat, alteration in growth rates), the population level (e.g., changes in distribution and range, abundance), and community/trophic levels (especially destabilization of predator-prey dynamics; Nelson *et al*. 2005). A paleolimnological study on Lake El'gygytgyn, an ancient crater lake in the Siberian Arctic, found that periods of the 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). Increased temperatures and stratification associated with decreases in ice cover, accompanied by larger nutrient inputs, may also favor the development of certain phytoplankton and bacterioplankton communities. Flagellate plankton populations have been observed to be abundant below the ice in Arctic lakes, while diatom communities become dominant once ice is gone (Vincent *et al*. 2008b). Primary production is also expected to increase with decreased ice thickness and snow cover. Although snow-free ice conditions are known to promote bloom concentrations of photosynthetic flagellates, under-ice plankton abundance could be negatively affected by the projected increases in surface accumulations of snow and/or the formation of white ice. Such changes in snow and white-ice coverage are also likely to affect levels of secondary productivity such as in fish (e.g., Borgstrøm and Museth, 2005; Prowse *et al*., 2007).

Patterns of species richness and diversity are also projected to change with alterations to ice and open-water durations. The diverse, highly stratified communities of single-celled *Archaea* in High Arctic lakes are likely to be disrupted by future changes in the duration of ice cover (Pouliot *et al*., 2009), although increased open water is also projected to promote the development of new trophic levels and the successful colonization of new aquatic species assemblages (e.g., Vincent *et al*., 2009).

28.3.1.2. Antarctic

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

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

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

In glacial forelands increased melting of glaciers has increased water supply in lake catchments. As the Antarctic continent has only two species of flowering plants, vegetation in lake catchments is limited to mosses, lichens and microbial communities so nutrient levels are typically low compared with sub-Antarctic and Arctic catchments. This can limit the supply of allocthonous carbon and catchment derived nutrients to the lakes by overland and subsurface flow. Nevertheless, under a warming climate an increase in this catchment microbial biomass would be expected both from increased water supply and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved organic carbon delivery to lakes. This organic supply will promote growth and reproduction in the benthos and plankton. Another observation is that where more melt water is available, input of freshwater into the mixolimna of deeper lakes can increase stability and this, associated with increased primary production, will lead to higher organic carbon flux. Such a change will have follow–on effects including potential anoxia, shifts in overall biogeochemical cycles and alterations in the biological structure and diversity of ecosystems (Lyons 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.

Increased temperatures may promote growth and reproduction, but may also contribute to drought and associated effects. At individual locations the susceptibility of lakes to these effects can be predicted from the palaeolimnological record of past warm periods (e.g. Hodgson et al 2005). Away from glacial forelands, future regional patterns of water availability are unclear, but increasing aridity is likely in some areas of the continent in the long-term (Robinson et al., 2003). In some areas of East Antarctica, longer periods of open water have led to increased evaporation and, together with sublimation of winter ice cover, have resulted in rapid increases in lake salinity in the last few decades (Hodgson et al., 2006). Similarly, on sub-Antarctic Marion Island a substantial decrease in rainfall has seen dramatic changes in mire communities (Smith, 2002). To date there are no documented examples of lakes drying up completely and causing local extinctions as experienced in Arctic lakes (Smol and Douglas, 2007).

Climate changes can also impact on species distributions. In the northern hemisphere, warming of the polar regions has resulted in populations of extant groups expanding their range as new sites become available for colonization. This has been possible because much of the Arctic represents the northern extension of continental landmasses and there are few barriers to dispersal of the biota. In marked contrast, the Antarctic is an isolated continent separated by steep oceanic and atmospheric thermal gradients, and circumpolar currents and winds which have provided formidable barriers to dispersal. The most obvious example of restricted dispersal is the absence of freshwater fish south of the Antarctic convergence. These barriers have resulted in major restrictions in colonization pathways and as a result Antarctic and sub-Antarctic freshwater ecosystems are very different, and in some cases more vulnerable, than their Arctic counterparts.

For some organisms with good dispersal capabilities, the onset of cold glacial conditions on the continent has resulted in their extinction, and then (re) colonisation from refuges in the maritime and sub-Antarctic islands and from the higher-latitude southern-hemisphere continents (South America, Australasia) during warm interglacials (Clarke *et al*. 2005; Barnes *et al*. 2006). The last interglacial (MIS 5e) is of particular interest, as many records show that temperatures were warmer than present and that global melting of the ice sheets contributed an additional 3–5 m to global sea level. Lake sediment records from MIS 5e provide a valuable opportunity to determine how a particular location and ecosystem responded to warmer conditions in the past, and are therefore a key tool in predicting the responses to the climate changes simulated by climate models in the immediate future. Analyses of biological and biogeochemical markers in a lake in the Larsemann Hills (East Antarctica) show a more productive biological community and greater habitat diversity during the warmer conditions of MIS 5e, together with a diatom flora that is today found in the sub- and maritime Antarctica. From the composition of these MIS 5e sediments it is safe to predict that future elevated temperatures will allow the sub- and maritime Antarctic taxa to re-invade and establish self-maintaining populations on the continent (Hodgson *et al*. 2006).

For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman et al. 2010). For these endemic species, molecular data shows that they have evolved on the continent over multiple glacial interglacial cycles, likely in non-glaciated lakes, epiglacial lakes, and cryoconite holes. Molecular evidence of endemism in cyanobacteria, diatoms, and other biota on the continent supports this view (Sabbe *et al*. 2003; Taton *et al*. 2006; Vyverman *et al*., 2007, 2010) and allows for the possibility that Antarctic lakes may contain species that are relicts of Gondwana (cf. Convey and Stevens 2007). This means that Antarctica has developed its own unique flora in some groups that cannot be replaced from lower latitudes if they were to experience local or continental extinction as a result of climate changes.

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

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Arctic

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

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

There is robust evidence, high agreement within the scientific community, and statistical evidence that global warming will very likely reduce ice cover and earlier ice breakup will result in a longer growing season (Wang and Overland 2009, Wassman 2011a, SWIPA 2011). There is evidence that the Bering Sea will warm by 2 degrees by 2050 (Hollowed et al. 2009). It is likely that the northern Bering Sea shelf will remain ice covered in winter and that the cold pool will remain present in the northern Bering Sea shelf (Stabeno et al. 2010). There is medium agreement and medium evidence that Arctic waters will become stratified due to glacial runoff and solar heating. Lower certainty is assigned to issues of stratification because it is unclear how climate change will impact the strength of inflow of Atlantic water into the Arctic and it is unclear how glacial runoff and solar heating will interact spatially within the Arctic (need reference here, Wassman 2011). There is evidence that that pH of the Arctic Ocean my decline and simulation models project a drop in pH of 0.45 in this century based on the A2 scenario (Steinacher et al., 2009).

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

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

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

Fewer commercial fish species from the Pacific are expected to colonize the Arctic because of the shallow depth of the Bering Strait, the continued formation of the cold pool in the northern Bering Sea, and the comparatively weaker flow into the Arctic. There is medium evidence and medium agreement that walleye pollock stocks in the Bering Sea will be negatively impacted by increased temperature and its associated impact on prey availability (Mueter et al 2011, Hunt et al. 2011). There is medium agreement that walleye pollock will exhibit moderate northward shifts in distribution in response to shifts in ocean temperature, however, since this species avoids the cold pool, its persistence in the northern Bering Sea will continue to block range expansions into the Arctic Ocean (Stabeno et al. 2011).

28.3.2.2. Antarctica and the Southern Ocean

The expected physical changes in the Southern Ocean include a strengthening of the Southern Annualar Mode (SAM), reflecting a southward movement of atmospheric circulation patterns, a freshening and warming of the ocean and a slowing of the overturning circulation. Ice shelves and fast ice are expected to continue to be lost, reducing potential breeding habitat for ice-dependent species, but exposing ice free land for land breeding species. Breakup of iceshelves will increase iceberg scour on the shallow continental shelf, at the same time exposing new marine habitats. Reduced ice on the margins of the continent will increase the potential for breeding habitat in higher latitudes. Increased carbon dioxide in the ocean will lead to acidification, which will be particularly acute in the Southern Ocean before any other region and is predicted to affect benthos in shelf areas within 20 years (Guinotte, Orr et al. 2006; Riebesell, Bellerby et al. 2008).

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

The prognoses for sea ice and its dependent biota are less clear. Sea ice is expected to thin and become much less extensive; the western margin of the Ross Sea and the Balleny Islands area are predicted to be least affected over the next 100 years. However, summer sea ice is expected to be lost from the West Antarctic Peninsula and much of the Bellingshausen Sea. Importantly, the change in duration of the winter sea ice season and the potential 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 (ref). This mismatch in timing can also propagate through the food web to impact on krill and upper trophic levels that depend upon krill (ref).

Many of the predicted consequences of increased atmospheric CO_2 levels remain uncertain and make it very difficult to assess the future threats to Antarctic krill and finfish fisheries. However, with increasing ice free areas near to the Antarctic continent, it seems highly likely that there could be more high latitude areas suitable for fishing in the not too distant future.

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

28.3.2.3. Predicting Changes in Fisheries (separately for the Arctic and the Antarctic)

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

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

[yet to be written due to absence of CA – Bruce may contribute text]

28.3.3.2. Predicted Terrestrial Biological Response to Climate Change in Antarctica

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

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

28.3.3.2.1. Direct human impacts on Antarctic terrestrial biodiversity

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

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

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

28.3.3.2.2. Anthropogenic transfer of non-indigenous species

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

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

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

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

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

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals (see 28.2.3 above) are likely to have far greater importance over the timescale under consideration than are those attributable to climate change itself (Convey et al., 2009; Turner et al., 2009; Convey, 2010).

28.3.4. Economic Systems

Projections of the economic costs of climate change impacts in the Arctic are limited, but current assessments suggest that there will be both economic benefits and costs (e.g. SWIPA 2011, D.L. Forbes, 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 G. K. et al, 2011).

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

Climate change impacts may exacerbate damage caused by anthropogenic drivers. At the circumpolar scale, certain geographic areas appear especially vulnerable to damages from anthropogenic drivers, such as oil and gas development, that may threaten their ability to supply goods and services in the near future. Climate change could exacerbate this situation in some places, e.g. in Russia where regulatory institutions for mitigating industrial damages to the environment remain weak (Forbes et al. 2004b). In Fennoscandia, persistent problems in the institutions governing reindeer management (cf. Forbes et al. 2006) present a similar threat in the face of increases in the intensity and extent of extreme weather (Bartsch et al. 2010).

Some attempts have been made at estimating the economic costs of climate change. One set of estimates suggests e.g. that economic costs based on three different estimates of the social cost of carbon – and high, medium and low range estimates of increased forcing due to changes in sea-ice and snow-cover albedo and increased methane releases that result from a thawing Arctic – fall in the range of an estimated rate of $61-371 billion annually, with the cumulative cost impact over the next 90 years could reach trillions of dollars (Goodstein et al. 2010). Economic cost estimates for the Alaska economy suggest that the heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries, renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). From the present to 2030, permafrost thawing, amplified flooding and coastal erosion from global warming could add $3.6 to $6.1 billion to future costs of public infrastructure in Alaska (SCEIGW 2010). Melting tundra can cause oil pipelines to buckle and break, causing spills (Epstein et al. 2008). A significant part of Alaska's economy is tourism. More than 632,000 people spent $1.4 billion on hunting, fishing, and wildlife viewing in 2001, which created 28,583 local jobs. 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 also been estimated that the Shishmaref, Kivalina, and Newtok tribal lands will be unliveable due to storm damage and coastal erosion in a number of years. The cost to re-locate these communities is estimated to be $355 million. These estimates do not include the costs of social upheaval associated with relocation of tribal groups that have occupied these territories for over 4,000 years (Williams et al. 2007).

28.3.5. Economic Sectors

28.3.5.1. Arctic

Projections of the economic costs of climate change impacts in the Arctic are limited

28.3.5.1.1. 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. Models are available to compute regional economic impacts of supply-side, and demand-side, changes (Seung and Waters 2010, Waters and Seung 2010). Economic models for making projections of global seafood demand under IPCC scenarios have been developed (Merino et al., 2010) but none exist for fisheries in the Polar Regions. O'Neill et al. (2010) provide a model that comes somewhat close to 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).

According to the ACIA (2007) report, projections made for Icelandic fisheries have suggested that over the next 50 to 100 years while fish stock availability is unlikely to be greatly impacted, climate change is very likely to benefit the most valuable fish stocks. Changes in fish stock availability most likely to be induced by climate change are unlikely to have any significant long-term impacts on Gross Domestic Product (GDP) in Iceland over the next 50 to 100 years, and any impacts is more likely to be positive rather than negative. A sudden change in fish stock availability could however have significant impacts on rate of economic growth (Vilhjálmsson & Hoel, 2006). In the case of Greenland, on the other hand, the range of impacts is projected to be much wider, ranging from a 30% increase in GDP at one extreme, to negligible at the other extreme. Economic and social impacts of climate change in Newfoundland and Labrador Seas, Northeastern Canada under different climate scenarios (13.4.7, p. 744) suggest that the social and economic effects of changes in fish stocks due to climate change are likely to be less than the historical changes experienced in the latter part of the 20th century in Newfoundland and Labrador (Vilhjálmsson & Hoel, 2006, p. 744).

[More contributions (incl. updated projections) to be included in next draft]

28.3.5.1.2. Forestry and farming

Climate change may lead to economic benefits and costs for forestry and farming. Predictions of a longer and more suitable growing season should bare in mind that the growing season is determined not only by temperature but also the length of daylight. The 23,5° tilt in the Earth's axis of rotation commands that there will always be darkness and cold at high latitudes. Thus farmers are not necessarily able to adapt by planting sooner (Smith 2010, 111, 260).

A warmer climate is likely to impact access conditions and plant illnesses. According to Grønlund (2009) about half of the arable land area in Northern Norway is at the moment covered by forest and 40% of it is marsh. If these areas were to be harnessed for farming, it would come 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 also increase conditions for plant illnesses and mushrooms (Grønlund 2009, 4). A warmer climate will increase vulnerability of forests to the threat of new illnesses and pests, and increase the distance to all-year roads (Grønlund 2009, 5). If the winter season were to shorten as a result of climate change, this would negatively affect access to logging sites, which is best when the frozen ground makes transportation possible in sensitive locations or areas that lack road. If the weather then i.e. changes when logging has already taken place, sanding of the road becomes necessary in order to ensure transportation within a specific timeframe, which carries significant economic costs (Keskitalo 2008, 228-229). Any impact on the carrying capacity of the ground or road accessibility will thus affect forestry economically. Challenges may also include limited storage space for wood (Keskitalo 2008, 229). Any change and need for larger storage, would lead to extra costs. A warmer climate may also have positive effects on forestry: In the case of Finland where forestry is of great economic importance, the risk of snow damage to forest is estimated to decrease with about 50% towards the end of the century (Hovelsrud et al, 2011).

28.3.5.1.3. Infrastructure

The risk to permanent infrastructure is likely to intensify with climate warming (National round table on the Environment and the Economy 2009, 3). Infrastructure built on permafrost, which has traditionally provided a strong foundation for buildings, is especially at risk as thawing of the ground leads to loss of strength and instability (Furgal and Prowse 2008, 80; NorAcia 2010, 115).

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

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent upon the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter. Communications towers and energy transmission infrastructure located in remote permafrost areas are becoming increasingly susceptible to the risk of failure and, since accessibility may also be an issue and the cost of redundancy is prohibitive, the threat posed by this hazard will 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 (National Round Table on the Environment and the Economy 2009, 61-62; Furgal and Prowse 2008, 59, 82). The implications for the sea-ice system may prove to have other major impacts as well, including environmental and socio-economic or geopolitical change which may substantially modify types of services offered and their uses by competing interests. Changing sea-ice (multiyear) conditions are suspected i.e. to have a regulating impact on marine shipping and coastal infrastructure through possible hazards on them (Eicken et al 2009, 123).

28.3.5.1.4. Inland transportation, communication, and drinking water

By adapting transportation models to integrate monthly climate model (CCSM3) predictions of air temperature and temperature, combined with datasets on land cover, topography, hydrography, built infrastructure, and locations of human settlements, estimates have been made about changes to inland accessibility for northern landscapes northward of 40ºN by mid-21st Century (Stephenson *et al.*, 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000 kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000-2014) for eight circumpolar countries was projected to be -14%, varying from -11 to -82%. In absolute terms, Canada and Russia (both at -13%) account for the majority of declining winter-road potential with ~$1x10^6$ 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, 52; Communities of Inuvialuit Settlement Region et al., 2005 In Furgal and Prowse 2008, 100). 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 and Prowse 2008, 104, 111).

28.3.5.1.5. Terrestrial resource management (oil and gas, mining, forestry in the Arctic)

Commercial opportunities including transport of cargoes, fisheries and access to offshore energy resources are expected to increase with reduced sea-ice coverage. Predicted new access to offshore energy resources are hypothesized to be a significant share of the global supply of oil and gas (Gautier et al. 2009; Berkman 2010, 19). Several barriers to increased large-scale resource development will continue to exist and translate into higher costs of doing business in the North. These include challenges to operating in cold climates, lack of linking infrastructure, distance to markets, and social regulatory, and environmental risks. The potential environmental and social consequences of large-scale development in the region may delay decisions and project implementation, as will considerations on the equitable distribution of benefits from resource extraction. The lasting impacts of e.g. the Alaskan Highway project illustrate the range of social and environmental problems linked to large-scale development in Canada's North (National round table on the Environment and the Economy 2009, 41). Gas development in the tundra zone is still in its early stages, and preliminary work has demonstrated that there are widespread terrestrial ecological problems associated with just seismic surveys, exploratory drilling, and new infrastructure, which includes road and railway constructions (Forbes et al. 2009, 22042).

28.3.5.1.6. Anticipated new resource exploitation development in the North

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

[INSERT FIGURE 28-4 HERE
Figure 28-4: Title? (be scanned from Mokhow and Khon, fig. 6 on page 25)]

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

[Boxes (potential) – to be considered for next draft
-Box: Suicide in the arctic
-Box: Language retention
-Box : Migration, relocation]

28.3.5.2. Antarctica

[ ]

28.4. Adaptation

Climate can determine the security of Northern people through access to resources; risks while travelling, hunting or fishing; infrastructure stability; resource productivity; power generation and the recreational use of nature (Hovelsrud and Smit, 2010). The impact of climate change on the peoples of the Polar Region must be seen in the context of other, often interconnected, stresses such as demographic, economic, cultural and health factors that affect their security. Indeed, climate change alone is not always the most important factor determining vulnerability in polar communities but is often a force that exacerbates other stresses. (Anisimov et al, 2007; Forbes and Stammler 2009; Forbes et al. 2009; Crate et al. 2010; Hovelsrud and Smit, 2010).

28.4.1. The Stresses of Climate Change in the Polar Regions

28.4.1.1. Direct Impacts in the Polar Regions

28.4.1.1.1. Sea ice

Sea ice extent in the Arctic has declined significantly and at a much larger rate than projected by climate models (Stroeve et al., 2007; Barber et al., 2008). The minimum sea-ice extent has been below normal since 2007 when a large amount of multiannual sea-ice was flushed out of the Arctic via the Fram Straits. There are also clear indications of thinning sea ice cover (Kwok and Rothrock, 2009), decreased multi-year ice cover (Kwok, 2007), and later occurrence of freeze-up and earlier break-up across the Arctic (Markus et al., 2009). These trends are consistent with the warming of the atmosphere and ocean in the Arctic (Serreze et al., 2000; Chapin et al., 2005; Furgal and Prowse, 2008). Although much of the Arctic could become ice free during the summer within the next few decades it is unlikely that this will be irreversible (Tietsche, Notz, Jungclaus and Marotzke, 2011).

Reduced sea ice could open new shipping routes across the Arctic (although narrow channels through the North West Passage may continue to provide navigational hazards) (Johnston, 2002; Barber et al., 2008; Howell et al., 2009; Somanathan et al., 2009; Ho, 2010). However, there will be less of the ice on which polar bears and some seals rely for feeding and giving birth, it also exposes coastline to the full force of ocean storms and makes hunting by indigenous people more risky.

28.4.1.1.2. Land ice

The estimated total volume of land ice in the circumpolar Arctic is approximately 3.1 million km3, which is equivalent to about 8 m of sea level rise. The majority of this is contained on the Greenland Ice Sheet. In general glaciers and ice caps across the Arctic (apart from the Greenland Ice Sheet) show a retreat in glacier fronts and volume decreases although there are large regional variations (Furgal and Prowse, 2008). The Arctic glaciers are expected to contribute significantly - as much as Antarctica - by 2100 to sea-level rise (Radic and Hock, 2011). Such sea level rise, with some expected post-glacial rebound in places, will threaten communities and cultural sites on the coasts through increased flooding and the infiltration of ground water supplies (Furgal and Prowse, 2008).

From 1846 to 1995, freeze-up and break-up trends for lakes and rivers in the Northern Hemisphere, including a long-term site on the Mackenzie River, show an average delay of 5.8 days per century in freeze-up dates and an average advance of 6.3 days per century in break-up dates (Magnuson et al., 2000). Changes in winter snowfall is likely to be a major factor in determining whether the severity of river-ice events, such as ice-jam flooding, increase or decrease (Walsh et al., 2005).

Lake and river ice have historically served as natural transportation routes, and modern engineering has led to increasingly sophisticated methods of winter-road construction. Ice roads and ice bridges that are constructed and maintained each winter provide a relatively inexpensive way to supply northern communities and industry, particularly the rapidly expanding mining sector that relies on ice roads to move heavy equipment, materials and fuel. Additionally, they form critical travel routes connecting communities and facilitating the ability to continue social and cultural activities during winter months. Changes in ice thickness associated with climate warming reduce the maximum loads that can be safely transported and forces transportation companies to reschedule shipments (Furgal and Prowse, 2008).

28.4.1.1.3. Permafrost

Approximately half of the area underlain by permafrost in Canada is warmer than - 2°C and could disappear under projected climate warming (Smith and Burgess, 2004). The removal of insulating vegetation cover and other land disturbances that generally accompany development can also significantly alter the ground thermal regime as was observed in the development of the Norman Wells pipeline in the Yukon (Burgess and Smith, 2003). Additional warming may further occur due to heat generated by the structure itself (e.g. heated buildings and buried water, sewage or hydrocarbon pipelines).

Thawing of the permafrost, especially if it involves differential settlement due to variations in soil characteristics, will not only threaten landscape stability but also infrastructure built on the permafrost (Nelson et al. 2001). It also has the potential to release large pools of carbon, which can act as feedback to the climate system. Frozen ground plays an important role in northern hydrology through its influence on infiltration, runoff and groundwater storage and flow. Changes in permafrost stability will have impacts for the storage of mining wastes and increase the likelihood of contaminant transport. Failure of frozen-core dams due to thawing and differential settlement could result in contaminants being released into the surrounding environment, with subsequent impacts on ecosystems and human health (Furgal and Prowse, 2008).

28.4.1.1.4. Freshwater regimes

Rivers flowing into the Arctic Ocean have low winter runoff, high spring flow rates (driven by snowmelt) and rain-induced floods in the summer and autumn. Snowmelt accounts for most of the flow in high-Arctic rivers and streams. Projections of future climate suggest that total annual discharge to the Arctic Ocean could increase between 10 and 20% by about 2050, with winter discharge likely to increase between 50 and 80%. It is also expected that 55 to 60% of annual discharge will enter the Arctic Ocean during the peak runoff season between April and July (Furgal and Prowse, 2008).

28.4.1.1.5. Weather variability

With warmer air temperatures there will be more water vapour in the atmosphere. This could give rise to heavier snow falls (Callaghan et al. 2011). In combination with the expected increased variability in weather patterns this could lead to more freeze/thaw cycles that is likely to increase the snow and ice loading on infrastructure. Warmer air temperatures will likely lead to more precipitation falling as rain rather than snow which when it freezes makes it more difficult to animals such as caribou and muskox to forage for food (Gunn et al., 2006; Miller and Barry, 2009; Bartsch et al. 2010). During the summer warmer temperatures will lead to drier forests and the greater threat of wildfires (Government of Canada, National Roundtable on Environment and the Economy, 2009).

Other weather-related impacts include the expected increase in the frequency and severity of extreme events with unpredictable and rapid onset of storms potentially causing risks to safety of travel particularly in isolated communities and more physical and psychological injuries (eve deaths) (Berner et al, 2005). Exposure to expected extreme high temperatures could lead to instances of heat exhaustion (even stroke), dehydration and respiratory problems (Epstein and Ferber, 2011).While temperatures are expected to rise there will still periods of extreme cold with the attendant risks of cold-related diseases and exposure.

28.4.1.2. Indirect Impacts in the Polar Regions

28.4.1.2.1. Health impacts

Climate change is likely to affect the health and well-being of people living in the Polar Regions. Among the impacts of climate are those related to extreme weather and temperatures and natural hazards (Furgal et al, 2008). Indigenous people have reported that the weather has become less predictable and, in some cases, that storm events progress more quickly today than in previous memory (Huntington et al., 2005; Ford et al., 2006; Nickels et al., 2006; Laidler et al., 2009; 2010). The unpredictability of weather limits traditional hunting and increases the risks of being stranded or involved in accidents on the land. (Ford and Smit, 2004; Ford et al., 2006; Nickels et al., 2006; Laidler et al., 2009; 2010)

Other indirect effects on health include risks to sanitation and waste infrastructure, changes in infectious disease vectors, contaminants (local and long-range) and harmful algal blooms (Berner et al, 2005; Epstein, 2011). Thawing of the permafrost could compromise the integrity of waste and sewage disposal sites exposing people to dangerous contaminants. The integrity of reservoirs for water supply or hydro-electric power generation could possibly be similarly affected by climate change threatening local communities. Furthermore, drinking water sources in coastal communities may be affected by rising sea-levels contaminating ground water (Warren et. al., 2005). Melting permafrost will also impact both natural and often untreated water sources (river and lakes) as well as water purification systems. Studies in Alaska have shown a 2-4 times higher hospitalization rates among children with water-related illnesses where the majority of homes had reduced water availability (Dartmouth 2011; Berner et al, 2005).
Warmer temperatures, especially in summer will also likely lead to the redistribution of existing and the introduction of new vector-borne diseases. Finally, indigenous populations who are losing the opportunities to practice their traditional customs and maintain their culture appear to suffer increased rates of suicide (Coyle and Susteren, 2011)

28.4.1.2.2. Infrastructure

Many communities in Polar Regions are distant from large administrative or economic centres and hence are critically dependent on reliable infrastructure for transportation as well as the provision of services such as energy, health care and communications. In most of the Arctic there is little redundancy of infrastructure and when one component fails it can lead to catastrophic disasters. Much of the critical infrastructure such as buildings, roads, airports and pipelines will be threatened by the melting of the permafrost. Equally threatened by permafrost melting, as well as greater snow and ice loads, are modern communications infrastructure (Government of Canada, National

Roundtable on Environment and the Economy (2009)). Infrastructure on the coast will also be threatened by erosion caused by more frequent and severe storms. The damage will be exaggerated by the loss during much of the year of ice cover that typically dampens wave action. In addition sea-level rise will add to the threat of coastal erosion. Poorly planned development such as [examples] also has the potential to expose the coastline to further erosion. (Anisimov, 2007).

Changes in the hydrological regime such as a larger spring freshet, the occurrence of ice-jams and more variable flows will have to be factored into infrastructure already built or being planned (Prowse et al 2004; Instanes et al 2005) - also there are implications for ice roads (Furgal and Prowse, 2008).

28.4.1.2.3. Wildlife impacts

The impacts of climate change on wildlife in the Arctic will bring changes in ecosystem structures that will bring both positive and negative to natural resource exploitation. There is already mounting evidence of local ecological changes in response to recent climate change (Rozensweig C. et. al., (2007). During the past 40 years, average annual temperatures have been increasing and winters have had fewer periods of prolonged severe cold that typically reduces over-wintering of forest pests. There has also been a decrease in average summer precipitation. One result of these changes has been a severe outbreak of spruce bark beetle infestation (Dendroctonus rufipennis) in Canada, causing widespread mortality of white spruce. The spruce beetle infestation has also increased the quantity, flammability and extent of forest fuels, thereby increasing the frequency and severity of forest fires and shifting age class distributions toward younger forests, triggering more frequent shifts from conifer to deciduous-dominated species, and decreasing the amount of terrestrial carbon stored in the boreal forest (Furgal and Prowse, 2008).

Arctic fish species will likely experience declining productivity and overall range contraction as local conditions exceed thresholds and southern species colonize and compete with or prey upon them. Both northern cold-water and southern cool-water species will likely increase in abundance and local productivity and perhaps also extend their geographic range farther northward as conditions allow. The projected impacts of climate change on sea-ice conditions will also have a significant effect on this inshore fishery. Although commercial fisheries in the Arctic are currently relatively small new opportunities might arise including sports fishing that can provide an important revenue stream for local people. Fishing also provides an important source of protein and underlies some indigenous social and cultural values.

The diverse range of wildlife in the Polar Regions has been critically important for the indigenous inhabitants for thousands of years and continues to play a vital role in their diet, traditions and cultures as well as an important component of local and regional economies (Nuttall et al. 2005). The increased frequency of rain rather than snow in the winter has lead to thicker ice layers making it more difficult for foraging animals to obtain needed food in winter (Bartsch et al. 2010).

The reduction of sea-ice cover has affected such marine animals as polar bears that rely on sea-ice for travelling, breeding and feeding. As polar bears feed almost exclusively on ringed seals, changes in ice distribution and extent that impact seal populations will also affect polar bear distribution and foraging success. Ultimately, this can lead to reproductive impairment in females and decreased health of cubs, as mothers have less fat stores during winter months [Derocher et. al., 2004; Stirling, 2005; Stirling and Parkinson, 2006; Hovelsrud and Smit, 2010). For some other seal species, including harbour seals and grey seals, climate warming and decreases in sea-ice cover will likely mean an increase in their prevalence in Arctic waters.

Added stresses to wildlife in the Arctic will result from the introduction of new animal-transmitted diseases as well as the redistribute some existing ones affecting economically or culturally important species and regional economies (Furgal and Prowse 2008, 59). This includes for example impacts on polar bears, which are not only an important component of the Arctic ecosystem but also a key attraction for many visitors to the North and play a significant role in the culture and economies of many Aboriginal communities (Furgal and Prowse 2008, 98).

28.4.1.2.4. Marine transportation

The most obvious impact of changing climate on Arctic marine transportation will be 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 (Loeng et al., 2005), although there is no similar expectation of a totally ice-free Arctic Ocean in winter. Even though a longer shipping season appears beneficial, ice conditions in all areas are highly variable from year to year and will likely remain that way. The persistence of multi-year ice on the Canadian side of the Arctic is likely to present challenges to northern shipping for at least several decades. The longer thaw season will tend to promote a longer period of weakness in the pack ice, resulting in more rapid drift of multi-year ice through the Arctic Archipelago and into the Northwest Passage and presenting a continuing hazard to shipping.

28.4.1.2.5. Ice roads

In the case of the loss of ice roads, some adaptation options are available at least in the early stages of reductions in ice duration or load-bearing capacity. These include: reductions in the maximum size of transported loads; modifications to techniques involved in ice-road construction, such as by enhanced surface flooding or spray-ice layering; and/or modification of transport schedules to concentrate more on the coldest part of winter (Prowse *et al.*, 2009). Continued warming will preclude ice roads as a major form of northern transportation, and there will be a need for alternative forms of transportation. In cases where an open-water network is feasible, transport by boat or barge could be possible. For land-locked locations, however, the only viable option for heavy-load transport will be the construction of land-based road or rail networks. The initial capital costs of these, however, will be very high, especially where they must pass over terrain that might be experiencing permafrost thaw and subsidence from the effects of similar warming.

Other indirect effects include 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), 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). (Berner et al, 2005; Epstein, 2011) Additional attention needs to be focused on solutions for the high suicide rates among impacted peoples of the North, particularly, the indigenous populations who are losing the means to practice their traditional customs and maintain their culture, and, therefore, their traditional role in that society. (Coyle and Susteren, 2011)

Water sources are necessary for drinking, personal hygiene, cleaning and cooking and Arctic warming is melting permafrost which is impacting both the community source water (river and lakes) and the piped water and water purification systems often built on permafrost. This will result in a reduction in both water volume and availability of treated water and will require community members to rely more on traditional (untreated) water sources. Studies in Alaska have shown a 2-4 times higher hospitalization rates among children less than 3 years of age for pneumonia, influenza, and childhood respiratory syncytial virus infections, and higher rates of skin infections in persons of all ages in villages where the majority of hoes had lower water availability because of no in-house piped water source, compared to homes that had higher water availability because of in-home piped water service. 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. (Dartmouth 2011; Berner et al, 2005)

28.4.1.3. Other Stresses in the Polar Regions

28.4.1.3.1. Demographic and economic changes

The Arctic is now home to some [Reference – see AHDR] residents. The proportion of indigenous as opposed to non-indigenous people has varied from time to time and country to country although it is generally declining everywhere. In the Canadian Arctic most live in settlements of around 1000 people. The trend to concentrating people into larger settlements has lead to pressure on local resources and traditional foods. In addition the influx of new residents into the Polar Regions has brought social, cultural and economic changes. Over the past 50 or more years, as the number of permanent settlements has grown, there has been a significant reduction in the number of nomadic people who traditionally followed game animals and fish resources although many indigenous people still retain a strong relationship to the land and a reliance on country food. There has also been an increase in the proportion of young people – birth rates are often above the national level.

Many of settlements are on low-lying coastal areas or beside lakes and rivers and are vulnerable to climate-induced impacts such as permafrost melting and sea-level rise. At the same time these settlements have been provided with greater access to potable water supplies, sewage disposal as well as health care, education facilities and government supported social support programs. In some of the larger communities some employment has been provided by the public sector and such new services as tourism but problems remain related to low high-school graduation rates for example. In addition the expansion of natural resource extraction, such as oil and gas and minerals, has brought new employment opportunities and increased wealth. The net result is that the many communities now have secured a measure of economic security through a mix of subsistence and cash incomes. (Anisimov, 2007; Furgal and Prowse, 2008).

28.4.1.3.2. Political and administrative factors

Governance regimes vary significantly from one country to another. For example, indigenous people in some countries such as Canada have achieved recognition of their traditional land claims and have won the right to self-determination (Abele et al., 2009). However, because of time spent by indigenous people in traditional pursuits such as herding or harvesting this may preclude them from fully participating in decision-making processes potentially affecting their interests (Hovelsrud and Smit, 2010). and vice-versa, those who are engaged in full time wage employment are much more involved in decision-making, but become more disconnected from traditional pursuits and often contributes to gap in cultural knowledge and skill transfer.

Enhanced shipping through the Arctic is likely to lead to a number of regulatory issues that will need to be addressed. These include the use of northern coastlines for illegal activities (e.g. smuggling), spread of new and exotic species and diseases, increased marine-traffic accidents and related threats from pollution and sovereignty questions (Kelmelis et al., 2005).

28.4.1.3.3. Industrial development

Multinational mining companies are expanding their exploration and extraction activities in the Polar Regions. Several new diamond mines have opened recently in Canada's Arctic and others are in the approval stage. Valuable resources include minerals with strategic importance [Check]. In addition multinational oil and gas companies are expected to increase their exploring and drilling for the estimated billion barrels of oil and natural gas (Mikkelsen and Langhelle, 2008; Kumpula et al,. 2011) that are believed to exist. This industrial development, if not well planned, could threaten contamination of the environment through the spillage of wastes and the disturbance of wildlife patterns.

28.4.1.3.4. Health considerations

The health status of many indigenous Northerners is typically lower than the national average, medical services are not always accessible and suicides are much higher than average (Statistics Canada, 2001, 2003; ITK, 2007) Need statistics for elsewhere. All of Canada's Territories report lower life expectancy and higher infant mortality rates than the national averages, and these disparities are particularly pronounced in Nunavut. Higher rates of mortality from suicide, lung cancer, drowning and unintentional injuries (i.e. accidents) associated with motor vehicle accidents occur in Canada's North relative to the rest of the country. Accidental deaths and injuries are likely associated, in part, with the increased exposure associated with the amount of time spent on the land and the high level of dependence on the various modes of transport for hunting, fishing and collection of other resources. (Furgal and Prowse, 2008).

Food insecurity in Canada is highest in the three territories, where there are significantly higher numbers of female single parent households and the cost of a standard list of grocery items can be up to three times higher than in southern Canada (Bolton et al., 2011; Berrang-Ford, 2011). In communities not accessible by road, access to market food items is reliant upon shipment via air or sea, which significantly increases the price. Data from Canada for 2001 show that 68% of households in Nunavut, 49% of those in the Northwest Territories and 30% of those in the Yukon had at least one occasion in the previous year when they did not have the financial resources for sufficient food.

Many environmental contaminants are transported towards Polar Regions by air and water currents and climate change will likely enhance the transport, deposition and uptake into Arctic wildlife of these contaminants, thereby influencing human health. These chemicals are known to adversely affect immune and neuromotor functioning in children (Arctic Monitoring and Assessment Programme, 2003). The Arctic could also become a more effective contaminant sink because of projected increases in precipitation [Check]. Climate-related changes that have already been observed in the North have influenced the exposure of wildlife to, and intake of, environmental contaminants. Since indigenous peoples rely heavily of wildlife that are at the top of the food chain and exhibit a significant accumulation of these contaminants, their health has suffered.

Changes in social, economic and environmental conditions influence the mental health and well-being of indigenous peoples whose livelihood, and identity are tied inextricably to the land and sea. Disruption of traditional hunting cycles and patterns, the reduced ability of elders to predict weather and provide information to others in the community, and concern over losses of cemeteries and homes due to coastal erosion represent forms of social disruption in communities already undergoing significant change. The stresses resulting from these multiple changes have been associated with symptoms of psychological, mental and social distress, such as alcohol abuse, violence and suicide (Berner et al., 2005; Curtis et al., 2005). Furthermore, the increased growth of the wage economy in many regions has reduced both the necessity for, and time available for, hunting, fishing and gathering country foods. This, in turn, has reduced the generation and transmission of traditional knowledge and environmental respect as well as diminishing the health benefits from the consumption of local foods.

28.4.1.3.5. Cultural changes

Chapin et al. (2005a) reported that the deterioration of cultural ties to land-based and subsistence activities among indigenous people is the most serious cause of decline in well-being within circumpolar regions. The loss of connection to the land through changes in ways of life, the decline in the transmission and retention of traditional knowledge and the dominance of non-indigenous education systems are some of the factors that are impacting the health and well-being of affected populations (see also Crate et al. 2010). Together these shifts are turning previously well-adapted Arctic peoples into "strangers in their own lands" (Berkes, 2002) and having a negative impact on the coherence and security of indigenous communities. However, there are some 'success stories' in which people have generally managed to navigate the shocks and pressures wrought by climate and land use change and these are worth highlighting, such as the Inuit hunters of Kangiqtugaapik, Nunavut and the Nenets reindeer herders of Yamal, West Siberia (Crate et al. 2010; Forbes et al. 2009).

28.4.2. Adaptation in the Polar Regions

When discussing adaptation to climate change, one must also bear in mind that we already adapt every day to climate and weather-related events such as floods, forest fires, changing snow and rain conditions, and wind-storms. What climate change is doing is rendering these incidents more unpredictable and irregular. Putting in place new, protective or precautionary measures such as early-warning systems, a floodway, or reinforced buildings are mechanisms to cope with these additional risks. Adaptation to climate change is planning under increased risks scenarios (NorAcia 2010).

The impact of climate change and capacities for adaptation can best be understood at the local and regional levels. This requires a good understanding of the current socio-economic and political situation in communities (Keskitalo, 2008). The adaptive capacity of actors and communities in the North fundamentally depends on the resources available (Keskitalo, 2008). Here national frameworks may be important. For example, the high level of social security in Norway means that trends such as depopulation and economic marginalization may take less of a toll on the standard of living of individuals than is the case elsewhere (Keskitalo et al. 2009).

As a result of the inertia of the climate system, even with global reductions in greenhouse gas emissions, further changes in the climate can be expected and thus adaptation, particularly at the local level, becomes increasingly imperative(National Roundtable on the Environment and the Economy, 2009). Adaptation, however, will be driven not only by climate but by the imposition of other stresses such as those discussed above. As was argued in the AR4, the most effective options will be those that recognize the nexus between adaptation and sustainable development (Yohe et.al., 2007). One consequence of this observation is the importance of “mainstreaming” adaptation into existing policy processes. Because of the uncertainty of future climate change and of economic and social developments, a determining factor of adaptive capacity will be the flexibility of enabling institutions (Forbes et al. 2009; Hovelsrud and Smit 2010).

28.4.2.1. Adaptation and Indigenous Peoples

For millennia, Arctic populations have adapted to climate and other changes by resettling amid favourable environments and along the paths of animal migration routes. The indigenous peoples of the Arctic have developed over time a remarkable array of coping strategies to deal with the extreme natural variability in the region. They have also been innovative and adaptive in the face of rapid cultural and technological change over the past 60 years (Bolton et al., 2011). This has been achieved by detailed local knowledge and skills, the sharing of knowledge and flexible social networks which provide support in times of need. Unfortunately, the rapid climate and weather changes that have been experienced recently have challenged the reliability of this indigenous knowledge. This has in some cases created insecurity on the part of the knowledge keepers (Berkes and Jolly, 2002; Chapin et al 2006, Hovelsrud and Smit, 2010).

Traditional capacity has also been threatened by the move to fixed settlements with modern amenities such as television and southern foods that are affecting lifestyles; by wage-earning opportunities in natural resource exploitation leading to frequent job changes and by a desire among the young for a more Western lifestyle. The increasing diversity of employment is leading to the possibility of indigenous people finding multiple jobs, and hence diversified income. Unfortunately, however, the current levels of skilled labour and formal education often limit the abilities to take advantage of such opportunities (Furgal and Prowse, 2008). Traditional capacity is also affected by the erosion of inter-generational knowledge transfer, land-based skills, and cultural traditions (Bolton et al., 2011). Some communities have put in place strategies to ensure the continued intergenerational transfer of knowledge through school curricula, land camps, and involvement in community-based monitoring programmes (Hovelsrud and Smit, 2010, Bolton et al., 2011).

Hunting has become a riskier undertaking. Adaptive responses include taking more supplies when going hunting such as additional warm clothing and extra food; constructing more permanent shelters on the land as refuges from storms; building improved infrastructure to communicate; greater use of global positioning systems (GPS) for navigation; and the use of larger or faster vehicles. These adaptive responses have in part been made possible by the increased incomes mentioned above. However, in some instances, this can lead to over harvesting (Chapin et al. 2005b).

Herding, such as reindeer, has also adapted to changes in the climate by moving herds to better pastures (Bartsch et al., 2010), providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009) and ensuring an optimal herd size (Forbes et al., 2009). Fisheries have adapted to changing regulations and climate by targeting different species and diversifying income sources (Hovelsrud and Smit, 2010).

In some Arctic countries indigenous peoples have won land claims rights and have become key players in addressing the issue of climate change. In some instances this has given rise to tensions over land use such as the contested land uses for traditional livelihoods (e.g. reindeer herding) and new opportunities (e.g. tourism and natural resource extraction) (Forbes et al., 2006; Hovelsrud and Smit, 2010). Many communities are already adapting in a reactive manner to local climate change (Aporta and Higgs, 2005; Gearheard et al., 2010 and 2011; Laidler et al., 2011). Many studies have noted the importance of combining scientific knowledge and traditional knowledge in an effort to understand climate change, its impacts and local responses. (Furgal and Prowse, 2007 and, 2008; Lafortune et al 2004; Huntingdon 2005; Bolton et al., 2011).

The health of indigenous people is being disproportionately affected by the interactions of ongoing changes in human, economic and biophysical systems as discussed above exacerbated by changes in climate (Chapin et al., 2005). The factors that influence community vulnerability vary significantly between small, remote, predominantly indigenous communities, regional centres and larger northern municipalities. Bolton et al. (2011) identified a need for research and policy priorities to be placed on assessing/addressing health factors which may predispose communities to negative impacts of climate change.

28.4.2.2. Traditional, Non-Market Economies

In many ways impacts of environmental change are stripping arctic residents of their considerable knowledge, predictive ability, and self-confidence in making a living from their resources. This may ultimately leave them as strangers on their own land: Especially as Northern land-based livelihoods depend on the peoples' ability to predict weather, judge the snow conditions, and predict animal movements and distributions, which is becoming more difficult. A hunter who cannot make right judgement about what to hunt and where, cannot stay a hunter for long (Berkes 2002, 339 but also Fox in the same volume 43-45). One already existing and reported way of adaptation to these changes includes the increased use of global positioning systems (GBS) for navigation, and of larger or faster vehicles. However, these adaptations can also increase exposure to risk by raising the sense of security among hunters and increasing the amount of travel in dangerous circumstances. (Furgal and Prowse 2008, 101). Even though the influx of wage employment may enhance adaptive capacity to some climate impacts, greater involvement in full time jobs will continue to be associated with current trends of social and cultural erosion (Furgal and Prowse 2008, 110). These changes in their turn have a negative impact on social cohesion and mental well-being by disrupting the traditional cycle of land-based practices (e.g. Furgal et al., 2002; Berner et al., 2005). The push for oil and gas development is hence one of the common threats connecting the communities in northern Alaska, northwest Canada, and the Russian North. Like unpredictability, it would have negative effects on the indigenous identity, which is tied in part to reliance on the land and sea, as knowledge of how to live there over many generations with or without large subsidies or interference from outside the region (Nelson, 1969; Berger 1985; Wenzel, 1991, In Forbes 2008,217 (Forbes 2008,217) A sad consequence of the lost cultural identity is revealed already in some Arctic areas by suicide rates among young indigenous peoples (15-24 years) that are nearly twice as high as non-indigenous peoples (Berkman 2010, 84).

Added stresses to the traditional livelihoods of the indigenous peoples of the Arctic by the fact that shifting environmental conditions will also be likely to introduce new animal-transmitted diseases and redistribute some existing diseases, affecting thus key economic resources and some human populations. Where these stresses affect economically or culturally important species, they will have significant impacts on people and regional economies (Furgan and Prowse 2008, 59). Similar negative effects on changes have been reported for freshwater ice and access to fish resources that are important for many Aboriginal and non-Aboriginal populations across the North (Furgal and Prowse 2008. 102). This includes access to polar bears, which are not only an important component of the Arctic ecosystem, but also a key attraction for many visitors to the North each year, and play a significant role in the culture and economies of many Aboriginal communities. The impacts on bears of shifting climate regimes will therefore have implications also for tourism, culture and local economies in many regions (Furgal and Prowse 2008, 98).

28.4.3. Adaptation and Industrial Development

It is not only indigenous peoples that are being affected by climate and other changes and forced to adapt. The Polar Regions are becoming increasingly tied economically and politically to global forces such as international fossil fuel and mineral markets. This is bringing in new workers and families and changing economies. It is also helping to diversify employment opportunities in some cases, but not in others. For example, very few local people are hired in the construction of the oil and gas fields of northern Russia, since they rely on the rapid deployment of skilled labour, e.g. carpenters, electricians, plumbers, stone masons, etc.

Some of the oil and gas that will be extracted may be transported by ship to southern markets. The prospect of further reductions on sea-ice extent will likely accelerate activities in off-shore areas such as in the Beaufort Sea. However, this is likely to require the adoption of design changes to drilling platforms (as were incorporated off the Canadian East Coast such as Hibernia where icebergs are a significant threat). Some of the oil and gas will likely be transported by pipelines whose design requirements, particularly when laid over permafrost, as is being proposed along the Mackenzie River in Canada, will need to be modified. Additional adaptation techniques such as more insulation or thermosyphons to induce artificial cooling will be required (Furgal and Prowse, 2008).

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

The resource extraction activities will all need energy and infrastructure. This is likely to increase the need for sustainable renewable energies and electricity transmission networks to serve not only the mines but also communities spread across the Arctic. This could reduce the need for expensively imported fossil fuels (traditionally transported by increasing unreliable ice-roads and river barge shipments) and enhance the well-being of these communities. However, there is also a need to better understand/address economic and cultural impacts of resource extraction activities on remote northern communities, and how these affect adaptive capacity in the context of climate change (Bolton et al., 2011). There is already a significant dependence on hydro-electric power in the Canadian North and there is further potential for more generating power on the major northern rivers as well for micro-hydro facilities. As with some existing hydro-projects, such as in Quebec and Labrador, there is the potential for selling some of this power to southern markets. However, climate change is likely to impact hydrological patterns – for example projected increases in winter run-off from rainfall and enhanced snow melt could affect dam operations.

The infrastructure needed for natural resource extraction will have to take into consideration potential impacts of the changing climate on permafrost and coastal erosion. Processing plants must be able to maintain their structural integrity over the expected long lifetime of a project. One recently proposed adaptation is to use barges as platforms for production facilities. Resupply of existing mines 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. Adapting to the reduced availability of ice roads will involve increasing the ice thickness by surface flooding or spray-ice techniques as well scheduling more transport when the ice is thickest. Further resource extraction development will likely necessitate the construction all-season roads and/or water-based transportation systems where this is feasible (Furgal and Prowse, 2008). With the expected extension of the ice-free period on Arctic rivers and lakes there could be a significant expansion of open-water transport – for example by 50% along the Mackenzie River system. However, lower expected flow levels in the summer could increase the need for dredging although given the changing bed morphology this may only be a short term adaptation option. For land-locked locations, however, the only viable option for heavy-load transport will be the construction of land-based road or rail networks. The initial capital costs of these, however, will be very high, especially where they must pass over terrain that might be experiencing permafrost thaw and subsidence from the effects of similar warming. While climate change is perceived as having negative impacts on the mining industry, companies are not currently taking action to plan ahead to account for future climatic changes (Ford et al., 2010).

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

In adapting to the expected impacts of changes on the management of natural resources such as forestry, it has been suggested that the principles and practice of sustainable development embody many of the activities that will be required (Spittlehouse and Stewart, 2003). Proactive adaptation, such as selective forest regeneration, is more likely to avoid or reduce damage than reactive responses.

As far as fisheries management is concerned, inshore coastal marine and lake-based commercial fisheries and aquaculture operations are likely to face significant adaptation challenges as a result of changing climate. Options that adopt an ecosystem approach and set attainable goals for sustainable management levels are likely to be more responsive to climate change impacts. As with the forestry sector sustainable management approaches such as area closures, quota limits and gear restrictions to limit both commercial and recreational activities will likely be important tools for dealing with the impacts of changing climate.

In general adaptive co-management strategies, particularly at the local level, involving indigenous interests and bringing together scientific and traditional knowledge, are becoming increasingly important in adapting to climate change (Klein et al., 2005; Parlee et al., 2005, Chapin, 2006, Government of Canada, 2009).

Institutional frameworks generally ill-suited to deal with rapidly changing environmental conditions can exacerbate sensitivities to, or impacts of climate change. More interaction between community-members, policy-makers, and decision-makers can assist in exploring innovative opportunities for resources management and facilitate enhanced adaptive capacity (Bolton et al., 2011).

28.5. Lessons Learned

[to be developed:

- Effect of multiple stressors
- Thresholds and irreversible changes
- Uncertainty of projected impacts]

28.6. Research and Data Gaps

[to be developed]

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[incomplete and yet to be integrated, sorted by contributor]

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Table 28-1: Commercial fishery areas, catches, and market products.

Area/scientific name	Common name	Market product
Bering Sea		
Theragra chalcogramma	Walleye pollock	Roe, frozen fillets, surimi
Gadus macrocephalus	Pacific cod	Fresh and frozen fillets
Limanda aspera	Yellowfin sole	Frozen fillets
Reinhardtius hippoglossoides	Greenland turbot	Frozen fillets
Atheresthes stomias	Arrowtooth flounder	Frozen fillets, surimi
A. evermanni	Kamchatka flounder	Frozen fillets
Lepidopsetta polyxystra	Rock sole	Roe, Frozen fillets
Hippoglossoides elassodon	Flathead sole	Frozen fillets
Pleuronectes quadrituberculatus	Alaska plaice	Frozen fillets
Sebastes alutus	Pacific Ocean perch	Fresh and frozen fillets
Sebastes polyspinis	Northern rockfish	Fresh and frozen fillets
Clupea harengus pallasi	Pacific herring	Roe, Fillets
Chionoectes opilio	Snow crab	Fresh whole, canned
Paralithodes camtschaticus	Red king crab	Fresh whole, canned
Chionoectes bardai	Tanner crab	Fresh whole canned
Onchorynchus keta	Chum salmon	Fresh fillets, canned
Onchorynchus tshawytscha	Chinook salmon	Fresh fillets
Onchorynchus nerka	Sockeye salmon	Fresh fillets
Onchorynchus gorbuscha	Pink salmon	Fresh fillets, canned
Coregonus autumnalis	Arctic cisco	Subsistence
Coregonus nasus	Broad whitefish	Subsistence
Coregonusardinella	Least cisco	Subsistence
Salvelinus malma	Dolly varden	Subsistence
Salvelinus alpinus	Arctic char	Subsistence
Thymallus arcticus	Arctic grayling	Subsistence
Norwegian Sea/Barents Sea		
Clupea harengus pallasi	Atlantic herring	Roe, Fillets
Mallotus villosus	capelin	Whole fish, canned
Scomber scombrus	Atlantic mackerel	Fillets
Micromesistius poutassou	Blue whiting	Fillets
Pollachius virens	Saithe	Fillets
Reinhardtius hippoglossoides	Greenland halibut	Fillets
Gadus morhua	NE Atlantic cod	Fillets, dried fish, roe
Gadus morhua	Coastal cod	Fillets
Greenland		
Gadus morhua	Atlantic cod	
Micromesistius poutassou	Blue whiting	
Scomber scombrus	Mackerel	
Clupea harengus pallasi	Atlantic herring	
Sebastes fasciatus, S. mentella	Redfish	
Chionoectes opilio	Snow crab	
Reinhardtius hippoglossoides	Greenland halibut	
Pandalus borealis & P. montgau	Northern shrimp	

Canada		
Reinhardtius hippoglossoides	Greenland halibut	
Sebastes fasciatus, S. mentella	Redfish	
Pandalus borealis & P. montgau	Northern shrimp	
Salvelinus alpinus	Arctic char	Subsistence
Coregonus nasus	Broad whitefish	Subsistence
Coregonus autumnalis	Arctic cisco	Subsistence
Onchorynchus nerka	Sockeye salmon	
Onchorynchus gorbuscha	Pink salmon	
Onchorynchus keta	Chum salmon	
Onchorynchus tshawytscha	Chinook salmon	
Iceland		
Gadus morhua	Iceland cod	Fillets
Melanogrammus aeglefinus	Haddock	Fillets
Pollachius virens	Saithe	Fillets
Molva molva	Common ling	Fillets
Brosme brosme	Cusk	Fillets
Reinhardtius hippoglossoides	Greenland halibut	Fillets
Pleuronectes platessa	European plaice	Fillets
Clupea harengus pallasi	Icelandic herring	Roe, Fillets
Mallotus villosus	Capelin	Whole fish, canned
Sebastes mentellas	Deepwater redfish	Fillets

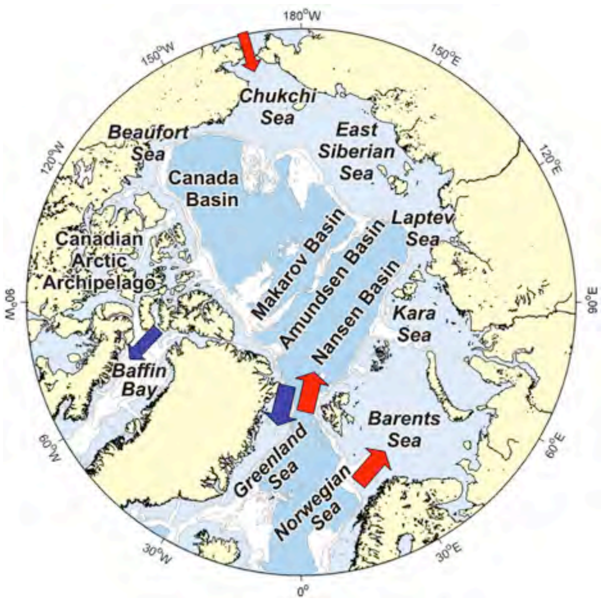

Figure 28-1: Map of the Arctic Ocean with shelves and basins. Blue arrows show areas of outflow of arctic water and red arrows show the places and strength of inflows of Pacific and Atlantic water. Source: Carmack and Wassman 2006.

Figure 28-2

Figure 28-3: Fishing vessel activity. Source: AMSA.