IPCC WGII Fourth Assessment Report – Draft for Expert Review

Chapter 15 – Polar Regions

Coordinating Lead Authors
Oleg A. Anisimov (Russia) and David G. Vaughan (UK)

Lead Authors
Terry Callaghan (Sweden), Christopher Furgal (Canada), Harvey Marchant (Australia), Terry Prowse (Canada), Hjalmar Viljalmasson (Iceland), John Walsh (USA)

Contributing Authors
Frederick E. Nelson (USA), Jef Vandenberghe (Netherlands), Fred J. Wrona (Canada), Jim D. Reist (Canada), Torben Christensen (Sweden), Mark Nuttall (Canada/UK), Donald Forbes (Canada), James Berner (USA)

Review Editors
Roger Barry (USA), Alfonso Rivera (Chile), John Stone (Canada)

Contents

Executive summary

Many future climate-induced changes that were forecast in the Third Assessment Report (Anisimov *et al.*, 2001), have now been observed and documented. This validation, together with improved models, data from new experiments and increasing use of Traditional Knowledge, has improved our ability to project future changes in physical and biological systems. Model projections appear to indicate that dramatic recent rates of climate change across wide regions of the Arctic will continue, and this together with a unique degree of sensitivity shown in these areas, suggests that the impacts of climate change in the Arctic over the next hundred years will exceed many other regions on Earth, a factor that has led to the preparation of a uniquely detailed assessment of impacts in this region (ACIA, 2004). However, the complexity of response in biological and human systems, and the fact that they are subject to additional and cascading stresses, means the impact of climate change on these systems is still difficult to predict. Changes on the Antarctic Peninsula and sub-Antarctic islands have also been rapid and similarly dramatic impacts are expected, but the evidence of ongoing change from the rest of the Antarctic continent is less conclusive and here prediction of the likely impacts is difficult.

Key findings:

- Substantial environmental impacts of climate change show profound regional differences both within and between the polar regions. However, areas in both the Arctic and Antarctic regions have shown the most rapid rates of warming in recent years and continue to be climate-change hotspots. The impacts of future climate change in the polar regions, may produce feedbacks that in time, have globally significant consequences.
- There has been a measured change in composition and range of plants and animals on the Antarctic Peninsula and on the sub-Antarctic islands as a response to climate change (especially, increasing temperature and changing precipitation). Such changes are likely to continue and produce increasing complex responses, as the disturbance to ecosystems increases.
- There is a documented increase in the overall greenness of the Arctic that represents an increase in biological productivity; a change in species ranges (e.g., changes from tundra to scrublands), some changes in position of the tree-line and changes in ranges and abundance of some animal species. Results from models and experiments predict that such changes in biodiversity and vegetation zone relocation will continue.
- Discharge of Eurasian rivers draining into the Arctic Ocean show an increase since the 1930s, largely consistent with increased precipitation although other changes to cryospheric processes (snowmelt and permafrost melt) are also modifying flow pathways and seasonality. If such hydrologic and cryospheric changes continue, as predicted, the regional impacts of this change on freshwater, riparian, fluvial morphology, and near-shore marine (*and potentially the thermohaline)* systems are likely to be profound.
- The retreat of sea ice in the Arctic in recent years (in recent years summer sea ice extents have reached record minima) has led to increased open water for navigation, changes in coastal ecology/production, and increased coastal erosion. Reductions in freshwater ice will also affect lake and river ecology/production and require changes in water-based transportation. Economic benefits may accrue but cultural lifestyles are likely to be adversely affected.
- Glacier volume continues to decrease in the Arctic, sub-Arctic, and parts of Antarctica, and predictions agree that this loss will accelerate in future. Beyond the clear impact on global sea level, a continued loss of glaciers will have regional impacts on aquatic and terrestrial ecology and hydropower.
- Although earlier claims that there was a substantial mid-20th Century reduction of sea-ice extent in Antarctica are now in doubt, a newly documented decline in krill abundance, together with an increase in salp abundance, has been attributed to a recent regional reduction in the extent of

antarctic sea ice. The trend requires monitoring as a further decline in krill may impact mammal and avian predators, with further consequences for higher predators.

- Continuing warming of the northern polar oceans is likely to further impact on the community composition and biomass of phytoplankton and zooplankton. The impact of these changes on higher predators, fish and fisheries, will be regionally-specific, some beneficial and some detrimental.
- Changes in the frequency, type and timing of precipitation will increase contaminant capture. This, combined with changes in the timing and rate of melt/thaw of snowcover, floating ice and permafrost will increase contaminant loading to freshwater systems. Increased loadings may more than offset the reductions that are expected to accrue from global emissions of contaminants.
- In both the Arctic and Antarctic, the poleward migration of existing species and competition from invading species, is already occurring, and will continue to alter species composition and abundance in terrestrial and aquatic systems. Impacts of arctic climate change will also have implications for biodiversity around the world because migratory species depend on breeding and feeding grounds in the Arctic.
- Most arctic human communities are already being required to adapt to climate change and the resilience that Indigenous people have exhibited to changes in their local environments for hundreds of years is now being tested. Indigenous communities already need to adapt to climate changes in their local environment, through practices such as changes in wildlife management regimes, and changes in hunting practice; and they retain capacity to adapt to environmental change. However, stresses in addition to climate change, together with a migration from the land into small remote communities and increasing involvement in employment economies and sedentary occupations, challenge this adaptive ability.
- Shifts in vegetation and wetting/drying of wetlands will have major impacts on the exchange of greenhouse gases and the albedo of the landscape. Recent models that predict displacement of significant areas of tundra by forest emphasize the importance of albedo, while biogeochemical models estimate that the tundra will be a small sink for carbon (although the uncertainty is large).
- Warming and thawing of permafrost will have a detrimental impact on the engineered structures built upon it. Substantial investments may be needed to adapt the existing structures to ongoing changes or relocate them to regions with safe conditions.

15.1 Summary of Knowledge Assessed in the TAR

IPCC in its Third Assessment Report (Anisimov *et al.*, 2001) summarised the climatic changes that have been observed in the Arctic and in the Antarctic (Figure 15-1 shows place names used in this chapter) over the 20th Century, the impacts those changes have had on the polar environments and the future projections of climatic and environmental change and its impacts in the polar regions. Some of the key findings of that assessment are the following.

Climatic changes in the 20th Century were different in the Arctic and Antarctic and have lead to different environmental impacts.

- In the Arctic, extensive land areas showed a warming trend in air temperature of up to 5°C. Over sea ice, there has been a slight warming in the 1961-1990 period. Precipitation has increased. Arctic sea ice extent has decreased by 2.9% per decade over the 1978-1996 period, sea ice has thinned and there are now more melt days per summer. Sea ice extent in the Nordic Seas has decreased by 30% over the last 130 years. Atlantic water flowing into Arctic Ocean has warmed and the surface layer has become thinner. The mixed layer in the Beaufort Sea has become less saline. The regions underlain by permafrost have been reduced in extent and a general warming of ground temperatures has been observed in many areas. There has been a statistically significant decrease in spring snow extent over Eurasia since 1915. In summary, many observations of environmental change in the Arctic show a trend consistent with warming and similar to that predicted by GCMs.

- In the Antarctic, over the last half century there has been a marked warming trend in the Antarctic Peninsula. Elsewhere there is a general, but not unambiguous warming trend. Precipitation in the Antarctic may have increased. There was no significant change in antarctic sea ice extent over the 1973-1996 period. Antarctic sea ice retreated south by 2.8 degrees of latitude between the mid-1950s and early-1970s[1]. Surface waters of the Southern Ocean have warmed and become less saline.

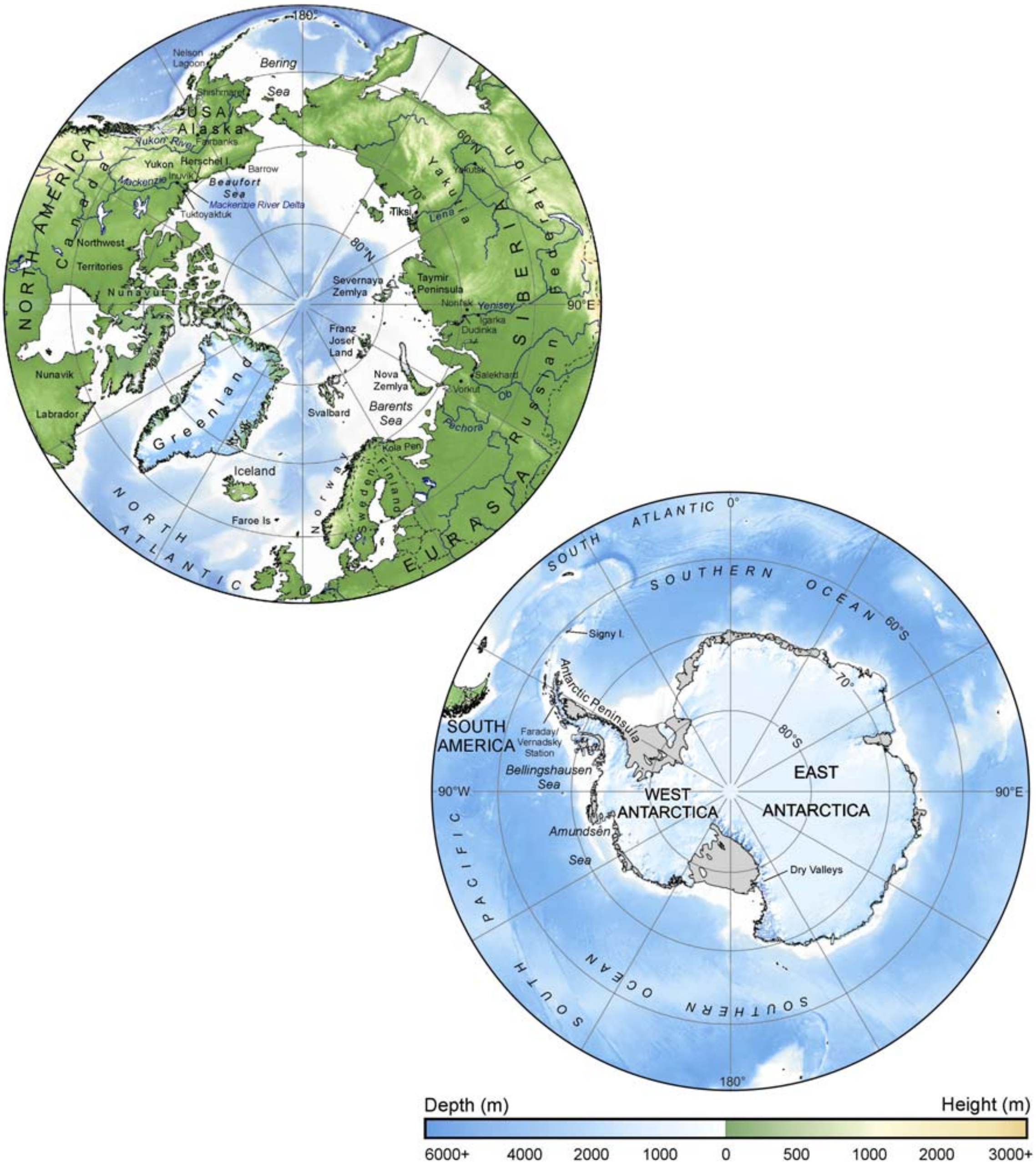

***Figure 15.1**: Location maps of the North and South Polar regions including place names used in the text. Note the ice-covered terrain is shown using a different shading scheme to the one given in the legend. (This other and maps drawn by Peter Fretwell, British Antarctic Survey)*

---

[1] This statement has now been called into doubt, see Section 15.3.4.2

Projected climate change in the polar regions has generated eight key regional concerns

- Increased melting is expected on arctic glaciers and the Greenland ice sheet, while the Antarctic ice sheet is likely to thicken due to increased precipitation. Together with the small risk that the West Antarctic and Greenland ice sheets retreat in coming centuries, suggest that the cryosphere changes will make a significant contribution to sea level rise.
- Projected warming is likely to expose more bare ground on the Antarctic Peninsula and cause changes in the terrestrial biology.
- Climate change is likely to produce long-term, perhaps irreversible, changes in the physical oceanography and ecology of the Southern Ocean.
- There will be substantial loss of sea ice. Predictions for summer ice indicate that its extent could shrink by 60% in the Arctic and by 25% or more in the Antarctic for a doubling of CO_2.
- Reduction of the area underlain by the near-surface permafrost, and thickening of the seasonally thawed layer about permafrost (active layer) is expected over large areas. This will lead to changes in drainage, increased mass movements, thermal erosion, altered landscapes in much of the Arctic and sub-Arctic, and ultimately to costly damage to human infrastructure.
- The hydrology of the Arctic is particularly susceptible to warming. There will be a shift to a runoff regime driven increasingly by rainfall, with less seasonal variation. There will be more ponding of water in some areas of peatlands/wetlands dry. Reduction in ice-jam flooding is expected on rivers with smaller spring runoff and ice thickness, whereas earlier breakups could enhance flooding. A major impact could result from a weakening of the global thermohaline circulation due to a net increase in river flow and the resulting increased flux of freshwater from the Arctic Ocean.
- Warming should increase biological production in the Arctic. As warming occurs, there will be changes in species compositions on land and in the sea, with a tendency for poleward shifts in species assemblages. Animals dependent on sea ice, such as seals, walrus and polar bears, will be disadvantaged.
- Climate change, when combined with other stresses, will affect human communities in the Arctic. Changes in sea ice, seasonality of snow, habitat and diversity of food species will affect hunting and gathering practices and could threaten long-standing traditions and ways of life. On the other hand, the communities that practice these lifestyles may be sufficiently resilient to cope with these changes. Increased economic costs are expected to affect infrastructure, in response to thawing permafrost and reduced transportation capabilities across frozen ground and water. However, there will be economic benefits, including new opportunities for trade and shipping across the Arctic Ocean, lower operational costs for the oil and gas industry, lower heating costs and easier access for ship-based tourism.

Climate change will affect key polar drivers of further climate change

- Warming will reduce sea ice and snow extent, particularly in the Arctic, causing additional heating of the surface, which will in turn further reduce ice/snow cover.
- The oceanic thermohaline circulation may slow down because of freshening of waters from increased arctic runoff resulting from increased precipitation over evaporation, greater glacial melt and reduced sea ice formation.
- Polar regions have oceans, wetlands and permafrost that act as both major sources and sinks for atmospheric CO_2 and CH_4 over vast areas. Projected climate change will alter these features and increase their contributions to greenhouse gases. The Southern Ocean's uptake is projected to decline, while CO_2 emissions from arctic tundra may rise initially, due to changes in water content, peat decomposition and thawing of permafrost.

15.2 Current sensitivity/vulnerability

15.2.1 Climate, environment and socio-economic state

Arctic

Over the past several decades, surface air temperatures in the Arctic have warmed at approximately twice the global rate (ACIA, 2004). The areally averaged warming poleward of 60°N is 1-2°C since the time of the temperature minimum in the 1960s and 1970s. In the marine Arctic, the 20th-Century temperature record is marked by strong low-frequency (multidecadal) variations (Polyakov *et al.*, 2002). The most recent (1980-present) arctic warming is strongest in spring and winter, and smallest in autumn; it is generally strongest over northern Asia and northwestern North America. The latter regions, together with the Antarctic Peninsula, are the most rapidly warming areas of the globe over the past several decades. The North Atlantic sub-polar seas show little warming during the same time period. Temperatures in the upper troposphere and stratosphere of the Arctic have cooled in recent decades, consistent with decreases in springtime stratospheric ozone estimated to have been 10-15% during spring and about 7% in the annual mean since 1979 (Weatherhead *et al.*, 2005). Precipitation in the Arctic shows indications of an increase over the past century, although such trends are small (~1% per decade), highly variable in space, and highly uncertain because of deficiencies in the precipitation measurement network. The discharge of Eurasian rivers draining into the Arctic Ocean show an irregular increase since the 1930s (Peterson *et al.*, 2002), but changes have not been uniformly consistent with changes in precipitation. Little is known about areally-averaged precipitation over Greenland.

In the Arctic and sub-Arctic, the changes of temperature at the surface are consistent with recent decreases of sea ice and glacier volume. Annually averaged arctic sea ice coverage decreased by about 10% over the period 1973-2002, the period of near-continuous satellite passive microwave measurements (Cavalieri *et al.*, 2003). The summer minima have decreased at a considerably greater rate than the winter maxima. Recent estimates of sea ice thickness decrease range from about 10% (Holloway and Sou, 2002) to about 32% (Yu *et al.*, 2004). Although, the importance of advective redistribution of sea ice, especially in areas that are poorly sampled by submarines and other thickness monitoring techniques is well-established (Tucker *et al.*, 2001; Holloway and Sou, 2002). Glaciers have lost mass over much of the Arctic and sub-Arctic during the past several decades. The especially rapid retreat of Alaskan glaciers represents about half of the estimated loss of mass by glaciers worldwide and also represents the largest contribution of glacial melt to rising sea level (Arendt *et al.*, 2002; ACIA, 2004). Scandinavian glaciers gained mass during the period from the 1960s to the 1990s due to increased precipitation, although their mass balance has turned negative in the past several years. The mass balance of Greenland is negative at low elevations, and the area covered by summer melt has increased irregularly during the past 20 years (Abdalati and Steffen, 2001).

Also consistent with the recent arctic warming are reductions of the duration of river and lake ice in much of the sub-Arctic (Prowse and Bonsal, 2004; Walsh *et al.*, 2005) and a warming of permafrost in nearly all areas for which permafrost temperature measurements are available (Romanovsky *et al.*, 2002; Walsh *et al.*, 2005). Visual evidence of permafrost degradation has been presented, although systematic measurements showing widespread thickening of the active layer are lacking. Changes of vegetation, particularly a transition from grasses to shrubs, has been reported in the North American Arctic (Sturm *et al.*, 2001), and satellite imagery has indicated an increase in photosynthetically active biomass (NDVI) over much of the Arctic (Slayback *et al.*, 2003). This increase is consistent with a longer growing season and with documented changes of the seasonal amplitude of atmospheric CO_2 concentrations in the Arctic as reported in the TAR.

The Arctic is home to approximately 4 million residents (Bogoyavlenskiy, 2004). During the 20th Century migration into the Arctic, increased such that the non-indigenous population has surpassed the number of indigenous inhabitants. With this migration came various forms of social, cultural and economic change (Huntington, 1992; Nuttall, 2000b).

For most arctic countries, only a small proportion of their total population lives in the Arctic, and settlement is generally sparse with densities ranging from 3 people per 100 km^2 (Canadian Arctic) to 3410 per km^2 (Faroe Islands, Bogoyavlenskiy, 2004). However, on average, two-thirds of the Arctic population lives in settlements of more than 5 000 people. In some countries, significant numbers continue to live in small villages (e.g. Norway), but in others larger settlements and nomadic peoples are more significant. Indigenous residents are, in most regions, encouraged to become permanent residents in fixed locations, to facilitate the provision of services and economic opportunities. The establishment of fixed-village locations has affected subsistence activities (exercise, diet, etc.) predominantly in a negative manner. Community infrastructure has similarly changed with most regions having experienced an increase in safe water supplies, sewage disposal, development of rural hospitals, and in some regions, community-based medical providers, access to tele-health technologies, and improved transportation infrastructure, which has resulted in and increased availability of such things as western food items, tobacco, and alcohol (Hild and Stordhal, 2004). In general, the Arctic is characterized by a young, rapidly growing population with most regions experiencing higher fertility rates than their national averages, and increasing but lower than national average life expectancy. Some exceptions exist, for example the Russian north, where population and life-expectancy has decreased since 1990.

Political and administrative regimes in arctic regions vary among countries. Various levels of self-determination and autonomy exist among indigenous groups. A number of land claims and self-government arrangements have been established. Some regions (e.g. Nunavut, Greenland) have formalized substantial land-claim settlements while in Eurasia indigenous claims have only recently begun to be addressed (Freeman, 2000). Wildlife management regimes and indigenous / non-indigenous roles in wildlife management similarly vary among regions. Today, the economies of many communities are a mix of traditional informal and formal wage-earning systems (Caulfield, 2004). Large-scale resource extraction initiatives and/or forms of social support play significant roles in the economies of many communities. Despite these changes, traditional ways of life remain important with hunting, fishing, and gathering of resources in the local environment and sharing among individuals in the community continuing to play vital roles of day-to-day life in many locations.

Regardless of its small number of dispersed inhabitants, the Arctic has become increasingly important in global politics and economies. Contaminant production and use and its deleterious effects on the health of residents of the Arctic, has been essential in finalizing international agreements such as the Stockholm Convention on Persistent Organic Pollutants (Downey, 2003).

Antarctic

The Antarctic continent has an area of around 14 million km^2 of which less that 0.4% is ice-free. Large parts of the continental ice sheet rise to over 3000 m, making this the highest continent. High-pressure systems over the interior result in generally light to moderate winds and low snowfall, while low-pressure cells around the coast lead to high windspeeds and heavier snowfall. In addition, cold air flows off the ice sheet in katabatic winds, the effects of which are controlled by local topography. The ice-free areas are confined to the so-called coastal “oases” and steep slopes on inland mountains.

These areas are exploited by wildlife for breeding as well as by humans as sites for scientific stations. Summer temperatures may rise above 0 ºC in a few coastal areas. Melting conditions promote growth of algae, lichens and mosses and associated protists and micro-invertebrates. The interior of Antarctica is much colder, never reaching 0 ºC, but growth of micro-organisms occurs where solar heating of rocks produces a little moisture.

Direct measurements at Antarctic meteorological stations reveal considerable spatial variability in temperature trends. All meteorological stations on the Antarctic Peninsula show strong and significant warming over the last 50 years, but of the other long-term (>30 years) records available from the Antarctic continent, 12 show warming in mean annual temperature, while seven cooling. However, only two of these (one of each) are significant at the 10% level (Turner *et al.*, 2005). If the individual station records are considered as independent measurements, then the mean trend is warming at a rate comparable to mean global warming (Vaughan *et al.*, 2003), but there is no evidence of a ubiquitous “polar amplification” in Antarctica.

A few areas, such as the Dry Valleys have shown short-term (decadal) cooling in recent decades. This has had specific local impacts, such as a 6-9 percent reduction in primary production in lakes in the Dry Valleys and a >10 % per year decline in soil invertebrates (Doran *et al.*, 2002). In contrast, the lakes on Signy Island, a sub-Antarctic island has warmed by around 1 ºC in the last 25 years. As a result phytoplankton growth has increased dramatically (Quayle *et al.*, 2002).

Climate models indicate that stratification in the Southern Ocean is likely to increase as a consequence of increased precipitation (Sarmiento *et al.*, 1998). The community structure of primary producers has been shown to be related to mixed-layer depth with diatoms dominating in highly stratified waters and a haptophyte (*Phaeocystis antarctica)* dominating in more deeply mixed water (Arrigo *et al.*, 1999). As the draw-down of CO_2 and the rate of new production is lower in diatoms than *Phaeocystis*, increased stratification would lead to the lower drawdown of atmospheric CO_2 and its transport to the deep ocean.

Increasing atmospheric concentrations are leading to an increased uptake of CO_2 by the oceans and as a consequence seawater becoming more acidic. As is the case in other parts of the world’s oceans, coccolithohorids and foraminifera are significant components of the pelagic microbial community of the warmer waters of the Southern Ocean. These organisms are covered by scales or shells made of calcium carbonate (calcite) and their sinking in the draw-down of atmospheric CO_2 in to the deep ocean. Experimental studies (Riebesell *et al.*, 2000) indicate that elevated CO_2 concentrations reduce CO_2 draw-down compared to the production of organic matter. In addition, as the process of calcification releases CO_2 to the atmosphere, decreased calcification could lead to increased CO_2 storage in the ocean - a negative feedback to atmospheric CO_2 concentration (Royal Society, 2005). Fishing is presently the only large-scale resource exploitation that is being conducted in Antarctica. Antarctic fisheries are regulated by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), a 1982 addition to the Antarctic Treaty System. Before CCAMLR came into force, heavy fishing around South Georgia led to a major decline in some stocks, which have still to recover fully. The illegal, unregulated and unreported fishing of the Patagonian toothfish is of concern because it has the potential to undermine attempts to manage the stock as a sustainable resource (Bialek, 2003). Further, those fishing illegally often use techniques that cause the death of by-catch species. For example albatrosses and petrels are under threat as they are drowned in large number following their taking bait being used in long-line fishing (Tuck *et al.*, 2001).

Over 20,000 tourists now visit Antarctica each year and the industry is growing. The International Association of Antarctic Tour Operators (IAATO), an organization of tour operators, travel agents and companies chartering ships and aircraft, has established a voluntary code of conduct for safe and environmentally sound private-sector travel to the Antarctic.

15.2.2 Vulnerability and adaptive capacity

15.2.2.1 Terrestrial and marine ecosystems.

Arctic

Many terrestrial arctic species are particularly vulnerable to climate change because they are specialised and have adapted to harsh conditions in ways that are likely to make them poor competitors with potential immigrants from environmentally more benign regions. Other species require specific conditions, for example winter snow cover, or a particular timing of food availability, for breeding and feeding. Many species face multiple, concurrent drivers of change (including increased UV-B radiation, increasing contaminant loads, habitat loss and fragmentation) that might add to impacts of warming. Plants and animals in the Arctic are vulnerable to attacks from pests, parasites and pathogens that develop faster and are more prolific in warmer conditions. Many terrestrial arctic ecosystems are vulnerable to climate change because biodiversity is low in general, redundancy within trophic levels is low, and redundancy within some species groups is particularly low. Some groups of species are particularly susceptible to competition from neighbours and immigrants that respond more to warming, and loss of a keystone (e.g. lemmings: Turchin and Batzli, 2001) species could have cascading effects.

The genetic adaptive capacity of terrestrial arctic species in general is small because many organisms are long-lived and have low fecundity, which limit rates of genetic recombination. However, adaptive capacity varies across species groups from clonally reproducing plants with low adaptive potential, through some insects (e.g. arctic aphids: Strathdee *et al.*, 1993) that can adapt their life cycles to micro-organisms that have great adaptive potential because of rapid turn-over and universal dispersal. The non-genetic adaptive capacity of current arctic ecosystems is small because their extent is likely to be reduced substantially by compression between the forests advancing from the South and flooding of northern coastal wetlands as sea level increases, and also as habitat is lost to land use (Figure 15-2). Responses (genetic and non-genetic adaptations) of arctic species and ecosystems to warming is likely to be similar to that in the past, i.e. relocation (Figure 15-2).
Arctic marine ecosystems cannot be defined easily by latitude; for example, hydrobiological conditions in large parts of the Barents Sea are sub-Arctic despite their high latitude (70-80°N), while the continental shelf waters off Labrador and Newfoundland, far south of the Arctic Circle (45°N-70°N) are best classified as arctic. The main arctic and sub-arctic marine ecosystems can be divided into four major zones: 1. The Bering Sea (sub-arctic); characterized by relative stability over time, high productivity and complete dominance by one fish species, the walleye pollock. 2. The Barents Sea and Icelandic waters (sub-arctic); characterized by relatively high productivity and resilient demersal fish stocks as well as large pelagic stocks like herring and capelin. Historically, these have fluctuated considerably in biomass and catches. 3. Seas around Greenland and NE-Canada (arctic); characterized by few slow-growing commercial species, this area has high productivity in some shelf areas, but is sensitive to variations in hydrographic climate and fishing pressure. 4. The Arctic Ocean, including the Siberian and North American shelf seas (arctic); sea ice covered in winter, and because of the resultant reduced light exhibiting lower productivity, they support no significant commercial fisheries.

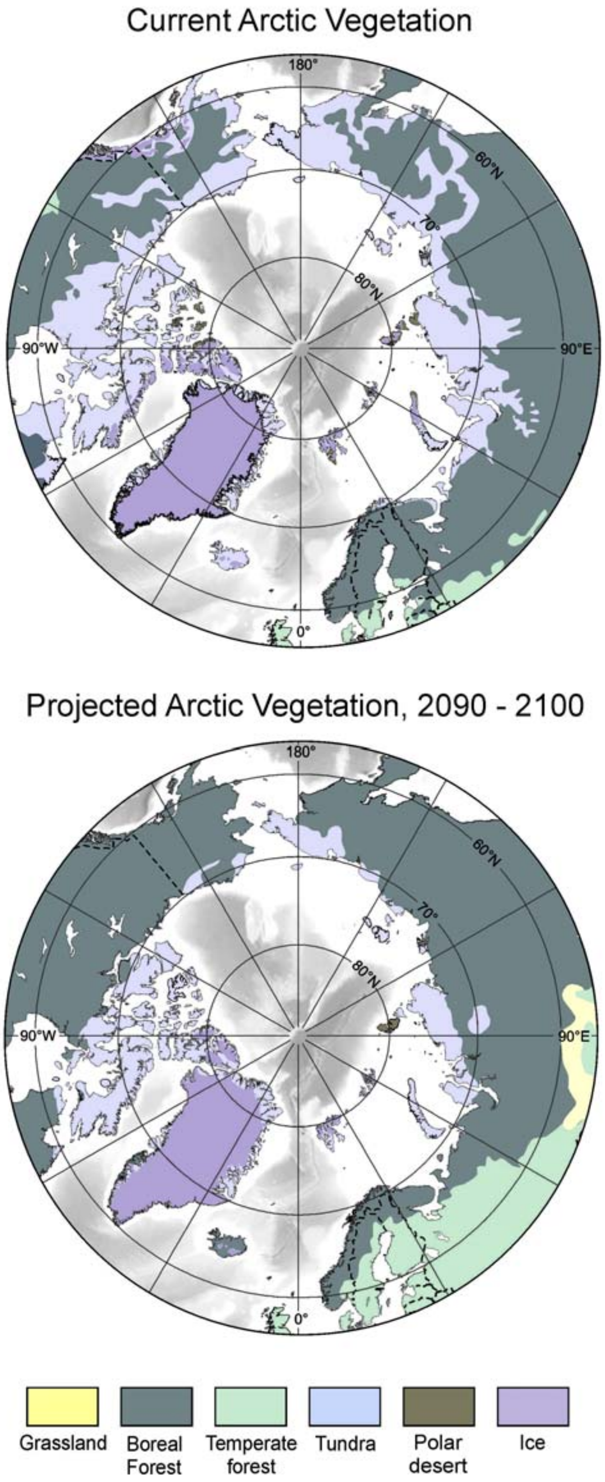

Figure 15.2: *Present day vegetation of the Arctic and neighbouring regions based on floristic surveys (top) and projected vegetation for 2090-2100, predicted by the LPJ Dynamic Vegetation Model driven by the HadCM2 climate model (bottom). Modified from (Kaplan et al., 2003) in (Callaghan et al., 2004). The original vegetation classes have been condensed as follows: grassland = temperate grassland and xerophytic scrubland; temperate forest = cool mixed forest, cool-temperate evergreen needle leaf and mixed forest, temperate evergreen needle leaf forest, temperate deciduous broadleaf forest; boreal forest = cool evergreen needle leaf forest, cold deciduous forest, cold evergreen needle leaf forest; tundra = low- and high-shrub tundra, erect dwarf-shrub tundra, prostrate dwarf shrub tundra; polar desert/semi-desert = cushion forb, lichen and moss tundra.*

Many arctic and sub-arctic seas (e.g. parts of the Bering and Barents seas) are among the most productive in the world (Sakshaug, 2003), but high productivity is not ubiquitous, and in other areas (e.g. Arctic Ocean) reduced light levels, due to sea ice, limit productivity. Nevertheless, present fisheries yield ~7 M tonnes per year, provide about $US 15 B in earnings (Vilhjálmsson *et al.*, 2005), and employ 0.6 – 1 M people (Agnarsson and Arnason, 2003). In addition, arctic marine ecosystems are important to indigenous peoples and rural communities (e.g. in northern Norway and Iceland) who strive to preserve traditional lifestyles (Vilhjálmsson *et al.*, 2005).

Recent studies reveal that sea surface warming in the northeast Atlantic is accompanied by increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions (Richardson and Schoeman, 2004). In addition, the seasonal cycles of activities of marine micro-organisms and invertebrates and difference in the way components of pelagic communities respond to change is leading to a mismatch between trophic levels (Edwards and Richardson, 2004). Continued warming is therefore likely to impact on the amount and community composition of primary and secondary producers with consequential stresses on higher trophic levels with impacts on economically important species, including fish, and dependent predators such as mammals and birds.

Antarctic

Substantial evidence indicates major changes in antarctic terrestrial and marine ecosystems. The temperature on sub-Antarctic islands and the Antarctic Peninsula has increased by up to 1 ºC in the latter half of the 20th Century. Precipitation has declined on sub-Antarctic islands over the same period of time by up to 50 percent (Bergstrom and Chown, 1999). Increasing abundance of shallow water sponges and their predators, declining abundances of krill, Adelie and Emperor penguins and Weddell seals have been recorded (Ainley *et al.*, 2005). Only two species of native flowering plant occur on the Antarctic continent. The antarctic pearlwort (*Colobanthus quitensis*) and the antarctic hair grass (*Deschampsia antarctica*) have similar distributions on the Antarctic Peninsula. They also grow on maritime antarctic islands. The number of individual plants and colonies of these two plants were monitored between 1964 and 1990 on the Argentine Islands adjacent to the Antarctic Peninsula. Over this time the population of *Deschampsia* increased by nearly 25-fold and *Colobanthus* by over 5-fold. The increase in the abundance and distribution of these vascular plants was ascribed to the increasing summer temperatures leading to increasing reproductive success (Fowbert and Smith, 1994).

The claimed marked reduction in the biomass of Antarctic krill (*Euphausia superba*) and an increase in the salp (principally *Salpa thompsoni*) abundance may be related to changing sea ice conditions (Atkinson *et al.*, 2004). It may also underlie the changes late in the 20th Century in the demography of krill predators reported from the southwest Atlantic (Fraser and Hoffmann, 2003), and this connection indicates a potential vulnerability to climate change whose importance cannot yet be determined.

Recent studies on sub-antarctic islands have shown increases in the abundance of alien species and their negative impacts on the local biota. Increasing human activities on these island on top of the increasing temperatures is exacerbating these successful alien invasions (Bergstrom and Chown, 1999). On the Antarctic continent itself, climate change is affecting the vegetation, which is largely composed of algae, lichens and mosses and further significant changes are expected as temperature, water relations and nutrient availability changes (Robinson *et al.*, 2003).

15.2.2.2 Freshwater resources

Climate variability/change has historically, and will continue, to have impacts on arctic freshwater resources. First-order impacts (e.g., changes to snow and ice or basic water budget) play a significant role via feedbacks in the vulnerability of important global climate processes (e.g., changes to radiative feedbacks, stability of the thermohaline, carbon/methane source-sink status). Cascading effects have important consequences for the vulnerability of the freshwater itself, as measured by its ecological or human resource value. From an ecological perspective, the degree of vulnerability to many of the higher order impacts (e.g., changes in aquatic geochemistry, habitat availability/quality, biodiversity) are related to gradual or threshold transitions such as those associated with abrupt water-phase changes (e.g., complete loss of ice cover) and step changes (e.g., precipitous declines in dissolved oxygen related to lake productivity) (Wrona *et al.*, 2005a).

While the overall magnitudes and nature of the ecological responses of freshwater ecosystems to climate change in the Arctic are not necessarily new (i.e., as ascertained from historical evidence, a limited number of recent studies of ecosystem response to environmental variability e.g., Ruhland and Smol, 2002; Ruhland *et al.*, 2003), what is new is the projected combination of high-magnitude events coupled with abnormally rapid rates of change, probably outstripping the natural ability of the biota and their associated ecosystems to adapt to the change. This will result in significant changes from current state, unforeseen consequences, and both positive and negative impacts. It is projected, however, that overall the negative will very likely outweigh the positive effects, making aquatic ecosystems highly vulnerable to climate change impacts (Wrona *et al.*, 2005a). Although little considered, it is possible for humans to implement adaptive measures that could reduce the negative impacts of climate change on freshwater ecosystems. One such example, is the use of flow regulation to assist in the flooding of riparian zones suffering from prolonged drought (Prowse *et al.*, 2002).

From a human-use perspective, adaptation measures are extremely diverse, ranging from measures to facilitate modified use of the resource (e.g., changes in ice-engineering approaches for ice-road construction; altered hydro-electric and drinking-water distribution strategies under different water supply and ice conditions; shifts in harvesting strategies because of changes in species composition/diversity/abundance), to adaptive methods to avoid increased freshwater hazards (e.g., relocation or construction of protective structures to reduce flood risks; changes to more land-based travel as hazard of ice-surface travel increases). Difficulties in pursuing adaptive measures may be largest for those who place cultural and social importance on traditional uses of the freshwater resource (Huntington *et al.*, 2005a; Nuttall *et al.*, 2005).

15.2.2.3 Permafrost

Permafrost, defined as subsurface earth materials that remain at or below 0 ^{o}C continuously for two or more years, is widespread in arctic, sub-arctic, and high-mountain regions, including the Northern Rockies, the Patagonian Andes, the Alps, the Urals, and the Tibet Plateau. The distribution of permafrost is less well known in the South Polar region, although it has been documented in the Antarctic Dry Valleys and many sub-antarctic islands. Knowledge about its extent elsewhere in Antarctica is limited by a general lack of information about subglacial environments.
The physical processes of climate-permafrost interactions and observations of permafrost change are discussed in detail in Chapter 4 of IPCC WG-1 report. Here we focus on the observed and projected for the future long-term changes of permafrost, and impacts it may have on natural and human systems.

Observational data about the long-term response of permafrost to climatic and other types of environmental change are limited. Precise measurements in boreholes indicate that permafrost temperatures increased markedly during the last 50 years (Romanovsky *et al.*, 2002). Although the magnitude of temperature changes is not geographically uniform, the preponderance of warming in Alaska (Hinzman *et al.*, 2004), Canada (Beilman *et al.*, 2001), Europe (Harris *et al.*, 2003), and Siberia (Pavlov and Moskalenko, 2002) provides strong evidence that permafrost is being affected by global warming (See Figure 15-3). Short-term and localized warming associated with the insulating effects of snowcover (Stieglitz *et al.*, 2003) and feedbacks associated with increased vegetation productivity (Sturm *et al.*, 2001; Anisimov and Belolutskaia, 2004) are, however, important considerations that must be taken into account.

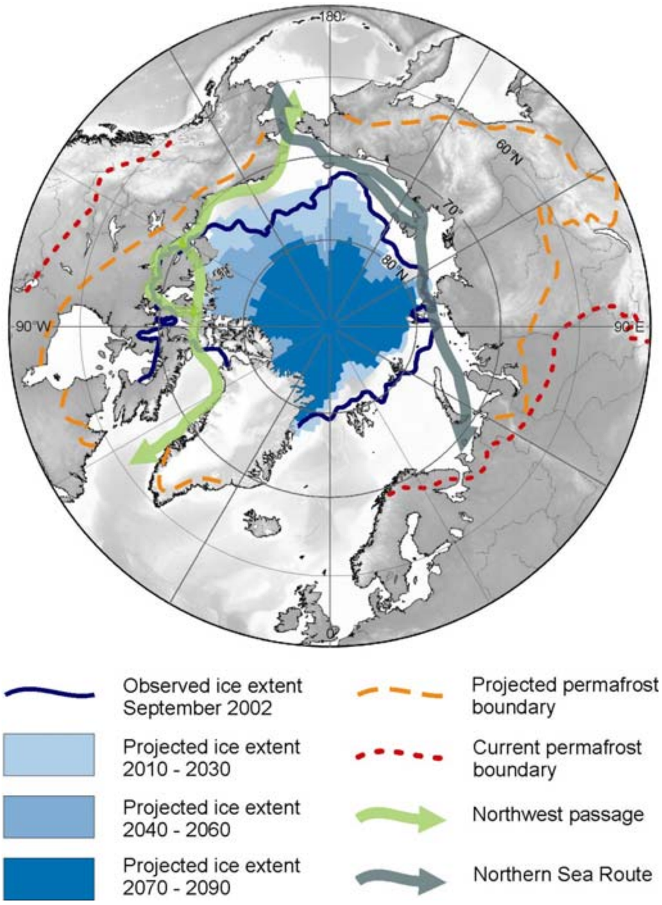

Figure 15.3: *Projections of permafrost and sea-ice extent changes , together with potential new sea routes (redrawn from, Instanes et al., 2005; Walsh et al., 2005)*

In the context of the future climate change there are two key concerns associated with the thawing permafrost: the detrimental impact on the engineering infrastructure built upon it, and the feedback to the global climate system through potential emission of greenhouse gases. These are discussed in Sections 15.7.1 and 15.4.2.3.

15.2.2.4 Populations

Neither Antarctica nor the sub-antarctic Islands have had indigenous populations, and for the most part, the only residents are staff at scientific and other stations and summer-only visitors. While there are some areas of particular sensitivity, where climate change might require some facilities to be abandoned, from a global perspective these can only be viewed as little more than logistical inconvenience to the organisations concerned.

In contrast, the Arctic is home to about 4 million residents of which approximately 10% are Indigenous People (Bogoyavlenskiy, 2004). The archaeological record shows that humans have existed here for thousands of years (Pavlov *et al.*, 2001). The survival and establishment of the many indigenous populations is a testament to their resilience and adaptive abilities. Arctic Indigenous Peoples have always lived with a high degree of environmental variability and their capacity to adapt is part of their cultures (Balikci, 1968; Langdon, 1995).

Since the turn of the 20th Century, migration into the Arctic has significantly changed the nature of indigenous populations. With immigration from the south came social, cultural, economic and political change. Previously moving with seasonal cycles and wildlife resources, the large majority of arctic residents now live in settled communities and have access to improved infrastructure. Community economies are a combination of traditional informal systems and wage-earning employment, in some cases strongly associated with mineral and resource extraction (Duhaime, 2004). Many communities are in low-lying coastal areas exposed to harsh environmental conditions and despite the socio-economic changes taking place, retain a strong relationship with the land, which is central to their identity, culture and traditions. Varying levels of self-determination exist among indigenous populations in relation with national or international governments; some groups have a land claim and self-government, while others are not yet recognized as Indigenous people within their country. The vulnerable nature of arctic communities, and particularly arctic indigenous populations, to climate change arise from their close relationship with the land, geographic location, reliance on the local environment for aspects of everyday life such as diet and economy, and the current dynamic state of social, cultural, economic and political change taking place in these regions. Communities are already adapting to climate changes in their local environment (Krupnik and Jolly, 2002b; Nickels *et al.*, 2002) via such things as changes in local wildlife management regimes, and changes in individual hunting practices (i.e. times and locations) and they retain great capacity to adapt to environmental change. The strong adaptive capacity is related to their flexibility in regards to seasonal cycles and harvesting techniques, the detailed local knowledge and related skill sets within groups to successfully hunt, fish, travel and survive in the arctic environment, and the sharing mechanisms and social networks that provide mutual support among individuals and groups in times of need (Berkes and Jolly, 2001).

However, the movement of individuals into permanent communities has limited this adaptive capacity and the transition towards a more sedentary lifestyle as it has minimized mobility and impacted the generation and transmission of local knowledge needed to adapt. With the increased involvement in wage-earning employment there has been an increased reliance on a smaller number of hunters in some communities to provide traditional foods and the sustainability of this trend is unknown. Small arctic communities, however remote, are tightly tied politically, economically and socially to the national mainstream, as well as being linked to and affected by the global economy (Nuttall *et al.*, 2005). Today, trade barriers, wildlife management regimes, political, legal and conservation interests and globalisation all affect, constrain or reduce the abilities of indigenous peoples to adapt and be flexible in meeting the challenges posed by climate variability and change. Circumpolar-wide examples illustrate the complexity of problems faced by indigenous peoples today (Nuttall *et al.*, 2005), underscoring the reality that climate change is but one of several, often interrelating problems affecting their livelihoods. Indigenous peoples are simultaneously exposed to a variety of different drivers of change that increase their vulnerability and reduce their capacity to respond effectively. Finally, some adaptive strategies effective in minimizing human exposure to a hazard may not be deemed acceptable because of their impacts on critical aspects of traditions and culture. For example, the Inuit Circumpolar Conference has framed the issue of climate change in a submission to the United States Senate Committee on Commerce, Science and Transportation as an infringement on human rights as it restricts access to basic human needs as seen by Inuit and will lead to the loss of culture and identity (Watt-Cloutier, 2004). We do not currently know where these thresholds exist or what the limits are to adaptive capacity for arctic indigenous populations. The assessment of community vulnerabilities and our understanding of the development of adaptive capacity are just beginning and participatory approaches to this work taken in some regions seem to be proving valuable.

15.3 Assumptions about future trends

15.3.1 Key regional impacts with importance to the global system

Key regional impacts of climate change in the Arctic include more readily accessible mineral and fossil fuel resources, increased marine access, risk to infrastructure in areas of permafrost, shifts of species (both plant and animal), and human health effects arising from altered disease vectors.

Arctic warming and its consequences may have worldwide implications through the following processes and feedbacks:

- **Reflectivity of Snow and Ice:** Snow and ice play several vital roles in the global climate system, and increasing confidence in estimates of future change requires better documentation of the type and extent of snow and ice and the changes that are occurring. Warming already seems to be leading to more rapid disappearance of spring snow cover in some areas (e.g., Alaska, Siberia), and the consequent forcing on albedo may lead to further forcing of climate change.
- **Freshwater Runoff, Sea Level, and Ocean Circulation:** Already extensive retreat of mountain glaciers in the Arctic is contributing to the increase in global sea level (Arendt *et al.*, 2002), and more rapid melting of the edges of the Greenland Ice Sheet has also been seen (Abdalati and Steffen, 2001). In addition, increases in river runoff, the major contributor to the freshwater budget of the Arctic Ocean, have been observed (Peterson *et al.*, 2002). Further changes in the freshwater budget of the Arctic Ocean, are expected and could influence ocean circulation with global impacts.
- **Arctic carbon flux:** The extent and character of vegetation and the uptake and release of carbon, both as carbon dioxide and methane, from the arctic soils (and potentially continental shelves) are likely to be altered as the climate and carbon dioxide concentration change, and permafrost thaws (e.g., Anisimov *et al.*, 2005a).
- **Migrating species:** The Arctic is the summer home of many migrating species, including terrestrial and marine mammals, birds, fish, and other species that winter over far to the south. Field and modelling studies will be essential to improve understanding the impacts of change in environments on which these species depend, and how competition for these habitats is likely to change as non-native species increase their presence in the Arctic.
- **Methane hydrates:** Significant amounts of methane are trapped in the permafrost present in the Arctic. As continental shelves and land areas warm, this methane is likely to be released. Whether these emissions reach the atmosphere as methane or as carbon dioxide is very important, because, on a per molecule basis, methane has more than 20 times the warming influence that carbon dioxide.
- **Southern Ocean circulation:** The expulsion of brine during the formation of Antarctic sea-ice is a major source of Antarctic Bottom Water (AABW). The production of AABW and its northward flow is a major driver of the global thermohaline circulation. Modelling studies

indicate that a three-fold increase in greenhouse gases would lead to a shutdown in thermohaline circulation (Budd and Wu, 1998). There has been considerable debate in the last decade on whether there was a marked reduction in the extent of antarctic sea ice between the 1950s and 1970s. The present consensus is that while it is likely that regional perturbations occurred, there was no substantial reduction in the mean ice extent (Ackley *et al.*, 2003).

- **Southern Ocean carbon flux:** Climate models indicate that stratification of the Southern Ocean. This could change the community structure of primary producers and lead to the lower draw-down of atmospheric CO_2 and its transport to the deep ocean.

15.3.2 Projected atmospheric changes

The IPCC models project continued warming of the Arctic. By the end of the 21st Century, the areally averaged warming ranges from about 2°C to about 9°C, depending on the model, forcing scenario and ensemble member. The warming is largest in the autumn and winter, and is largest over the polar oceans in areas of sea ice loss. Over land, the projected warming shows less seasonal variation. Through to approximately 2070, the variance between forcing scenarios is comparable to the inter-model variance for a particular forcing scenario. However, after about 2070, the variance between forcing scenarios becomes larger than the inter-model variance, implying that the uncertainty in forcing will become the greater source of uncertainty by the latter portion of the 21st Century (Chapman and Walsh, Submitted).

While all models show an arctic polar amplification in the projected warming, the inter-model variance of the projected warming is also greater in the Arctic than elsewhere. As a result, the projected warming as a multiple of model variance, which we take to be a proxy for natural variability, is no larger in the Arctic than in some mid-latitude and even some tropical areas of the Northern Hemisphere (Raisanen, 2001).

In contrast to the unanimity of the models in predicting a polar amplification of the northern hemisphere warming, there is wider disagreement among models concerning polar amplification in the Antarctic, especially over the continent. In several models' simulations, however, the warming is amplified over a narrow Southern Ocean band from which sea ice retreats during the greenhouse simulation.

Precipitation is projected to increase during the 21st Century by about 10% to about 20% in the B2 scenario used by the Arctic Climate Impact Assessment, however, spatial patterns of the precipitation increase vary among the models. Similar results have emerged from the IPCC AR4 simulations (Kattsov *et al.*, Submitted). The projected increases of precipitation are largest in the autumn and winter. Interestingly, the ratio of signal to noise (the latter being the model's natural variability) is greater in the Arctic than elsewhere in the globe - unlike the geographical pattern of the signal-to-noise ratio for temperature. The difference between precipitation and evapotranspiration (P-E), which over multiyear timescales is approximately equivalent to runoff (river discharge), is also projected to increase by the late 21st Century. The projected increases by 2080 are generally in the range of 15-30%, largest in the A2 scenario and smallest in the B1 scenario. Of the major river basins, the largest increases are projected for the Lena River Basin.

The mean projected increase of precipitation over Greenland in the IPCC models is about 20%, ranging among the models from a slight decrease to an increase of more than 30%. The increase is largest over eastern Greenland. As shown in WG1's Chapter 11, the change of mass balance projected for 2071-2100 is negative, consistent with increasing temperatures and an increasing proportion of precipitation falling as rain rather than snow. The projected increases of antarctic precipitation, when averaged over all the IPCC AR4 models, are close to zero over much of the Antarctic ice sheet. However, increases of about 1 cm/month are projected over much of the Southern Ocean, with smaller increases in the immediate vicinity of the Antarctic coast.

15.3.3 Projected changes in the oceans

The projected increases of arctic river discharge and precipitation over polar oceans, as well as the projections of an increasingly negative mass balance of Greenland (WG1 Chapter 11), point to a freshening of the ocean surface in northern high latitudes. However, the projected changes of calving rates are not available for the IPCC simulations, since the calving rate is not included explicitly in coupled global models.

Near-surface salinities are projected to decrease in most coupled models due to increases of P-E, river discharge and sea-ice melt. Additional stabilization of the water column will likely result from the warming of the upper ocean layers, but it should be noted that current global models are seriously deficient in their simulations of the polar oceans. In particular, control and greenhouse simulations show such a wide inter-model differences in Arctic Ocean currents that the consequences of upper-ocean stabilization cannot be reliably inferred. Assessments of impacts on marine ecosystems are thus tentative but based on the tendencies toward fresher and warmer surface waters, together with the loss of sea ice.

The Southern Ocean hydrography and currents also vary widely between models in the control and greenhouse simulations. For example, the volume fluxes of the Antarctic Circumpolar Current (ACC), which is the largest ocean current system on Earth, vary by factors of 2-3 in the simulated present-day climate, and no systematic changes across the suite of IPCC AR4 models have been reliably identified.

15.3.4 Projected changes in cryosphere

Changes can be expected in all the significant components of the cryosphere (glaciers, seasonal snow-cover, sea-ice and permafrost) in both polar regions.

15.3.4.1 Arctic

An assessment of recent and projected changes in the Arctic was completed as part of the ACIA and this represents a comprehensive and up-to-date review of the subject (Walsh *et al.*, 2005). Reductions in arctic sea ice extent have continued in recent years (Cavalieri *et al.*, 2004), with satellite records showing an especially pronounced decrease in summer minima of 9% per decade (Comiso, 2002). Evidence collected by submarines has continued to indicate thinning of ice (Wadhams and Davis, 2000). The projected 21st Century retreat of sea ice in the arctic ranges among the models from essentially no change to a complete loss of summer sea ice. The large range has been a characteristic of recent model-based evaluations (ACIA, 2004; Covey *et al.*, 2004; Flato, 2004). A new study (Zhang and Walsh, Submitted) based on the IPCC AR4 model simulations, showed mean reductions of annually averaged sea ice area by 2080-2100 of 31%, 33% and 22% in the A2, A1B and B1 scenarios, respectively (See Figure 15-3). All studies find that the sea ice retreat is larger in summer than in winter, so the multiyear sea-ice coverage decreases by a greater percentage than does first-year ice coverage, which actually increases in many models. Sea ice thickness decreases accordingly (cf. WG-1 Chapter 11, Fig. 11.36). The models with the least sea ice in the present climate (1981-2000) tend to predict sea-ice-free conditions during summer earlier in the 21st Century (Zhang and Walsh, Submitted).

Seasonal snow-cover on land is highly variable but nevertheless is important in its effect on ground beneath and its influence on local climate through albedo. In Eurasia and to a lesser extent North America there has been persistent increase in the duration of snow-free conditions of 5-6 days/decade for almost 3 decades (Dye, 2002), this is primarily as a result of earlier snow loss in spring. Projections from different climate models generally agree that these changes will continue, with notable impacts likely for the timing of spring melt-water pulses, transport and agricultural opportunities (Anisimov *et al.*, 2005a).

Glaciers and ice caps, the permanent features covering the majority of the more northerly islands and archipelagos in the Arctic, respond to climate change over years and decades, whereas the some of the changes in the massive Greenland ice sheet may be responses to changes during past millennia. Although exceptions arise as individual glacier fluctuations (e.g. surges), regular monitoring shows that there are clear decadal trends of retreat in the most glaciers and ice caps across, Alaska (Arendt *et al.*, 2002), the Canadian Arctic and Svalbard. In Iceland and Scandinavia, there have been periods of advance in recent decades, but in both cases this appears to have turned to retreat within the last decade (Sigurdsson, 2002). Across the Russian archipelagos of Novaya Zemlya, Franz Josef Land and Severnaya Zemlya, there is no programme of routine monitoring, but there is evidence of retreat from repeated observations of glacier extent (Walsh *et al.*, 2005). Projections of change agree that retreat of glaciers will continue across arctic glaciers, with a consequent impact on global sea level (Lemke *et al.*, In press). Recent changes in the Greenland ice sheet have been somewhat complex. The colder interior appears to have thickened slowly as a result of recently high precipitation rates, while the coastal zone appears to be thinning rapidly (Krabill *et al.*, 2000), this appears to be a combined response to recent increases in summer melt (Abdalati and Steffen, 2001), and glacier acceleration through enhanced lubrication (Rignot *et al.*, 2005).

Warming, thawing and disappearance of part of the permafrost are expected in response to climatic change in the 21st century (Lemke *et al.*, In press). Results from models forced with a range of IPCC climatic scenarios indicate that the permafrost area in the northern hemisphere is likely to reduce by 10%-18%; 15%-30%, and 20%-35% by 2030, 2050 and 2080, respectively, largely due to the thawing of the southern zone of sporadic and discontinuous permafrost but also due to the decrease in the areal continuity of the frozen ground in other zones (Anisimov and Belolutskaia, 2004). Projected changes of the depth of seasonal thawing are not uniform in both space and time. In the following three decades they are likely to be within 10%-15% over most of the permafrost area. By the middle of the century depth of seasonal thawing may increase on average by 15%-25%, and by 50% and more in the northernmost locations. By 2080 it is likely to increase by 30%-50% and more all over the permafrost area (Anisimov and Belolutskaia, 2004). The impacts such changes may have on the engineering infrastructure built permafrost, and the feedback to the global climate system through potential emission of greenhouse gases are discussed in sections 15.7.1 and 15.4.2.3.

15.3.4.2 Antarctica

The two major components of the cryosphere in the south polar region are the sea ice and the Antarctic ice sheet. Permafrost, seasonal snow cover, and lake-ice do exist but in such small areas that they are only discussed in respect to particular impacts.

Evidence for sea-ice changes taken from records of whaling activities (de la Mare, 1997), has been recently called into question (Ackley *et al.*, 2003) and is no longer considered as reliable. Thus for the period before the beginning of satellite observation only direct observations (e.g. Murphy *et al.*, 1995) and proxies (e.g. Curran *et al.*, 2003) for local-area changes are available. In distinct contrast to the Arctic, there has been no ubiquitous trend in antarctic sea ice extent or duration in the period of satellite measurements (since the late-1970s). However, there are strong regional trends; sea ice in the Ross Sea has increased, while in the Bellingshausen and Amundsen Sea it has decreased, with high statistical significance in each case (See Figure 15-4, and Parkinson, 2002; Zwally *et al.*, 2002). These regional changes strongly reflect the trends in atmospheric temperature measured at coastal climate stations (Vaughan *et al.*, 2003).

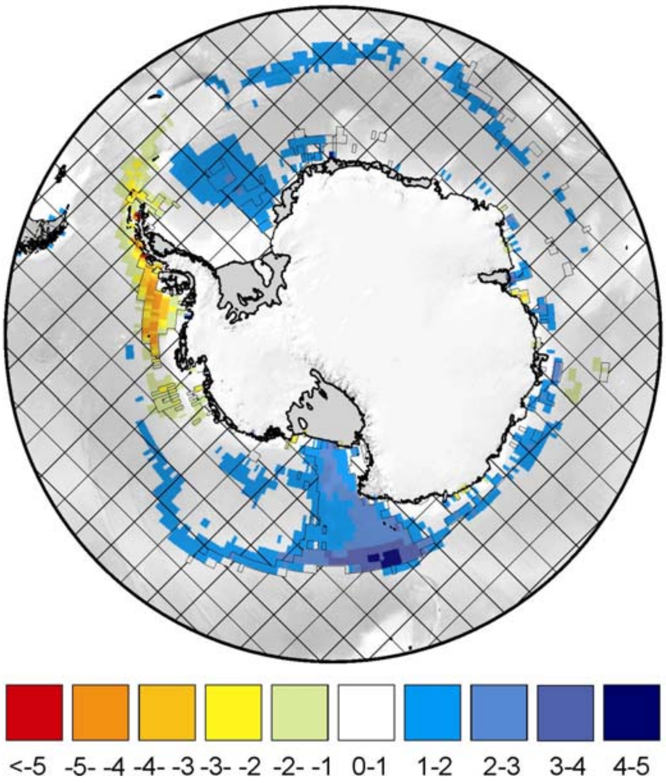

Figure 15.4: *Changes in sea-ice duration in days per year, for the period 1978-2004, after Parkinson (Parkinson, 2002). Hatched areas show where trends are not significant at the 95 % level.*

Several models exhibit a definite shortcoming in showing very little sea ice around Antarctica in the present climate, even during winter. Predictions for 21st-Century changes range from complete loss to a slight increase of antarctic sea ice. There is a tendency for models with more extensive ice coverage in present-day simulations of the Southern Hemisphere to exhibit greater antarctic warming, although the opposite is true for the Arctic, albeit with low statistical significance (Flato, 2004).

Recent changes in volume of the Antarctic ice sheet are much better mapped and understood than they were in the TAR (Davis *et al.*, 2005), but competing theories still prevent confidence in prediction of the future changes. The ice sheet on the Antarctic Peninsula is probably alone in showing a clear response to contemporary climate change (See case study 15.6.3), and the larger West Antarctic and East Antarctic ice sheets are showing changes whose attribution to climate change are not clear but cannot be ruled out. In West Antarctica, there is some evidence that the dramatic recent thinning of the ice sheet throughout the Amundsen Sea sector is the result of recent ocean change (Payne *et al.*, 2004; Shepherd *et al.*, 2004), but this is not supported by the corresponding measurements of ocean change. Furthermore, there is emerging evidence that deglaciation of some parts of West Antarctica, as a response to climate change at the end of the last glacial period is not yet complete (Stone *et al.*, 2003). There are still competing theories, but the recent observations of change, have reinvigorated debate about whether we can expect a future a deglaciation of this portion of the West Antarctic ice sheet on century to millennial timescales. Evidence from satellite altimetry data seems to indicate that the thickness of the East Antarctic ice sheet has increased over the last 12 years, and it is possible that this is due to increases in accumulation rate (Davis *et al.*, 2005).

15.4 Summary of expected key future impacts and vulnerabilities

15.4.1 Freshwater systems and their management

15.4.1.1 Arctic freshwater systems and historical changes

Some freshwater systems exist wholly within the Arctic but many others are fed by river and lake systems in more temperate latitudes. These include, five of the world's largest river catchments, the Lena, Ob', Mackenzie, Yenisey and Yukon that act as major conduits for water, heat, sediment, nutrients, contaminants and biota. For such systems basin-wide effects especially those from the south will be critical in determining both individual and cumulative impacts.

Historically, the largest changes to northern river systems have been produced by flow impoundment and regulation, much of it occurring in headwater areas south of the Arctic Circle. For Canada and Russia, it is the northward flowing rivers that hold the largest remaining potential for large-scale hydroelectric development. The Yenisey is the largest of the major arctic rivers, the one most strongly affected by regulation, and the arctic Eurasian river predicted to experience the largest further impoundment (~+50%) over the next few decades (Shiklomanov *et al.*, 2000). In the case of North America, although the dominant Mackenzie River is regulated in its southern headwaters and plans exist for expanded regulation, downstream effects of regulation have been difficult to identify because of the dampening effects of major lake systems. Moreover, climatic shifts in the late-20th Century have both amplified and reduced the effects of regulation on its headwater river flow (Peters *et al.*, In press) and lake levels (Gibson *et al.*, 2005). Part of the energy-based rationale to expand regulation of such northern rivers is that hydroelectricity production is considered a relatively low emitter of greenhouse gases, although knowledge about emissions from reservoirs is incomplete (Prowse *et al.*, 2004).

Regardless of size, the typical effect of regulation for hydro-electric production has been to decrease summer flow and increase winter flow, and thereby overall reduce seasonal flow variability. Recent observed trends in winter discharge for some major rivers (Ob' and Yenisei rivers) previously thought to be a result of climatic effects have now been largely ascribed to this redistribution (e.g. Yang, 2004; Yang *et al.*, 2004). In the case of the Lena River, however, winter flow increases have primarily resulted from increased winter precipitation and warming (Yang *et al.*, 2002). Although regulation has also obscured trends in the timing of spring freshet, circumpolar trends over the last 60 years have not been consistent, with adjacent major Siberian rivers showing both earlier (Lena, Yang *et al.*, 2002) and later (Yenisei, Yang *et al.*, 2004) occurrence. Changes in the amount and distribution of permafrost have also been cited as a potential modifier of river flow, both because of flow additions through the contributions of melting ice and because of altered flow pathways that can affect the seasonality of the response.

The Arctic also contains numerous types of lentic systems, including shallow tundra ponds and thermokarst lakes to extensive peatlands and river-delta perched basins. Seasonal shifts in flow; changes in duration, thickness and composition of ice cover; alterations to precipitation/evapotranspiration combinations; and stream-flow inputs of sediment and nutrients have all been identified as controlling their biodiversity, storage regime, and carbon-methane source-sink status (Wrona *et al.*, 2005b). Paleoclimatic records from many lentic systems around the circumpolar north since the end of the Little Ice Age (~1850) have shown synchronous changes in lake biota and sedimentological parameters with increasing mean annual and summer temperatures and corresponding shifts in thermal stratification/stability and ice cover duration (e.g. Korhola *et al.*, 2002; Ruhland *et al.*, 2003). In contrast, systems without such warming have shown little or no change (e.g., Paterson *et al.*, 2003).

As for arctic lotic systems, permafrost plays a large role in the hydrology of lotic systems, primarily through its influence on substrate permeability and surface ponding of water. Appreciable changes have been observed in lake abundance and area over a 500 000 km^2 zone of Siberia during an approximate three-decade period at the end of the last century (See Figure 15-5, Smith *et al.*, 2005). The spatial pattern of lake disappearance strongly suggests that permafrost thawing is driving the changes. Melting of surface permafrost was proposed to be the cause of increasing lake areas and numbers in northern continuous permafrost zones, whereas more extensive and deeper melt accompanied by thermokarst development and surface to groundwater drainage was suggested as being responsible for draining and shrinkage of lakes in more southerly (discontinuous, sporadic and isolated) permafrost zones.

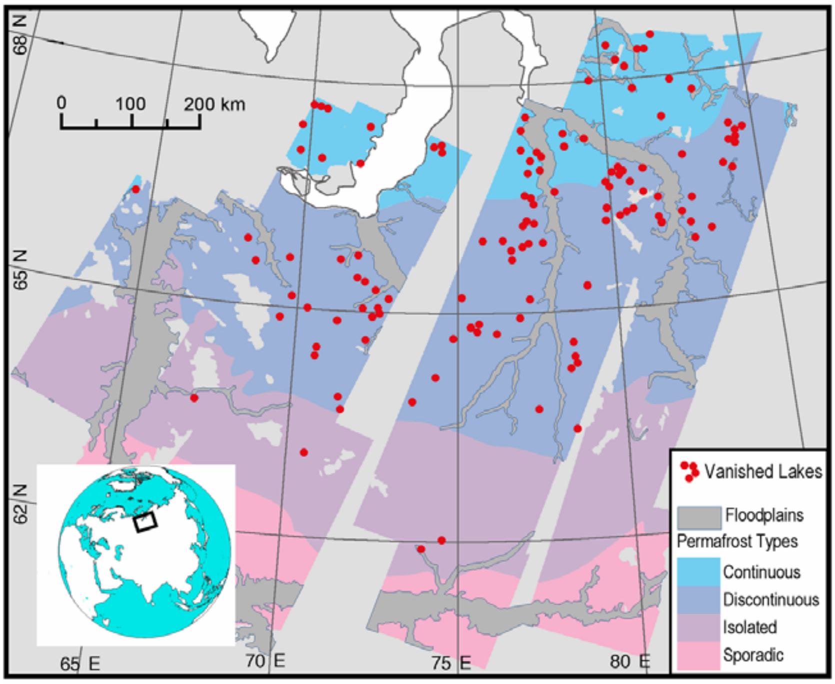

Figure 15.5: *Locations of Siberian lakes on various permafrost landscapes that have vanished after a three-decade period of rising soil and air temperatures (changes registered from satellite imagery from early 1970's to 1997-2004). The spatial pattern of lake disappearance suggests that permafrost thawing has driven the observed losses (Data and Figure from, Smith et al., 2005).*

15.4.1.2 Impacts on physical regime

Changes in the arctic freshwater system will have impacts on the physical regime of the Arctic, in particular hydrologic extremes, global feedbacks and contaminant pathways.

Increases in arctic precipitation will produce numerous changes in freshwater systems. Numerous hydrologic modelling studies driven by evolving output from newer generation AOGCMs have consistently also predicted increases in flow for the major arctic river systems (e.g., Miller and Russell, 1992; Shiklomanov, 1994; Arnell, 1999; Miller and Russell, 2000; Arora and Boer, 2001; Georgievsky *et al.*, 2003; Mokhov *et al.*, 2003). Most seasonal analyses also indicate the largest increases will occur during the cold season. Despite a projected shortening of the winter snow season, increases in winter precipitation (assuming temperatures remain below freezing) will lead to increased peak snowpack and larger spring snowmelt runoff and possibly flood events. Less clear is what may occur during the summer months, some results suggesting that flow may actually decrease because of evaporation exceeding precipitation (e.g., Walsh *et al.*, 2005). Reductions in summer flow could be enhanced for many watersheds because of increases in evapotranspiration as dominant terrestrial vegetation shifts from non-transpiring tundra lichens to various woody species (e.g. Callaghan *et al.*, 2005).

Changes in total river flow to the Arctic Ocean can produce a number of global feedbacks, such as through sea-ice production and related albedo changes, and via its supply of freshwater to the North Atlantic and effects on thermohaline circulation (See WGI Chapter XXX); arctic river flow is the major component of the freshwater budget of the Arctic Ocean (Lewis *et al.*, 2000). Flow from the major Eurasian rivers has been increasing by an average 2 km^3/yr over the last half century (Peterson *et al.*, 2002). Potential controlling factors such as permafrost melt, effects of forest fires and dam storage have been eliminated as being responsible (McClelland *et al.*, 2004), but the precise factors remain to be identified including the role of precipitation because of difficulties in quantifying trends in such a data-sparse region (Walsh *et al.*, 2005). Changes to seasonal and inter-annual variations in runoff production from precipitation are possibly linked to permafrost melt and related alterations to flow pathways (Serreze *et al.*, 2003). Increased runoff to the Arctic Ocean from circumpolar glaciers and ice caps has also been noted to have occurred in the late 20th Century and to be comparable to the increase in combined river inflow from the largest pan-arctic rivers (Dyurgerov and Carter, 2004). Under conditions of doubling atmospheric CO_2, the total annual river inflow in the Arctic Ocean is expected to increase by approximately 10-20% (Walsh *et al.*, 2005). An additional source of future freshwater input will be from melting of large glaciers and ice caps, most notably from Greenland (Gregory *et al.*, 2004). The cumulative effect of these increasing freshwater supplies in the Arctic region on the rate or possibly even shutdown of the thermohaline circulation remain unclear but are a critical area of concern (ACIA, 2004).

Warming is also forecast to cause reductions in river and lake ice covers, some of the most pronounced decreases in ice cover duration being in near-coastal regions that experience enhanced warming created by ice-free ocean conditions (Prowse *et al.*, in prep.). Two of the most important secondary impacts of altered ice conditions are changes in lake thermal structures, quality/quantity of under-ice habitat (Wrona *et al.*, 2005a) and effects on ice jamming and related flooding. Specific to the latter, forecasts of earlier snowmelt freshets could create conditions more conducive to severe breakup events (Prowse and Beltaos, 2002). This effect, however, is likely to be offset on some large northward flowing rivers because of reduced regional contrasts in south-to-north temperatures and related hydrological and physical gradients (Prowse *et al.*, in prep.).

Various changes in arctic hydrology have the potential to effect large changes in the proportion of pollutants (e.g., Persistent Organic Pollutants and Mercury) that enter arctic aquatic systems, either by solvent-switching or solvent-depleting processes (e.g. Macdonald *et al.*, 2003). Of particular importance are changes in the frequency, type and timing of precipitation that scavenge pollutants from the atmosphere, and the rate and timing of snowcover, floating ice and permafrost melt/thaw that control the movement into streams and lakes. Given that the Arctic is predicted to be generally "wetter", the increase in loadings of particulates and contaminants that partition strongly into water might more than offset the reductions expected to accrue from reductions in global emissions (e.g. Macdonald *et al.*, 2003). Shifts in other hydrologic regime components such as vegetation (especially non-transpiring to transpiring plants), runoff patterns and thermokarst drainage (Hinzman *et al.*, 2004) all have the capacity to increase contaminant capture. Changes in aquatic trophic structure and related rate functions (see 15.4.1.3) have further potential to alter the accumulation of bio-magnifying chemicals within foodwebs.

Projected changes of permafrost, vegetation and river-runoff may have noticeable impacts on river morphology, ultimately leading to the transformation between multi and single channel types. Geologic reconstructions and numerical simulations, indicate transformations occur especially at times of permafrost degradation (Bogaart and van Balen, 2000; Vandenberghe, 2002). Such changes are largely controlled by thresholds in the density of the vegetation cover (Vandenberghe, 2001). However, historical examples have shown that variability in discharge is less important than variability in sediment supply to the river, which is, in part, determined by the vegetation cover (Huisink *et al.*, 2002; Vandenberghe and Huisink, 2003). Thus an increasingly denser vegetation cover may counter increased sediment availability.

15.4.1.3 Impacts on aquatic productivity and biodiversity

Projected changes in runoff, river- and lake-ice regimes and seasonal and inter-annual water balance and thermal characteristics will alter biodiversity and productivity relationships in aquatic ecosystems (Walsh *et al.*, 2005; Wrona *et al.*, 2005a; Prowse *et al.*, in prep.). On rivers that experience decreased severity of ice breakup, the corresponding decreased frequency and intensity of physical disturbance will reduce the biogeochemcial replenishment and sediment loading of riparian ecosystems (particularly in river deltas) and negatively affect overall productivity and biodiversity. Increased warming will also increase flows and reduce ice-cover growth and thickness for systems that typically freeze to the bottom. This will increase habitat availability, and the probability of winter survival of species previously restricted by the limitation of under-ice habitat and refugia (Prowse, 2001; Prowse and Culp, 2003). Ultimately the dispersal and geographical distribution patterns of aquatic species will be altered, particularly for fish (Reist *et al.*, in prep-c). The projected enhanced river flows will also increase sediment transport and nutrient loading into the Arctic Ocean, thereby affecting estuarine and marine productivity (Carmack and Macdonald, 2002).

Changes in ice-cover regimes (i.e., decreasing thickness, altered composition and duration) will also affect thermal and radiative regimes and corresponding physical/chemical properties of freshwater systems. Reduced lake-ice thickness will increase the availability of under-ice habitat, winter productivity and dissolved-oxygen concentrations. Extension of the ice-free season will increase water temperatures and lengthen the overall period of productivity, affecting lake stratification and circulation patterns and biogeochemical processes. Fish habitat availability and suitability may decline as a result of these changes, particularly affecting species such as lake trout that prefer colder waters (Hobbie *et al.*, 1999; Reist *et al.*, in prep-b).

Increased permafrost melting and deepening of the active layer will increase nutrient, sediment and carbon loadings, thereby enhancing microbial and higher trophic level productivity in systems that were previously carbon and/or nutrient limited. As water-column Dissolved Organic Carbon (DOC) concentration increases, there will be a corresponding reduced penetration of damaging UV radiation and a decline in photochemical processing of organic material, although the opposite effect may occur in heavily nutrient-enriched waters where increased light-limitation may actually occur (Wrona *et al.*, 2005a). Enhanced sediment transport and loadings will negatively affect benthic and fish-spawning habitats in lake and river systems by increasing the biological oxygen demand and hypoxia/anoxia associated with sedimentation, and contribute to habitat loss through infilling (Wrona *et al.*, 2005b; Reist *et al.*, in prep-c). Pond/wetland habitats will also be affected through nutrient enrichment, thereby enhancing biogeochemical cycling and productivity and altering the generation and consumption of trace carbon-based gases. Enhanced decomposition of organic materials will increase the availability of DOC and the emission of carbon dioxide. Whether such systems will function as net carbon sinks or sources will depend on the complex interactions among temperature, nutrient status and water levels. Initial permafrost thaw will form depressions for new wetlands and ponds interconnected by new drainage networks. These new habitats will allow for the dispersal and establishment of new aquatic communities in areas formerly dominated by terrestrial species (Wrona *et al.*, 2005a). As permafrost and ground ice further melts, surface waters will become increasingly couple and drain to groundwater systems resulting in a change in limnology and decreases in habitat suitability/availability.

Species from more southerly latitudes presently limited by temperature/productivity constraints will likely extend their geographic range northward, resulting in new species assemblages. Many of these, particularly fishes, will directly compete with established faunas for resources, and since many arctic species are poor competitors, such shifts will negatively affect local species (Reist *et al.*, in prep-c). As well as fishes, southern species of invertebrates, birds and mammals will also extend their current ranges northward, bringing with them new parasites and/or diseases to which arctic species are not adapted, thereby increasing their mortality (Wrona *et al.*, 2005a). This combination of direct environmental change and indirect ecosystem shifts resulting from species range changes will significantly impact local faunas by reducing their productivity, abundance, and biodiversity. Such effects will be most severe for taxa such as freshwater fishes that rely entirely upon local aquatic ecosystems (Reist *et al.*, in prep-b). Anadromous fish species distributions will probably shift as oceanic conditions and freshwater drainage patterns are affected (Reist *et al.*, in prep-a), as will the geographic patterns of habitat use of migratory aquatic birds and mammals (Wrona *et al.*, 2005a). Northern fish species such as broad whitefish, arctic char complex, inconnu and Arctic Cisco will likely have geographic ranges that will contract in response to habitat impacts and from enhanced competition from invasive species (Reist *et al.*, in prep-a; Reist *et al.*, in prep-b; Reist *et al.*, in prep-c). Other fish such as arctic grayling may be less reproductively successful with warming of waters, potentially causing elimination of entire populations (Reist *et al.*, in prep-c).

15.4.1.4 Impacts on resource use and traditional economies/livelihoods

Given the large hydrologic changes expected for arctic rivers, particularly regarding the magnitude of the spring freshet, climate-induced changes must be factored into the design, maintenance and safety of existing and future development structures (e.g., oil and gas drilling platforms, pipelines, dams and impoundments for hydro-electric production (World Commission on Dams, 2000)). Although some detailed evaluations of the effects of continuing present-day trends in hydrologic conditions on future IDFs (Inflow Design Floods) for dams have been made, predictions based on future climate scenarios modelled by GCMs are, for the most part, yet to be conducted (Prowse *et al.*, 2004).

In arctic regions, freshwater sources are critical to human health, especially for many northern communities that rely on surface and/or groundwater, often untreated, for drinking water and in-home use (United States Environmental Protection Agency, 1997; Martin *et al.*, 2005). Direct use of untreated water from lakes and rivers in summer, or from melting snow or ice in winter and spring is considered to be traditional, on the same basis as hunting or fishing despite the fact that it poses certain risks in a region with an abundant presence of migratory animals and therefore poses a risk to human health via the transmission of water-borne diseases (e.g., Giardia lambia, cryptosporidiosis and gastroenteritis E. coli, Martin *et al.*, 2005). Such risks may increase with changes in migration and northward movement of species and their related diseases. Changes in hydrology may also decrease the availability and quality of surface and groundwater as sources of drinking water, particularly for coastal communities affected by rising sea levels where sea-water contamination could affect groundwater reserves (Warren, In press).

Northern freshwater ecosystems provide many services to arctic peoples particularly in the form of harvestable biota used to support both subsistence and commercial economies (Reist *et al.*, in prep-c). Shifts in ecosystem structure and function will result in substantive changes in the abundance, replenishment, availability and accessibility of such resources which, in turn, will alter local resource use and traditional lifestyles (Nuttall *et al.*, 2005; Reist *et al.*, in prep-c). It is unlikely that such changes related to natural freshwater systems would be offset by increased opportunity for freshwater aquaculture resulting from a warming climate. Thus, conservation of arctic aquatic biodiversity, maintenance of traditional lifestyles, and continued viability and sustainable use of arctic freshwater resources will present significant challenges for arctic peoples, resource managers and policy makers (Wrona *et al.*, 2005a; Reist *et al.*, in prep-c).

15.4.2 Terrestrial ecosystems and their services

15.4.2.1 Historical and current changes in arctic terrestrial ecosystems

Climatic changes during the past 20 000 years have shaped current biodiversity, ecosystem extent, structure and function. Arctic species diversity is currently low because of past extinction events, and large mammals are in general more vulnerable to change than in the past. Also, ecosystem extent is now less than during the glacial period (Callaghan *et al.*, 2004). Modern habitat fragmentation, stratospheric ozone depletion, and spread of contaminants compound ongoing impacts of anthropogenic climate change and natural variability on ecosystems and their services. Traditional Ecological Knowledge (TEK) from Canada (Riedlinger, 2001a; Thorpe *et al.*, 2001; Krupnik and Jolly, 2002a) has recorded current ecosystem change such as poor vegetation growth in eastern regions associated with warmer and drier summers; increased plant biomass and growth in western regions associated with warmer, wetter and longer summers; the spreading of some existing species, new sightings of southern species; and changing grazing behaviours of musk oxen and caribou as availability of forage increases in some areas.

In northern Fennoscandia, cycles of lemming and vole populations have broken down since the 1990’s due to changing winter snow conditions (Yoccoz and Ims, 1999; Henttonen and Wallgren 2001); arctic fox, lesser white fronted goose and shore lark have declined towards extinction, and moose, red fox, and some southern bird species have spread northwards. Throughout the Arctic, many migrant bird populations have declined substantially (Stroud *et al.*, 2004) due to climate and other changes. Many populations of caribou/reindeer that are essential to the culture and subsistence of many arctic peoples are currently in decline (Russell *et al.*, 2002; Chapin *et al.*, 2005). Wild herds of Russian caribou/reindeer have been reduced over the last 10 years from 2 to 1 million (Baskin,

2000) whereas populations of herded reindeer have increased, mainly due to social and cultural factors. Icing events during warmer winters have impacted some high-arctic ungulate populations (See references in, Callaghan *et al.*, 2004) whereas some protected arctic animal populations have increased.

Aerial photographs show increased shrub abundance in Alaska in 70% of 200 locations (Sturm *et al.*, 2001). Treeline has moved northwards (2% of Alaskan tundra displaced by forest in the past 50 years (Lloyd *et al.*, 2003)), and upwards (about 60 m in the 20th Century in sub-arctic Sweden) although bog growth has caused tree death in parts of the Russian European Arctic (Crawford *et al.*, 2003). Dry habitat vegetation in sub-arctic Sweden has been partly displaced by wet habitat vegetation because of discontinuous permafrost degradation (Christensen *et al.*, 2004; Malmer *et al.*, In press) whereas arctic ponds are disappearing in some areas permafrost (Figure 15-5, Smith *et al.*, 2005).

Satellite images show an increased growing season length in Alaska (3 days per decade) and in northern Eurasia (1 day per decade) (Smith *et al.*, 2004b; McGuire *et al.*, In Press), but a reduction in primary productivity in the eastern Russian Arctic (Nemani *et al.*, 2003) and a delayed onset of the growing season in the Kola Peninsula during recent climatic cooling (Høgda *et al.*, In press).

15.4.2.2 Projected changes in biodiversity, vegetation zones and productivity

Species richness will increase as species-rich forest displaces tundra (Figure 15-2, Callaghan *et al.*, 2004). Some species in favourable microenvironments far north of their centres of distribution are very likely to spread rapidly during warming. Arctic species will extend their ranges northwards and upwards in altitude while the dominance and abundance of many will decrease. Trophic level structure is simple in the Arctic, and decreases in the abundance of keystone species are expected to lead to ecological cascades. Local changes in distribution and abundance of genotypes will be the initial response of genetically diverse species to warming (Crawford, 2004). Arctic animals are likely to be most vulnerable to warming-induced desiccation (invertebrates), changes in snow cover and freeze-thaw cycles that affect access to food and protection from predators, changes that affect the timing of behaviour (e.g. migration and reproduction), and influx of new competitors, predators, parasites and diseases. Southern species constantly reach the Arctic but few become established (Chernov and Matveyeva, 1997). During climate change, establishment will increase and some species, such as North American mink) will become invasive.

Warming experiments across the Arctic showed that plant communities respond rapidly to 1 to 3 ^{o}C warming after 2 growing seasons, that shrub growth increases as observed under natural climate warming, and that species diversity decreased (Walker *et al.*, In Press). Experimental warming and nutrient addition showed that mosses and lichens became less abundant when vascular plants increased their growth (Cornelissen *et al.*, 2001; Van Wijk *et al.*, 2003). CO_2 enrichment produced transient plant responses, but effects on microbial communities (Johnson *et al.*, 2002) and frost hardiness (Beerling *et al.*, 2001) with longer-term consequences. Supplemental UV-B caused few plant responses but reduced nutrient cycling (Callaghan *et al.*, 2004).

Models project replacement of 11% (Sitch *et al.*, 2003) to 50% (White *et al.*, 2000) of tundra by forest by 2100, although impacts of changing land use, hydrology and permafrost are excluded. Narrow tundra coastal strips (e.g. in parts of the Russian European Arctic) will be completely displaced as forest reaches the Arctic Ocean. During 1960 to 2080, tundra is projected to replace 14 to 23% of the polar desert and net primary production to increase by 72% (2.8 to 4.9 Pg C per year) (Sitch *et al.*, 2003). Geographical constraints on vegetation relocation result in large sub regional variations in projected increases of NPP, from 44% in fragmented landmasses to 144% in extensive tundra areas (Callaghan *et al.*, 2004).

Climate warming is likely to increase the incidence of pests, parasites and diseases such as musk ox lung worm (Kutz *et al.*, 2002) and abomasal nematodes of reindeer (Albon *et al.*, 2002).

15.4.2.3 Consequences of changes in ecosystem structure and function for feedbacks to the climate system

Climate warming will decrease the reflectivity of the land surface due to reduced snow cover and expansion of shrubs and trees into tundra (Eugster *et al.*, 2000): this could influence regional (Chapin *et al.*, 2005) and global climate (Bonan *et al.*, 1992; Thomas and Rowntree, 1992; Foley *et al.*, 1994; McGuire *et al.*, In Press).

Measurements suggest the Arctic is a small carbon source whereas models suggest it is a small sink of about 20 g C m^{-2} yr^{-1} with a large standard deviation of about 40 g C m^{-2} yr^{-1}) (McGuire *et al.*, 2000; Sitch *et al.*, 2003), however uncertainties in both methods overlap zero. The circumpolar arctic vegetation and active layer are, thus unlikely currently to be a large source or sink of carbon in the form of CO_2 (Callaghan *et al.*, 2004; Chapin *et al.*, 2005). They are, however, most likely a source of positive radiative forcing due to large methane emissions (Christensen *et al.*, in prep): even in tundra areas that are net sinks of carbon, significant emissions of methane lead to positive forcing (Friborg *et al.*, 2003; Callaghan *et al.*, 2004).

Higher temperatures, longer growing seasons and northward movement of productive vegetation are likely to increase photosynthetic carbon capture in the longer-term whereas soil warming is likely to increase trace gases emissions in the short-term. Drying or wetting of tundra concurrent with warming will critically determine the magnitude of carbon fluxes. Drying has increased source status in Alaska (Oechel *et al.*, 2000), whereas wetting has increased sink status in Scandinavian and Siberian peatlands (Aurela *et al.*, 2002; Smith *et al.*, 2004a; Johansson *et al.*, Submitted). Wetlands occupy almost 2 M km^2 of the Arctic, contain about 50 Gt of carbon, and favour the production of methane rather than carbon dioxide. Methane fluxes have pronounced spatial and temporal variability thus complicating generalization of results from sparse observations. Models, driven by the mid-21st Century climate, project methane emission increases from the Russian Arctic wetlands of 30% – 40%, 50% - 80% over most of the central Siberia and Yakutia, more than 80% over the Russian Arctic coast, and up to 20% in the eastern and south-eastern parts of the cryolitozone (Anisimov *et al.*, 2005a; Anisimov *et al.*, 2005b).

Models project that the Arctic and sub-Arctic are likely to become a weak sink of carbon during future warming (an increase in carbon storage in vegetation, litter and soil of 18.3 Pg C between 1960 and 2080: (Sitch *et al.*, 2003; Callaghan *et al.*, 2004)), although the uncertainty overlaps zero. Increased carbon emissions from projected increases in disturbances and land use, and net radiative forcing resulting from the changing balance between methane and carbon dioxide emissions (Friborg *et al.*, 2003; Johansson *et al.*, Submitted) are particular uncertainties. Wetting, from increased precipitation and permafrost thawing, will increase fluxes of methane relative to carbon dioxide from the active layer and thawing permafrost.

According to one coupled climate model, the negative feedback of carbon sequestration and the positive feedback of reduced albedo interact such that eastern Canadian arctic forests will give net negative feedback through dominance of increased carbon sequestration, while in the forests of Arctic Russia decreased albedo will dominate giving net positive feedback (Betts and Ball, 1997;

Betts, 2000).

15.4.2.4 Impacts on resource use, traditional economies and lifestyles

Arctic Peoples maintain strong social, cultural and economic connections to the environment through traditional hunting, herding, fishing, trapping and gathering of renewable resources (Arctic Monitoring and Assessment Programme, 2003; Chapin *et al.*, 2005). Per capita consumption by rural Alaskans is 170 kg yr^{-1} of wild foods (16% land mammals, 10% plant products) valued at about $200 million: consumption by urban Alaskans is 22 kg yr^{-1} of wild foods. Consumption in Canadian arctic communities ranges from 106 g day^{-1} to 440 g day^{-1}, accounting for 6 to 40% of total energy intake and 7 % to 10 % of the total household income in Nunavik and Nunavut (Kuhnlein *et al.*, 2001; Chabot, 2004). Wood, sod, peat, and coal are used locally as fuels throughout the north. Terrestrial ecosystem resources include caribou/reindeer, moose, musk-ox, migratory birds and their eggs, and plants and berries (Arctic Monitoring and Assessment Programme, 2003; Chapin *et al.*, 2005). Wild and domesticated caribou/reindeer are particularly important as they provide food, shelter, clothing, tools, transportation and in some cases marketable goods (Klein, 1989; Paine, 1994; Kofinas *et al.*, 2000; Jernsletten and Klokov, 2002). In North America, there is an estimated annual harvest equivalent to over $30 million annually and in Russia, large-scale commercial hunting of wild reindeer produces more meat than all reindeer husbandry of both Central Siberia and Yakutia. Approximately 400 g day^{-1} of reindeer are consumed by Russian Indigenous Peoples of the Taymir Peninsula, while non-indigenous people consume 80-200 g day^{-1} (Klopov as cited by, AMAP, 2002) and this species accounts for 7 % of the total diet of Saami in northern Norway (Nilsen *et al.*, 1999). Ties to subsistence activities among Indigenous Peoples are deteriorating because of changes in life styles, cultural, social, economic and political factors (Chapin *et al.*, 2005) and these ties are expected to decrease as changes in conditions for hunting, decreases in natural resources and loss of traditional knowledge convert previously well-adapted arctic peoples into “Strangers in their own lands” (Berkes, 2002).

Agriculture in the southern parts of the Arctic is limited by short, cool growing seasons, and lack of infrastructure including limited local markets because of small populations, and long distances to large markets (Juday *et al.*, In press). The northern limit of agricultural may be roughly approximated by a metric based on the cumulative degree-days above +10 ^{0}C (Sirotenko *et al.*, 1997). By mid-21st Century climatic warming may displacement of its position to the north by a few hundreds kilometres over most of the Siberia, and up to one hundred kilometres elsewhere in Russia (Anisimov and Belolutskaia, 2001). Thus climate warming is likely to lead to the opportunity for expansion of agriculture and forestry. And while, conservation management and protected areas are extensive in the Arctic, these only protect against direct human actions, not against climate-induced vegetation zone shifts and decisions need to be made about the goals and methods of conservation in the future (Callaghan *et al.*, 2004; Klein *et al.*, 2005; Usher and *al.*, 2005).

15.4.3 Marine ecosystems and their services in the Arctic

15.4.3.1 Changes in a warming climate

Changes in climatic conditions in the waters of the Arctic and sub-Arctic will drive changes in biota and productivity, most obviously through a retreat and reduction of sea ice. The distribution of species of amphipods, adapted for life at the ice edge, and coldwater species such as polar cod foraging on them, will move northward, but it is likely that their abundance will also diminish. This may have serious secondary consequences for predators (e.g., seal) specialized in life at the ice edge.

For these, food sources and habitat will shrink and their numbers reduce. In turn, there will be consequences for higher predators (e.g. polar bears) as well as for indigenous populations. It likely that some capelin stocks will decrease and impact the well-being of their many consumers, (e.g. baleen whales, seals, seabirds and fish predators, especially cod, Loeng *et al.*, 2005; Vilhjálmsson *et al.*, 2005). However, with an increase in open water, primary and secondary production will increase, and this will benefit almost all of the most important commercial stocks in arctic, and more especially sub-arctic seas. Prime examples are cod and herring in the North Atlantic and walleye pollock in the Bering Sea – at the present time these comprise ~70% of all catches in these areas. Exceptions are coldwater species (northern shrimp, king and snow crab and possibly capelin), which may lose habitat.

More difficult to predict are the impacts of species migration from the south as happened from the late-1920s to at least 1940 (Loeng *et al.*, 2005; Vilhjálmsson *et al.*, 2005), and the increased risk of blooms of poisonous algae as well as the occurrence of marine pests and pollution accidents; risks that are multiplied by increased ship traffic following the possible opening of northern passages. It is extremely difficult to accurately predict responses of commercially utilized fish stocks to changes of ocean climate. There is a lack of models coupling predictions of global warming to variations of ocean temperatures and currents, especially at regional scales, and these are required for predictions of survival, growth and drift of plankton as well as larval and juvenile fish. Furthermore, the multiple stress of commercial exploitation has already altered stock size and thereby biology and the stocks affected will likely not respond in the same way as they have during recorded history. Nevertheless, experience based on historical episodes is the most valuable tool we have for trying to predict future reactions of exploited stocks to changes in climate. There are many such examples, including distribution shifts and changes of recruitment and biomass, related to climatic variations and, in many cases, also to exploitation (Rose and Kulka, 1999). Thus, effective future management will require an understanding of the relative role of past impacts of climate change and exploitation rates, as well as successful resolving of difficult political issues. For example, for those species that migrate through the exclusive economic zones (EEZs) of two or more sovereign states, effective management depends on successful multinational negotiations (Vilhjálmsson *et al.*, 2005). This is not only true for species high in the food chain but also for forage fish, especially short-lived species like capelin. A crucial issue is the necessity to maintain stocks, especially of long-lived species like Atlantic cod, at sufficient level to ensure viable recruitment, in the face of natural environmental variability.

The knowledge base required to manage stocks and yields is considerable and growing rapidly, although it will need to be continuously updated by monitoring of stock and environmental variables. And it is important that this knowledge is utilized by successful agreement to manage stocks in the face of climate change, because there is a great deal at skate. It is possible that effective management could produce yield increase of up to 50% over the present, given a moderate rise of temperature (2-3°C) in arctic/sub-arctic oceans. This is both due to the warming effect, but also and no less to the present depleted state and low yield of many of the potentially most productive stocks, especially in the North Atlantic. But, an equivalent amount could be lost as a consequence of inappropriate management, or lack of enforcement.

BOX

15.4.4 Atlantic cod in the 20th Century – two historical examples

The complexity of potential response is well illustrated by examples of what has happened to two cod stock complexes in two arctic/sub-arctic areas. In each case ocean climate variability and fishing pressure have had a large impact on the fish populations, but in each the balance of the stresses was different and the overall effect quite different.

Greenland/Iceland

Numerous attempts to find and fish cod off West Greenland in the period 1900-1920 failed and older records of similar activities indicate that for all practical purposes there was no Atlantic cod in Greenland waters in the latter half of the 19th Century either (Jensen, 1926; Buch *et al.*, 1994). However, ocean temperature records, begun in the 1870s west of Nuuk, showed very cold conditions until a sudden warming in the 1920s (Figure 15-6). Variable temperatures from 1935-1950, steadied and then warmed again until they dropped suddenly in the late-1960s (Jensen, 1939; Buch *et al.*, 1994; Vilhjálmsson, 1997).

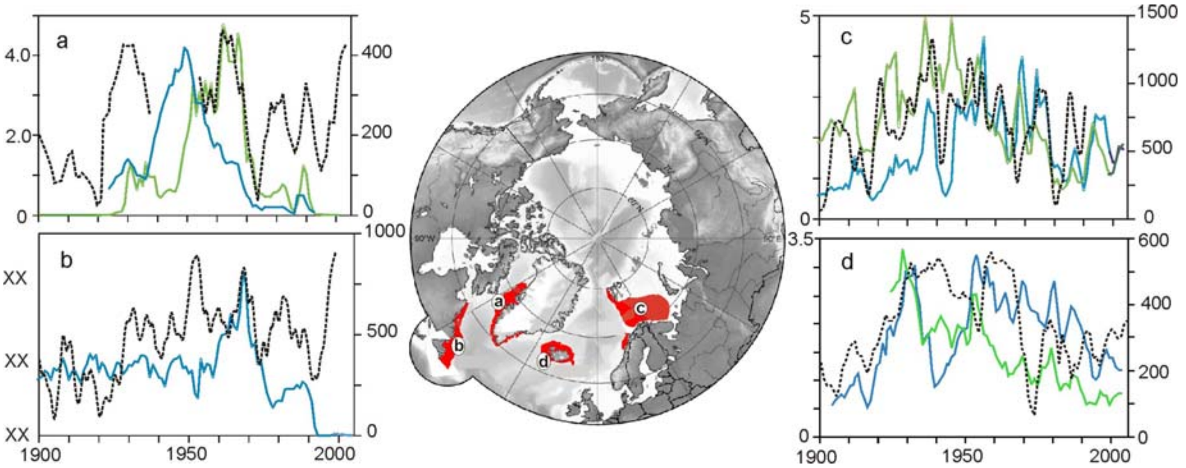

Figure 15.6: *The map shows the geographic distribution of four major cod stocks in arctic and sub-arctic waters in the North Atlantic. The graphs (a: West Greenland; b: Newfoundland/Labrador; c: Barents Sea and d: Iceland) show the developments of fishable stock (green line), catches (blue line) and temperature (black broken line) during the period 1900-2005. Data are from various official and published sources (XXX references to be inserted later).*

In the early 1920s very large numbers of larval and juvenile cod drifted from Iceland to West Greenland and started a self-supporting cod stock at Greenland. From comparison of catches and temperature records it is quite clear that the occurrence and propagation of cod off Greenland depends foremost on the marine climate of West Greenland waters. However, it is equally clear that fishing pressure in the mid-to-late 20th Century was far too high. If fishing pressure had been lower, it is conceivable that the local Greenland stock of cod might have survived and increased again following the mild oceanographic conditions in recent years. However, this did not happen and therefore the reappearance of cod off Greenland will now likely depend on drift of larval and juvenile cod from Iceland as it did in the 1920s. Such a drift may have begun in 2002 (ICES, 2005), but the numbers are small. The depleted spawning stock of Icelandic cod has not produced a strong year class for 20 years, even under the mild climatic conditions in recent years (ICES, 2005). Therefore, it seems doubtful whether Icelandic cod are capable of producing year classes large enough to seed West Greenland as quickly as it did in the late-1920s.

Newfoundland/Labrador

A fishery of the so-called ‘northern cod’ on the banks east of Newfoundland and Labrador began on a small scale early in the 16th Century following the discovery and exploration of these waters. To begin with this was a small fishery but landings had increased to about 200 000 t by the early-1800s and again to roughly 300 000 t in the early-1950s (Rose, 2004). Between 1920 and 1960 annual catches varied between about 300 and 400 000 t, but increased rapidly in the 1960s. Catches peaked in 1968 at 810 000 t, but then dropped equally quickly and were about 170 000 t when Canada extended its exclusive economic (fisheries) zone (EEZ) to 200 miles (Lilly *et al.*, 2000).

It was assumed that rapid growth in the cod stocks would ensue, and in preparation Canada built a large number of modern trawlers. In fact total allowable catches (TACs) were increased from about 140 000 t in 1978 to over 250 000 t in the mid- to- late-1980s. After 1989 catches dropped sharply until a moratorium on the fishing of 'northern cod' was enforced in 1993. The ‘northern cod’ remains in an extremely depleted state and although a very minor fishery was allowed for a few years, a fishing moratorium has been reinstated, even for recreation (Lilly *et al.*, 2000; Lilly *et al.*, 2003). It is likely that a number of factors contributed to the crash of the 'northern cod (e.g., Rose *et al.*, 2000). In retrospect it is clear that over-fishing, was allowed to continue after the implementation of the EEZ (Lilly *et al.*, 2000). There are probably four main reasons for this: a) The rate of recruitment was only one third of that assumed when setting up the recovery plan (Harris, 1990). b) Harsh climate from about 1970 onwards may have negatively impacted recruitment and growth (Drinkwater, 2002) and the abundance of capelin, the main food of ‘northern cod’ (Rose and Kulka, 1999; Rose *et al.*, 2000). c) Assessments of the stock were too optimistic (Walters and Maguire, 1996; Rose and Kulka, 1999). d) The moratorium on hunting harp and hooded seals led to an explosion in their abundance and thus increased mortalities of their pray - which includes not only capelin but also cod (Lilly *et al.*, 2003). It is also possible that fishing prior to 1977 had disrupted the age and size composition of the stock and reduced recruitment.

At present, the northern cod stock complex is at 1-2% of its historical average biomass. And even though the climatic conditions in the late-1990s have been more favourable, the other factors have limited stock growth. It is likely that the northern cod can, and given time, will re-grow, and that a warming climate could assist in that process. But it is also likely that capelin will have to increase and seals decline before improved recruitment and a decrease in mortality enable stock recovery to occur (O'Driscoll *et al.*, 2000; Rose and O'Driscoll, 2002). However, the complexity of the situation is such that reliable prediction is not possible as yet.

15.4.5 Marine ecosystems and their services in the Antarctic

Southern Ocean ecosystems are far from pristine. Over the last 200 years, seals and then whales, were exploited almost to extinction, then fisheries developed. From the 1960s fin-fish were exploited. In the Scotia Sea and surrounding areas stocks of these fish were reduced to very low levels from which most have not recovered. In contrast to the Arctic, however, the management of Southern Ocean fisheries is based on an ecosystem approach, within an international convention. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), part of the Antarctic Treaty, was designed to maintain the natural marine ecosystem while allowing the sustainable exploitation, and emphasizes the need to consider the wider context of the exploitation of individual species, taking account of the entire food web and environmental variations. CCAMLR applies to areas south of the Antarctic Polar Front and management decisions are made by consensus of the member states (Constable *et al.*, 2000).

The current major fin-fish fishery is for the Patagonian toothfish (*Dissostichus eleganoides*), and to a lesser extent for the mackerel icefish (*Champsocephalus gunnari*). The fishery for antarctic krill (*Euphausia superba*) developed during the 1970s, peaked in the 1980s at over 500 000 tonnes and now operates at about 100 000 tonne per year (Jones and Ramm, 2004), a catch that is well below the precautionary limits set within CCAMLR for maintaining the stock.

During the 20th Century there were significant changes in air-temperatures, sea-ice and ocean temperatures around the Antarctic Peninsula (See case study 15.6.3) and in the Scotia Sea. Over 50% of the krill stock in the Scotia Sea region (Atkinson *et al.*, 2004), which is the major area for krill fishing. The decline in the abundance of krill in this area appears to be associated with changes in sea-ice in the southern Scotia Sea and around the Antarctic Peninsula (Atkinson *et al.*, 2004). Future reductions in sea-ice may therefore lead to further changes in distribution and abundance across the whole area, with consequent impacts on food-webs where krill are currently key prey items for many predator species and where krill fishing occurs.

For other species the uncertainty in climate predictions leads to uncertainty in projections of impacts, but increases in temperatures and reductions in winter sea-ice would, undoubtedly, affect the reproduction, growth and development of fish and krill leading to further reductions in population sizes and changes in distributions. But the potential for species to adapt is mixed, some “cold-blooded” (poikilothermic) organisms may die if water temperatures rise to 5 – 10 ºC (Peck, 2005), while the bald rock cod (*Pagothenia borchgrevinki*), which uses the specialization of antifreeze proteins in its blood to live at subzero temperatures, can acclimatize so that its swimming performance at +10ºC is similar to that at -1ºC (Seebacher *et al.*, 2005).

The importance of ocean transport for connecting ecosystems Southern Ocean ecosystems has been increasingly recognised. Simple warming scenarios may indicate that exploitation effects would be shifted south, but it is also likely that other species may become the target of new fisheries, in the same areas. More complex changes in patterns ocean circulation could have profound effects on ocean ecosystems and fisheries, although not all changes may be negative and some species may benefit. Complex interactions in food-webs may, however, generate secondary responses that are difficult to predict. For example, reductions in krill abundance may have negative effects on species of fish, as they become a greater target for predators.

Finally is it important to note that the impact of changes in Southern Ocean ecosystems will not be confined to the Southern Ocean. Many higher predator species depend on lower latitude systems during antarctic winter or the breeding seasons.

The fundamental precautionary basis for managing exploitation in a changing system is in place in CCAMLR, but longer duration and more spatially extensive monitoring data are required to help identify change and its effects.

15.4.6 Human health and Well-being

The impact of projected climate change on the diverse communities of the Arctic, can only be understood in the context of the interconnected social, cultural, political and economic variables acting on them (Hamilton, 2003). However, such impacts, on the health and well-being of arctic residents are and will be tangible and ongoing.

15.4.6.1 Direct Impacts of climate and UVB on arctic health and well-being

Direct impacts (injury and death) are expected to result, in part, from exposure to temperature extremes and weather events and increased levels of and exposure to UVB radiation. Changes in precipitation are expected to affect the frequency and magnitude of natural disasters such as debris flow, avalanches, and rock falls (Koshida and Avis, 1998). Thunderstorms and high humidity have been associated with short-term increases in respiratory and cardiovascular diseases (Kovats *et al.*, 2000). In northern Sweden, a temperature rise of 1^o C was associated with an increase in non-fatal acute myocardial infarctions (AMIs), a type of heart attack (Messner, In review) and a strong correlation existed between the Arctic Oscillation and the number of AMIs. Residents in some regions of the Arctic report respiratory stress associated extreme warm summer days not previously experienced (Furgal *et al.*, 2002.).

The frequency of injuries such as frostbite, hypothermia and unintentional injuries, and diseases (cardiovascular, respiratory, circulatory, musculoskeletal, skin) is increased by cold exposure (Hassi, In review). An estimated 2000-3000 extra deaths occur in Finland during the cold season, with 20% of these among the working age population. This excess winter mortality is much higher than from other common causes of death in the country (e.g. from traffic accidents, 400 cases per year). Evidence suggests that a general warming in winter months in arctic regions will reduce excess winter mortality, primarily through a reduction in cardiovascular and respiratory deaths. A reduction in cold-related injuries will likely be seen, assuming that the standard of cold protection, including individual behavioural factors, do not deteriorate (Nayha, In review).

Increased exposure to ultra-violet (UV) radiation among arctic residents has the potential to affect immune system response to disease, and to increase the development of skin cancer and possibly of non-Hodgkin’s lymphoma and cataracts. As the current incidence rates for many of these ailments are low in arctic communities, it is difficult to detect, let alone predict, trends in their future incidence (DeFabo, In review).

15.4.6.2 Indirect Impacts of climate on arctic health

Climate warming and increased variability will have a series of more complex, indirect impacts on arctic human-environment interactions (Berner *et al.*, 2005). Arctic Indigenous populations in nearly all regions report increasingly unpredictable environmental conditions and extremes not experienced before in their regions (e.g. Krupnik and Jolly, 2002b) and there is anecdotal evidence that injuries associated with “strange” or changing environmental conditions, such as thinning and earlier break up of sea ice, are related to a general warming trend (e.g. Lafortune, 2004).

Climate warming during El Nino Southern Oscillation (ENSO) events has been associated with illness in marine mammals, birds, fish, and shellfish. Disease agents associated with these illnesses have included botulism, Newcastle disease, duck plague, influenza in seabirds, and a herpes-like virus epidemic in oysters. It is likely that temperature changes arising from longer duration climate change will be associated with an increased occurrence of disease and epidemics in these species which can be transmitted to humans (Bradley, In review). Such was the case in the 1980s in Sweden where tick-borne encephalitis (brain infection) increased substantially following two years of mild winters and extended autumn temperatures (Lindgern and Gustafson, 2001). Similarly, in association with warming waters, ringed seals (*Phoca hispida)* and bowhead whales (*Balaena mysticetus)* in the Arctic Ocean north of Alaska have for the first time been found to be infected with parasites which can also infect humans, *Giardia* spp. and *Cryptosporidium* spp. (Hughes-Hanks *et al.,* In press). Many zoonotic diseases currently exist in arctic host species such as tularemia in rabbits, muskrats and beaver, rabies in fox (Dietrich, 1981), brucellosis in ungulates, fox and bears, echinococcus in rodents or canine species (Chin, 2000), trichinella and cryptosporidium. These are spread via temperature-controlled mechanisms (e.g. movement of animal populations). Similarly, the over-wintering survival and distribution of many insect species that act as vectors of disease (e.g. west Nile virus – Figure 15-7) are positively impacted by warming temperatures and these changes create opportunities for new diseases to appear in arctic regions (Parkinson, In review).

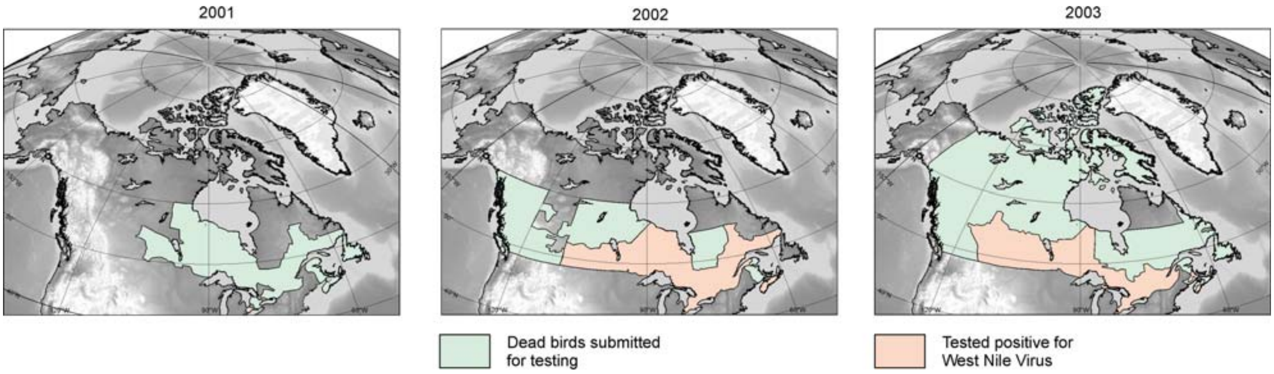

Figure 15.7: *The distribution of West Nile virus through Canada as detected in submitted bird species, between 2000-2003 (Redrawn from Berner et al., 2005).*

Traditional foods collected from the land, sea, lakes, and rivers, provide cultural and economic benefits, but also continue to contribute significant a proportion of the daily requirements for several vitamins and essential elements (e.g. Blanchet *et al.*, 2000). Through changes in accessibility and distribution of particular species, climate change in combination with other trends, may influence the diet of circumpolar residents (Furgal and Curtis, In review). An additional concern is that traditional foods comprise the greatest source of exposure to environmental contaminants such as Hg, PCBs and some radionuclides. The uptake, transport and deposition behaviour of many of these chemicals is influenced by temperature, and therefore climate warming may indirectly influence human exposure (Arctic Monitoring and Assessment Programme, 2003; Kraemer *et al.*, In review).

In some regions shifts among indigenous populations away from a traditional diet and the exercise required to obtain these foods, towards a more western diet and sedentary lifestyle have produced increased levels of cardiovascular diseases, diabetes, dental cavities, and obesity. Even more than just physical health, these food systems are the basis of traditions, socio-economic and cultural well-being. Furthermore, hunting, fishing, gathering and reindeer herding provide the basis for food production, they also figure prominently in the cash-economy of local households and communities. Indigenous peoples maintain a strong connection to the environment through these activities in a way that marks them off from non-indigenous communities, and may indeed contribute to how specific peoples retain a fundamental identification to a particular area (Gray, 1995). Traditional resource use activities not only have crucial economic and dietary importance, but remain important for maintaining social relationships and cultural identity in indigenous communities (Nuttall *et al.*, 2005).

While climate related changes threaten aspects of traditional food security, increased temperatures and shifts in animal population movements mean potential introduction of new food species and longer growing seasons in regions such as the western North American Arctic enhance opportunities for northern agriculture, creating a possibly more cost efficient local source of food. As a result, the combined effects on food security and health are difficult to predict as they are influenced by economic, technological and political forces and presuppose an understanding of what the local environment can provide and sustain.

Through increases in the frequency and severity of river and coastal flooding and erosion, drought, and degradation of permafrost, climate change is likely to threaten community and public health infrastructure in low-lying coastal arctic communities (e.g., Shishmaref, Alaska, USA and Tuktoyaktuk, Northwest Territories, Canada). Community water sources may be subject to saltwater intrusion and increased contaminant levels. Similarly, the quantity of water available for basic hygiene can become limited due to drought and damaged infrastructure. The incidence of disease caused by contact with human waste may increase when flooding, damaged infrastructure, or inadequate hygiene, spreads sewage. However, treatment efficiencies in wastewater lagoons may also improve due to warmer water temperatures resulting from longer periods of warm weather, delaying the need to expand natural wastewater treatment systems as local populations grow (Warren, In press).

The combined force on community and individual well-being from climate related changes, and the underlying social, cultural, economic and political change have significant implications for some arctic residents (Curtis *et al.*, In review). The relationship between physical or social environments and community health are complex, but studies have shown relationships between, for example, social isolation and mortality (Berkman and Syme, 1979), socio-economic status and numerous health endpoints, and decreased social capital and poor self-rated health (Kawachi *et al.*, 1999). Alterations in the physical environment threatening such things as a village site (e.g. erosion and melting permafrost) and leading to forced relocation of some or all of the community's inhabitants, or permanent shifts or declines in wildlife populations resulting in the loss of a group's ability to hunt an iconic species (e.g. Inuit hunting of polar bear) can lead to rapid and long-term cultural change and loss of traditions. Such loss can, in turn, create psychological distress and mental health challenges among the group (Hamilton, 2003; Curtis *et al.*, In review). However, in many arctic locations climate change will likely not be the only driving force behind such transformations but rather one of many factors initiating and fuelling the acculturation process by forcing people to change their ways of living, and to replace or drop old traditions which are positively related to social, cultural and psychological health (Berry, 1997).

The social, cultural, and economic transition that arctic communities have seen over the past 50 years has influenced all aspects of health, and this relationship is highly likely to continue in the future. Climate change is likely going to further influence these rapid changes in communities by challenging individuals' and community's relationship with their local environment which has for thousands of years, been the basis of Aboriginal peoples' identity, culture, social and physical well-being (Berner *et al.*, 2005).

15.4.7 Coastal zone and small islands

15.4.7.1 Arctic coastal erosion

Coastal stability in polar regions is affected by factors common to all areas (exposure, relative sea-level trend, climate, and lithology), and by features particular to the high-latitudes (low temperatures, ground ice, and sea ice). The most severe erosion problems affecting community or industrial infrastructure, or cultural heritage resources are found in areas of rising relative sea level, seasonally-free of sea ice and ice-rich but otherwise unlithified coastal sediments (Forbes, 2005). Ice-rich terrain is widespread in the western Canadian Arctic, northern Alaska, and along much of the Russian Arctic coast (.e.g., Smith, 2002; Nikiforov *et al.*, 2003). Wave erosion and high summer air temperatures promote distinctive thermal, mechanical, or combined processes that promote particularly rapid shoreline retreat, in some cases contributing a significant proportion of regional sediment and organic carbon inputs to the marine environment (Aré, 1999; Rachold *et al.*, 2000).

Coastal stability may be further magnified by maladapted development. For example, in places such as Varandey (Russian Federation) industrial activity has promoted erosion, leading to destruction of housing estates and industrial facilities (Ogorodov, 2003). Interacting human and natural effects may also increase the sensitivity to changes in the potential for erosion (such as may result from less sea ice). For example, in Shishmaref (Alaska, USA) and Tuktoyaktuk (Northwest Territories, Canada), the combined effects of reduced sea ice, thawing permafrost, storm surges and storm waves have led to significant loss of property, leading to abandonment and relocation of homes and other facilities (ACIA, 2004) and may require relocation, despite a cultural aversion in this Inuvialuit community to moving from this traditional site. Although hard evidence for accelerated erosion is sparse, there has been a documented increase in erosion rates between 1954-1970 and 1970-2000 for coastal terrain with very high ground-ice content at Herschel Island, Canada (Lantuit and Pollard, 2003). A modelling exercise (Rasumov, 2001) suggested that erosion rates in the eastern Siberian Arctic could increase by 3-5 m/year in response to a 3°C increase in average summer air temperature. Furthermore, the projected reduction of sea ice in the Arctic Ocean would also contribute to increased erosion, as has already observed at Nelson Lagoon in Alaska, USA (ACIA, 2004).

15.4.7.2 Sub-antarctic islands

Several sub-antarctic islands have undergone substantial recent climate change, the impacts of which have been significant physical and biological changes (Specific examples can be found in Chapter 11: Australia And New Zealand, and Chapter 16: Small Islands).

15.4.7.3 Shelf processes

Changes in the key physical processes occurring on the continental shelf seas are discussed in Working Group I. (XXX – need to check with other chapters for completeness).

15.5 Adaptation: practices, options and constraints

While the circum-arctic nations contribute about 40% of global CO_2 emissions and the Arctic is an important source of the fossil fuels that lead to emissions; the arctic residents, especially those following more traditional lifestyles contribute only a very small component of those emissions. So while their ability to participate in mitigation is limited, the burden they face is magnified by the projected amplification of climate change in arctic areas and the potential for this to cause dramatic environmental impacts. Thus, as with other populations living in vulnerable regions of the world, adaptation is critical for all arctic residents, and particularly so for those attempting to maintain traditional cultures and lifestyles.

Historically, cultural adaptations and the ability of the Arctic's indigenous peoples to utilize their local resources have been associated with, or affected by, seasonal variation and changing ecological conditions. Climatic variability and weather events often greatly affect the abundance and availability of animals and therefore the abilities and opportunities to harvest and process animals for food, clothing and other uses. One of the hallmarks of successful adaptation strategies in arctic indigenous resource use has been flexibility in technology and social organization, and the knowledge and ability to cope with climate change and circumvent some of its negative impacts. Indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. Many people work flexibly, changing jobs frequently and having several part-time jobs (Chapin *et al.*, Submitted). In the past, responses to major climatic and environmental changes included an altering of group size or moving to appropriate new locations, flexibility with regards to seasonal cycles and harvesting, and the establishment of sharing mechanisms and networks for support (Krupnik, 1993; Freeman, 1996). Many of these strategies, with the exception of group mobility, are still employed in various forms today (e.g. Berkes and Jolly, 2001; Nickels *et al.*, 2002; McCarthy, 2005) yet may in future be constrained by the establishment of permanent settlements, increased infrastructure, national boundaries, land ownership and difficulties in access to resources.

Traditional knowledge held by Indigenous populations and the institutions in which this knowledge exists are critical foundations of understanding about interactions between people and their environment and therefore vital to community adaptability (See Case Study 15.6.1).

Yet the generation of this knowledge requires active engagement with the environment, and as the nature of this interaction changes as a result of social, economic and cultural trends in communities so does the information it provides (e.g. some hunters now use GPS and snowmobiles, so there is an increasing need to know how to detect safe ice conditions, a task previously done to some extent by dogs leading the sled). Changes in local environments further challenge this knowledge and increases human vulnerability to climatic and social changes.

Greater uncertainty and threats to food security resulting from increased climate variability and threats to transport of western goods, stresses the need for resilient and flexible resource procurement activities. Yet, resilience and adaptability depends not only on ecosystem diversity, but on the institutional rules which govern social and economic systems (Adger, 2000). It is the links to co-management regimes bringing together western scientific and traditional knowledge approaches that might enhance aspects of adaptability by allowing flexibility in such things as hunting seasons with shifts in species ecology. Innovative co-management of both renewable and non-renewable resources could also provide opportunities to enhance local economic benefits and ecological and societal resilience (Chapin *et al.*, 2004).

Non-indigenous populations are similarly affected by social, economic and political ties to outside regions.

Opportunities for adaptation exist within some changes already taking place. The arrival of new species (e.g. Babaluk *et al.*, 2000.; Huntington *et al.*, 2005b) or an increase in growing seasons and opportunities for high latitude agriculture provide chances to supplement local diets. Increased ecotourism may increase incentives for protection of environmental areas. However to take advantage of these potentially positive impacts requires increased institutional flexibility and forms of economic support.

Although arctic peoples show great resilience and adaptability to change, some traditional responses to environmental change have been compromised by socio-political change. The Arctic's indigenous peoples live within different institutional settings than a generation or two ago. The political, cultural and economic diversity that exists means that indigenous communities are affected by, and respond to, environmental change in different ways. Such diversity also means that local experiences of climate impacts and responses to climate variability and change may not be universal. Yet little is known about how communities and individuals, indigenous or non-indigenous, differ in the way that risk is perceived, or how they differ in the ways they utilize such things as harvesting strategies or other forms of resource procurement for mitigating negative change. Furthermore, the effectiveness of local adaptive strategies is uneven across the Arctic and there are large gaps in knowledge about why some arctic communities do well, while others are more vulnerable and exposed to drivers of change, even when they share similar resources and ecological settings. An understanding of adaptation can only derive from a better understanding of social and economic vulnerability among arctic residents, both indigenous and non-indigenous (Handmer, 1999).

15.6 Case studies[2]

15.6.1 Cross-chapter case study - Traditional knowledge for adaptation

The Arctic is home to about 4 million residents (depending on where the boundary is drawn) of which just less than 10% are Indigenous People (Bogoyavlenskiy, 2004). Archaeological evidence suggests humans have existed there at least since the last ice age and perhaps as far back as 40 000 years in some regions (Pavlov *et al.*, 2001). Among these peoples, the selection pressures for the evolution of an effective knowledge base have been exceptionally strong, driven by the need to survive off highly variable natural resources and in the remote, harsh arctic environment. In response, they have developed a strong knowledge base concerning weather, snow and ice conditions as they relate to hunting and travel, and natural resource availability (Krupnik and Jolly, 2002a). These systems of knowledge, practice, and belief have been gained through experience and culturally transmitted among members and across generations (Huntington, 1998; Berkes, 1999). Although there is no formally accepted methodology for assessing uncertainties within it, the knowledge that can be documented offers detailed information that adds to conventional science and environmental observations as well as a holistic approach of environment, natural resources and culture (Huntington *et al.*, 2004). Thus there is an increasing awareness of the value of indigenous knowledge and a growing emphasis on collaborative research to document this information. In addition, this knowledge base is an invaluable basis for developing adaptation and natural resources management strategies in response to environmental and other forms of change.

Understanding local knowledge is essential for comprehending the effects of climate change on indigenous communities (Riedlinger, 2001b). In some communities, many changes have been absorbed through flexibility in traditional hunting, fishing and gathering practices that are grounded in the local knowledge of the environment, and wildlife. However, although arctic peoples show great resilience and adaptability, some of their traditional responses to environmental change have already been compromised by recent socio-political changes, and their ability to cope with substantial climatic change in future, without a fundamental threat to their cultures and lifestyles, cannot be considered as unlimited.

The generation and application of this knowledge is evidenced in the ability for Inuit hunters to navigate new travel and hunting routes because of decreasing ice stability and safety in regions such as Nunavik (e.g. Lafortune, 2004); in the ability of many Indigenous groups to locate and hunt species that have shifted in their regular migration times and routes such as geese or caribou or to locate and hunt alternate species (e.g. Krupnik and Jolly, 2002a; Nickels *et al.*, 2002; Huntington *et al.*, 2005b); the survival skills and ability to detect safe ice and weather conditions when travelling in an environment with increasingly unpredictable weather systems and a dangerous near shore ice environment (e.g. George, 2004); or the knowledge and skills required to hunt narwhal in open water later in the year versus off the ice in the early spring because of an earlier ice break up and changing

---

[2] Format note: each of the following case studies should appear as boxed text, not constrained to sit in the normal sequence of headings.

ice conditions (Community of Arctic Bay, 2005). This information is indicative of the adaptive nature of arctic indigenous societies and the critical role that indigenous knowledge plays in this adaptive capacity.

15.6.2 Cross-chapter case study – Mega-deltas

Numerous river deltas populate the arctic coast and the rivers that flow to it. Of particular importance are the mega-deltas of the Lena (44 x 10^6 km^2) and Mackenzie (9 x 10^6 km^2) rivers, draining the largest arctic rivers of Eurasia and North America, respectively. In contrast to non-polar deltas, the physical development and ecosystem health of these systems are strongly controlled by cryospheric processes and hence highly susceptible to the effects of climate change. Currently, advance/retreat of arctic marine deltas is highly dependent on the protection afforded by near-shore and land-fast sea ice (Solomon, 2005; Walsh *et al.*, 2005). Loss of such protection will lead to increased action from waves and storm surges, both of which are also forecast to increase because of enhanced storm activity, greater wind fetch produced by shrinking sea-ice coverage, and rising sea levels. Similarly, melting of the permafrost and ground ice that currently consolidates deltaic material will induce hydrodynamic erosion on the delta front as well as along river banks. Melting of permafrost on the delta plain will also lead to similar changes expected in other terrestrial environments, i.e., initial development of more ponded water produced by enhanced thermokarst activity but eventual drainage of these systems as taliks link the surface and groundwater systems. Climate warming may have caused the loss of wetland area as lakes expanded on the Yukon River delta in the late 20th Century (Coleman and Huh, 2004).

The current water budget and sediment-nutrient supply for the multitude of lakes and ponds that dot the tundra plains of arctic deltas depends strongly on the supply of floodwaters produced by river-ice jams during the spring freshet. Studies of future climate conditions on a major river delta of the Mackenzie River (Peace-Athabasca Delta) indicates that a combination of thinner river ice and reduced spring runoff (due to smaller winter snowpack) will lead to decreased ice jam flooding (Beltaos *et al.*, In press). This combined with greater summer evaporation from warmer temperatures will cause a decline in delta-pond water levels (Marsh and Lesack, 1996). For many arctic regions, evaporation already exceeds precipitation and hence, the loss of ice-jam flooding could lead to a drying of delta ponds and a loss of sediment and nutrients known to be critical to their ecosystem health (Lesack *et al.*, 1998; Marsh *et al.*, 1999). An adaptation strategy that has been successfully used to counteract the effects of climatic drying of delta ponds involves the use of flow enhancement via water releases from reservoirs to increase the probability of ice-jam formation and related flooding (Prowse *et al.*, 2002).

15.6.3 Case Study - Antarctic Peninsula: rapid warming in a pristine environment

The Antarctic Peninsula, a rugged mountain chain generally more than 2000 m high, which protrude from the Antarctic continent towards South America. It is one of several high-latitude regions that have recently experienced dramatic warming at rates several times the global mean. Since the TAR, substantial progress has been made in understanding the causes and profound impacts of this warming.

The short summer season during which melting occurs at low elevations differentiates the Antarctic Peninsula from most of Antarctica. Summer melt produces many isolated snow-free areas that provide a foot-hold for relatively simple biological communities of cryptogamic plants, microbes and invertebrates, and a breeding ground for marine mammals and birds.

Since records began 50 years ago, mean annual temperatures on the Antarctic Peninsula have risen rapidly (more than 2.5 C at Faraday/Vernadsky Station, Turner *et al.*, 2005). On the west coast, summer warming has been much slower than either winter, or autumn, but has still been sufficient to raise the number of positive-degree-days by 74% (Vaughan, in press). It is the consequent increase in melt that has caused the dramatic impacts on the Antarctic Peninsula.

Ten floating ice shelves have retreated with loss of around 14 000 km^2 (King, 2003), 87% of glacier termini have retreated (Cook *et al.*, 2005), and seasonal snow cover has decreased (Fox and Cooper, 1998). The loss of seasonal and floating ice does not have a direct impact on global sea level, but increases run-off of melt water (Vaughan, in press), and acceleration of inland glaciers due to the loss of ice shelves (De Angelis and Skvarca, 2003; Scambos *et al.*, 2004; Rignot *et al.*, 2005) and an increased supply of melt water to glacier beds (Pritchard and Vaughan, in prep) will cause an increased contribution to sea level rise. If summer warming continues these effects will grow in coming decades.

Marine sediment cores show that ice shelves have now reached a minimum, not previously reached probably in the last 10 000 years (Domack *et al.*, 2005), but undoubtedly in the last 1000 years (Pudsey and Evans, 2001; Domack *et al.*, 2003), but the causes of rapid warming are disputed. The persistent retreat of sea ice in the Bellingshausen Sea (Figure 15-4, Parkinson, 2002) is related to winter warming on the west coast, and the spring depletion of ozone over Antarctica (the Ozone Hole) has also been implicated (Thompson and Solomon, 2002), but has been also disputed (Marshall *et al.*, 2004). Furthermore, it has been shown that warming is correlated with atmospheric circulation (van den Broeke and van Lipzig, 2003), and is consistent with changes in circulation patterns caused by anthropogenic influence (Southern Annular Mode) (Marshall *et al.*, 2004). The warming on the west coast is limited to the lower troposphere (Marshall *et al.*, 2002). Current GCMs do not simulate the observed warming in this area over the past 50 years (King, 2003) and there is little basis for prediction that rapid warming will continue in future, and this limits our ability to predict the likely impacts.

Notwithstanding our uncertainty over the cause of recent warming, continued warming would cause further retreat of coastal ice, and seasonal snow cover, resulting in newly exposed rock and permafrost – providing new habitats for colonization by expanding and invading flora and fauna. However, the direct impacts of climate change on the flora and fauna are difficult to predict since ecosystems are subject to multiple stresses and their responses are complex. Increased damage by UV exposure because of reduced ozone levels, and summer desiccation may oppose the direct responses to warming (Convey *et al.*, 2002). In addition, there is a growing threat of alien species invasion, encouraged by climate amelioration and potentially linked to human activity. This has already occurred on many sub-antarctic islands with detrimental consequences for native species (Frenot *et al.*, 2005). Furthermore, slow reproductive rates during a period of rapid climate change may limit the relocation of native species, while climatic barriers to natural migration of alien species are eroded by climate change. Two decades of monitoring of the marine ecosystems west of the Antarctic Peninsula have revealed trends in all trophic levels. The main driver of these appears to be sea ice duration and distribution, although changes in primary production of phytoplankton may also have been affected by changes in the supply of glacial melt water (Smith *et al.*, 2003). It is likely that this loss of sea ice was the cause of the dramatic change in the balance between krill and salps, the main grazers of phytoplankton (Atkinson *et al.*, 2004). This loss of krill, will likely have impacts on higher predators (albatrosses, seals, whales and penguins: populations of the latter are already changing, Smith *et al.*, 2003), but could have more far reaching impacts, perhaps even affecting CO_2 sequestration in parts of the Southern Ocean (Walsh *et al.*, 2001).

The global significance of the Antarctic Peninsula warming is difficult to assess and the main concern is for the loss of a unique landscape and biota. The rates of warming on the Antarctic Peninsula are, however, among of the highest seen anywhere on Earth in recent times, and is a dramatic reminder of the regionality we should expect in future climate change, and complexity of its impacts in an environment where human influence is at a minimum.

15.7 Implications for sustainable development

15.7.1 Economic activity and infrastructure in the Arctic

Because of its potential for settlement, thawing of ice-rich permafrost is a significant environmental hazard in high-latitude regions, particularly in the context of climatic change. Serious concerns are associated with the effects warming and thawing of permafrost may have on the infrastructure built upon it.

Deeper seasonal thawing and higher temperature of the frozen ground will stimulate destructive processes, particularly thermokarst formation, which may cause detrimental impacts on northern infrastructure. Such potential risks have been evaluated using the "permafrost hazard" index (.e.g., Nelson *et al.*, 2001; Anisimov and Belolutskaia, 2004; Anisimov and Lavrov, 2004). Despite discrepancies in details, by the mid-21st Century all IPCC scenarios yield a discontinuous high-risk zone around the Arctic Ocean, indicating a high potential for coastal erosion. Within this zone there are several population centres (Salekhard, Igarka, Dudinka, Tiksi in Russia, Barrow and Inuvik in North America), pipelines, and extraction facilities including the Nadym-Pur-Taz natural gas production complex and associated infrastructure in northwest Siberia fall within this zone. Within the zone of medium hazard are several large population centres (Yakutsk, Noril'sk, Vorkuta), and much of the Trans-Siberian and Baikal-Amur Railroads. Substantial investments are necessary to maintain the existing infrastructure in permafrost regions and mitigate the detrimental impacts of warming.

An important challenge facing climate-change science is discerning between the effects of climate change on permafrost and more localized, human-induced changes (Nelson, 2003). Several media reports in recent years have suggested widespread damage to human infrastructure caused by thawing permafrost (e.g., Zernova, 2003; Gribchatov, 2004; Vasilieva, 2004), with some making unequivocal statements implying that climate change is responsible. However, the effect of heated buildings on underlying ice-rich permafrost has been known for a very long time and may be mistaken for an impact of climate change. Similarly, significant urban heat-island effects have been documented in high-latitude regions (e.g. Hinkel *et al.*, 2003) that may be an important factor in localized degradation of permafrost.

Urbanization has a confounding effect on our ability to assess a straightforward relation between climatic change and the effects of thawing permafrost on the built environment (Tutubalina and Rees, 2001). In Fairbanks, Alaska, for example, the Permafrost Technology Foundation has identified more than 350 structures affected by differential thaw settlement, although not all of this is attributable to climatic change. Inappropriate positioning and construction practices have continued as the sprawling suburbs Fairbanks have grown. Experience here illustrates how thawing permafrost can affect the real estate industry. Significant amounts of money being associated with subsidence-damaged structures, but once a structure has been identified as having been affected by degrading permafrost it becomes effectively unmarketable as loans cannot be secured on it, the effect of which can be devastating on individuals.

The cost of rehabilitating community infrastructure damaged by widespread thawing of permafrost could be overwhelming (Couture *et al.*, 2000). Even buildings designed specifically for permafrost environments are subject to severe damage if design criteria are exceeded (Khrustalev, 2000). The impervious nature of ice-rich permafrost has been used as a design element in landfills and contaminant holding facilities in some areas of the Arctic (Snape *et al.*, 2003), and thawing of such facilities could result in severe contamination of hydrological resources and large cleanup costs, even for small spills affecting small areas (Roura, 2004). Rates of coastal erosion in areas of ice-rich permafrost are among the highest documented anywhere, threatening coastal settlements. Relocation of settlements would incur very large expenses; a study by the U.S. Corps of Engineers indicated that moving the small village of Kivalina, Alaska to a nearby site would require $54 M (U.S. Arctic Research Commission Permafrost Task Force, 2003).

Conventional tourism, eco-tourism and travel associated with research are likely to increase as the Arctic becomes more accessible. The increased possibility of a navigable Northwest Passage will likely create new tourism opportunities for cruise ships and in some cases longer and more benign summer temperatures and less summer ice are already leading to such increases in the North American Arctic (Eagles, 2004).

Even without the complication of projected climate change, the complexity of the task faced in producing a viable plan for sustainable development of the Arctic would be daunting, but with the added uncertainty of the apparent amplification of climate change in many arctic areas, the task is enormous. These impacts on infrastructure discussed above, together with the probable lengthening of growing seasons, increase in agricultural land, opening of new sea routes (See Figure 15-3), and changing fish stock, ecosystem changes (discussed elsewhere in this chapter) will provide new opportunities for development of arctic economies, but will also place limits on how much development is actually sustainable. Indeed, virtually every other change discussed in this chapter will have, in some more or less predictable way, impact on sustainability. However, there does now appear to be an increasing understanding, in government and residents that environmental protection and sustainable development are two sides of the same coin (Nuttall, 2000a). Furthermore, a reasonable framework for circum-arctic decision-making exists in the Arctic Council, which involves eight states, and six indigenous people’s organizations, and which contained an emphasis on sustainable development in its original mandate. The Arctic Council now has an active Sustainable Development Working Group with a permanent secretariat and ten research and information-gathering projects, but in addition, the Arctic Council was responsible for the recent, Arctic Climate Impact Assessment, whose synthesis has substantially improved the understanding of the impacts of climate change in the Arctic, and may in time become the benchmark for regional impact assessments, and the basis for a sustainable management plan for the entire arctic region.

15.7.2 Economic activity and infrastructure in the Antarctic

With the exception of Southern Ocean fisheries, which have already been discussed (see 15.4.4), the only economic activity in the Antarctic at present is tourism. This, along with other activities that might become economically viable in future, is effectively limited to sustainable levels by the environmental provisions of the 1991 Madrid Protocol of the Antarctic Treaty.

Tourism in Antarctica is likely to benefit from climate change, as a reduction in the extent and duration of sea ice will probably increase the access of tourist ships to areas of interest. However, any effect due to climate change is likely to be gradual and widespread, unlike the current rapid, but localised impacts from the continuing growth in Antarctic tourism resulting from increasing disposable incomes, and the current popularity for "eco-tourism" and personal exploration. The relatively small value of infrastructure in Antarctica, which is limited to a handful of scientific stations, means that the impact of climate change, while locally dramatic, have little human consequence or global significance.

15.8 Key uncertainties

The key uncertainties listed below, are gaps in our understanding or an predictive capacity that restrict our ability to make reasonable predictions about the likely impact of climate change in the polar regions, and the important of those changes on the Earth system.
We have insufficient…

- understanding of the potential for methane hydrate release from arctic permafrost, and high-latitude continental shelves, to cause a significant feedback to global climate.
- ability to predict whether rapid recent rates warming on the Antarctic Peninsula and sub-Antarctic islands will be sustained.
- Ability to predict the future of the West Antarctic Ice Sheet both as a response to contemporary climate change, or other drivers, or to predict whether increasing precipitation over the East Antarctic Ice Sheet could offset sea level rise from other sources.
- …XXX More to be added after further discussion.

References

Abdalati, W., and K. Steffen, 2001: Greenland ice sheet melt extent: 1979-1999. *Journal of Geophysical Research-Atmospheres*, 106(D24), pp. 33983-33988.

ACIA, 2004: *Impacts of a Warming Arctic: Arctic Climate Impacts Assessment.* Cambridge University Press, Cambridge, 139pp.

Ackley, S., P. Wadhams, J.C. Comiso, and A.P. Worby, 2003: Decadal decrease of Antarctic sea ice extent inferred from whaling records revisited on the basis of historical and modern sea ice records. *Polar Research*, 22(1), pp. 19-25.

Adger, W.N., 2000: Social and ecological resilience: are they related? *Progress in Human Geography*, 24(3), pp. 347-364.

Agnarsson, S., and R. Arnason, 2003: The Role of the Fishing Industry in the Icelandic Economy. An Historical Examination. *Working paper W03:08. Institute of Economic Studies*

Ainley, D.G., E.D. Clarke, K. Arrigo, W.R. Fraser, A. Kato, K.J. Barton, and P.R. Wilson, 2005: Decadal-scale changes in the climate and biota of the Pacific sector of the Southern Ocean, 1950s to the 1990s. *Antarct. Sci.*, 17(2), pp. 171-182.

Albon, S.D., A. Stien, R.J. Irvine, R. Langvatn, E. Ropstad, and O. Halvorsen, 2002: The role of parasites in the dynamics of a reindeer population. *Proc. Royal Soc. London Ser.*, B 269, pp. 1625-1632.

AMAP, 2002: *Arctic Pollution 2002: Persistent organic pollutants, heavy metals, radioactivity, human health, changing pathways.* Arctic Monitoring and Assessment Program, Oslo, Norway, Xii + 112pp.

Anisimov, O., B.B. Fitzharris, J.O. Hagen, B. Jefferies, H. Marchant, F. Nelson, T. Prowse, and D. Vaughan, 2001: Chapter 16: Polar regions (Arctic and Antarctic). In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, Cambridge, pp. 801-841.

Anisimov, O.A., and M.A. Belolutskaia, 2001: Predicting agroclimatic parameters using geographical information system. *Meteorology and Hydrology*(9), pp. 89-98.

Anisimov, O.A., and M.A. Belolutskaia, 2004: Predictive modelling of climate change impacts on permafrost: effects of vegetation. *Meteorology and Hydrology*(11), pp. 73-81.

Anisimov, O.A., and C.A. Lavrov, 2004: Global warming and permafrost degradation: risk assessment for the infrastructure of the oil and gas industry. *Technologies of oil and gas industry*(3), pp. 78-83.

Anisimov, O.A., S.A. Lavrov, and S.A. Reneva, 2005a: Emission of methane from the Russian frozen wetlands under the conditions of the changing climate. In: *Problems of ecological modeling and monitoring of ecosystems*. Hydrometeoizdat, S.Petersburg, pp. 124-142.

Anisimov, O.A., S.A. Lavrov, and S.A. Reneva, 2005b: Modelling the emission of greenhouse gases from the Arctic wetlands under the conditions of the global warming. In: *Climatic and environmental changes*. Hydrometeoizdat, S.Petersburg, pp. 21-39.

Arctic Monitoring and Assessment Programme, 2003: *AMAP Assessment 2002: Human Health in the Arctic*. Arctic Monitoring and Assessment Programme, Oslo, Norway, Xiv + 137pp.

Aré, F.E., 1999: The role of coastal retreat for sedimentation in the Laptev Sea. In: *Land-ocean systems in the Siberian Arctic: dynamics and history*. Springer, Berlin, Germany, pp. 287-299.

Arendt, A.A., K.A. Echelmeyer, W.D. Harrison, C.S. Lingle, and V.B. Valentine, 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, 297(5580), pp. 382-386.

Arnell, N.W., 1999: Climate change and global water resources. *Global Environmental Change*, 9, pp. 31-49.

Arora, V.K., and G.J. Boer, 2001: Effects of simulated climate change on the hydrology of major river basins. *Journal of Geophysical Research*, 106(D4), pp. 3335-3348.

Arrigo, K.R., D.H. Robinson, D.L. Worthen, R.B. Dunbar, G.R. DiTullio, M. VanWoert, and M.P.

Lizotte, 1999: Phytoplankton community structure and the drawdown of nutrients and CO2 in the Southern Ocean. *Science*, 283(5400), pp. 365-367.

Atkinson, A., V. Siegel, E. Pakhomov, and P. Rothery, 2004: Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, 432(7013), pp. 100-103.

Aurela, M., T. Laurila, and J.-P. Tuovinen, 2002: Annual CO2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux. *J. Geophys. Res.*, 107, pp. 4607.

Babaluk, J.A., J.D. Reist, J.D. Johnson, and L. Johnson, 2000.: First records of sockeye (Oncorynchus nerka) and pink salmon (O. gorbuscha) from Banks Island and other records of pacific salmon in Northwest Territories, Canada. *Arctic*, 53, pp. 161-164.

Balikci, A., 1968: The Netsilik Eskoimos: adaptive processes. In: *Man the Hunter*. Aldine, Chicago, Illinois, pp. 72-78.

Baskin, L., 2000: Reindeer husbandry/hunting in Russia in the past, present, and future. *Polar Research*, 19, pp. 23-29.

Beerling, D.J., A.C. Terry, P.L. Mitchell, D. Gwynn-Jones, J.A. Lee, and T.V. Callaghan, 2001: Time to chill: effects of simulated global change on leaf ice nucleation temperatures of sub-Arctic vegetation. *Am. J. Bot* 88(4), pp. 628-633.

Beilman, D.W., D.H. Vitt, and L.A. Halsey, 2001: Localized permafrost Peatlands in Western Canada: Definition, distributions, and degradation. *Arctic Antarctic and Alpine Research*, 33(1), pp. 70-77.

Beltaos, S., T. Prowse, B. Bonsal, R. MacKay, L. Romolo, A. Pietroniro, and B. Toth, In press: Climatic effects on ice-jam flooding of the Peace-Athabasca Delta. *Hydrological Processes*

Bergstrom, D.M., and S.L. Chown, 1999: Life at the front: history, ecology and change on southern ocean islands. *Trends in Ecology and Evolution*, 14, pp. 472-477.

Berkes, F., 1999: *Sacred Ecology: Traditional Ecological Knowledge and Resource Management.* Taylor and Francis, xvi+209pp.

Berkes, F., 2002: Epilogue: Making sense of arctic environmental change? In: *The earth is moving faster now*. Arctic Research Consortium, Fairbanks, Alaska, pp. 335-349.

Berkes, F., and D. Jolly, 2001: Adapting to climate change: social-ecological resilience in a Canadian Western Arctic Community. *Conservation Ecology*, 5(2), pp. 18.

Berkman, L.F., and S.L. Syme, 1979: Social networks, host resistance, and mortality: A nine-year follow-up study of Alameda County residents. *Am. J. Epidemiol.*, 109, pp. 186-204.

Berner, J., C. Furgal, P. Bjerregaard, M. Bradley, T. Curtis, E. De Fabo, J. Hassi, W. Keatinge, S. Kvernmo, S. Nayha, H. Rintamaki, and J. Warren, 2005: Chapter 15: Human Health. In: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge UK., Cambridge, pp. (pre-release version).

Berry, J.W., 1997: Immigration, acculturation and adaptation. *App. Psychol.*, 46, pp. 5-34.

Betts, A.K., and J.H. Ball, 1997: Albedo over the boreal forest. *Journal of Geophysical Research-Atmospheres*, 102, pp. 28901-28909.

Betts, R.A., 2000: Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature*, 408, pp. 187-190.

Bialek, D., 2003: Sink or swim: measures under international law for the conservation of the Patagonian toothfish in the Southern Ocean. *Ocean Dev. Int. Law*, 34(2), pp. 105-137.

Blanchet, C., E. Dewailly, P. Ayotte, S. Bruneau, O. Receveur, and B. Holub, 2000: Contribution of selected traditional and market foods to te diet of Nunavik Inuit women. *Canada J. Dietetic Prac. and Res.*, 61(2), pp. 1-9.

Bogaart, P.W., and R.T. van Balen, 2000: Numerical modeling of the response of alluvial rivers to quaternary climatic change. *Glob. Planet. Change*, 27, pp. 124-141.

Bogoyavlenskiy, D., and Siggner, A., 2004: *Arctic Demography*. Steffanson Arctic Institute, Akureyri, Iceland.

Bonan, G.B., D. Pollard, and S.L. Thompson, 1992: Effects of boreal forest vegetation on global climate. *Nature*, 359, pp. 716-718.

Bradley, M., Kutz, SJ, Jenkins, E., and TM O'Hara, In review: The Potential Impact of Climate Change on Infectious Diseases of Arctic Fauna. *International Journal for Circumpolar Health*, In review

Buch, E., S.A. Horsted, and H. Hovgaard, 1994: Fluctuations in the occurrence of cod in Greenland waters and their possible causes. *ICES Marine Science Symposia*, 198, pp. 158-174.

Budd, W.F., and X. Wu, 1998: Modeling long term global and Antarctic changes resulting from increased greenhouse gases. In: *Coupled Climate Modeling, Research Report, 69*. Bureau of Meteorology, Canberra, Australia, pp. 71-74.

Callaghan, T.V., L.O. Björn, Y.I. Chernov, F.S. Chapin III, T.R. Christensen, B. Huntley, R. Ims, M. Johansson, D. Jolly, N.V. Matveyeva, N. Panikov, W.C. Oechel, and G.R. Shaver, 2004: Climate Change and UV-B Impacts on Arctic Tundra and Polar Desert Ecosystems. *Ambio*, 33(7), pp. 95.

Callaghan, T.V., L.O. Björn, Y.I. Chernov, F.S. Chapin III, T.R. Christensen, B. Huntley, R. Ims, M. Johansson, D. Jolly, N.V. Matveyeva, N. Panikov, W.C. Oechel, and G.R. Shaver, 2005: Chapter 7: Arctic tundra and Polar ecosystems. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

Carmack, E.C., and R.W. Macdonald, 2002: Oceanography of the Canadian Shelf of the Beaufort Sea: a setting for marine life. *Arctic*, 55, pp. 29-45.

Caulfield, R.A., 2004: *Resource Governance.* Steffanson Arctic Institute, Akureyri, Iceland.

Cavalieri, D.J., C.L. Parkinson, and K.Y. Vinnikov, 2003: 30-Year satellite record reveals contrasting Arctic and Antarctic decadal sea ice variability. *Geophysical Research Letters*, 30(18), pp. art. no.-1970.

Cavalieri, D.J., C.L. Parkinson, and K.Y. Vinnikov, 2004: 30-year trends in sea ice extent. *Bull. Amer. Meteorol. Soc.*, 85(3), pp. 348-349.

Chabot, M., 2004: Consumption and standards of living of the Québec Inuit: Cultural permanence and discontinuities. *Canadian Review of Sociology and Anthropology*, 41(2), pp. 147-170.

Chapin, F., G. Peterson, F. Berkes, T.V. Callaghan, P. Angelstam, M. Apps, C. Beier, C. Bergeron, A.S. Crepin, T. Elmqvist, C. Folke, B. Forbes, N. Fresco, G. Juday, J. Niemela, A. Shvidenko, and G. Whiteman, 2004: Resilience and vulnerability of northern regions to social and environmental change. *Ambio*, 33(6), pp. 342-347.

Chapin, F.S., III, M. Hoel, S.R. Carpenter, S. Barret, T.V. Callaghan, A.-S. Crepin, K. Danell, C. Folke, S. Levin, J. Lubchenco, K.-G. Mäler, C. Nilsson, T. Rosswall, D. Starrett, B. Walker, and T. Xepapadeas, Submitted: Building Resilience to Manage Arctic Change. *Science*

Chapin, I., F. S., M. Berman, T.V. Callaghan, P. Convey, A.-S. Crepin, K. Danell, H. Ducklow, B. Forbes, G. Kofinas, A.D. McGuire, M. Nuttall, R. Virginia, O. Young, S.A. Zimov, T.R. Christensen, A. Godduhn, D. Wall, and C. Zöckler, 2005: Chapter 25 - Polar Systems. In: *The Millenium Ecosystem Assessment*. Island Press, Washington, USA

Chapman, W.L., and J.E. Walsh, Submitted: Simulations of Arctic temperature and pressure by global coupled models. *Journal of Climate*

Chernov, Y.I., and N.V. Matveyeva, 1997: Arctic ecosystems in Russia. In: *Ecosystems of the World.* Elsevier, Amsterdam, pp. 361-507.

Chin, J., 2000: *Control of communicable diseases in Man.* American Public Health Association, Washington, DC, XXXpp.

Christensen, T.R., T. Friborg, W. Oechel, L. Groendahl, J. Gudmundsson, Y. Harazono, P. Martikainen, and H. Oskarsson, in prep: Circumpolar carbon stocks and current annual trace gas flux estimates. *Ecological Applications*

Christensen, T.R., T. Johansson, H.J. Akerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B.H. Svensson, 2004: Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters*, 31, pp. L04501.

Coleman, J.M., and O.K. Huh, 2004: *Major World Deltas: A Perspective from Space*, pp. http://www.geol.lsu.edu/WDD/PUBLICATIONS/introduction.htm.

Comiso, J.C., 2002: A rapidly declining perennial sea ice cover in the Arctic. *Geophysical Research Letters*, 29(20), pp. art. no.-1956.

Community of Arctic Bay, 2005: *Inuit Observations on Climate and Environmental Change: Perspectives from Arctic Bay, Nunavut.* ITK, Nasivvik, NAHO, NTI, Ottawa, ON, 57pp.

Constable, A.J., W.K. de la Mare, D.J. Agnew, I. Everson, and D. Miller, 2000: Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES Journal of Marine Science*, 57, pp. 778-791.

Convey, P., P.J.A. Pugh, C. Jackson, A.W. Murray, C.T. Ruhland, F.S. Xiong, and T.A. Day, 2002: Response of antarctic terrestrial microarthropods to long-term climate manipulations. *Ecology*, 83(11), pp. 3130-3140.

Cook, A., A.J. Fox, D.G. Vaughan, and J.G. Ferrigno, 2005: Retreating glacier-fronts on the Antarctic Peninsula over the last 50 years. *Science*, 22, pp. 541-544.

Cornelissen, J.H.C., T.V. Callaghan, J.M. Alatalo, A.E. Hartley, D.S. Hik, S.E. Hobbie, M.C. Press, C.H. Robinson, G.R. Shaver, G.R. Phoenix, D. Gwynn-Jones, S. Jonasson, M. Sonesson, I. Chapin, F. S. , U. Molau, and J.A. Lee, 2001: Global change and Arctic ecosystems: is lichen decline a function of increases in vascular plant biomass? *Journal of Ecology*, 89, pp. 984-994.

Couture, R., S.D. Robinson, and M.M. Burgess, 2000: *Climate change, permafrost degradation, and infrastructure adaptation: preliminary results from a pilot community study in the Mackenzie Valley*. Geological Survey of Canada, 9pp.

Covey, C., K.M. Achutarao, P.J. Gleckler, T.J. Phillips, K.E. Taylor, and M.F. Wehner, 2004: Coupled ocean-atmosphere climate simulations compared with simulations using prescribed sea surface temperature: effect of a "perfect ocean". *Glob. Planet. Change*, 41(1), pp. 1-14.

Crawford, R.M.M., 2004: Long-term plant survival at high latitudes. *Bot. J. Scotl.*, 56(1), pp. 1-23.

Crawford, R.M.M., C.E. Jeffree, and W.G. Rees, 2003: Paludification and forest retreat in northern oceanic environments. *Ann Bot-London*, 91, pp. 213-226.

Curran, M.A.J., T.D. van Ommen, V.I. Morgan, K.L. Phillips, and A.S. Palmer, 2003: Ice core evidence for Antarctic sea ice decline since the 1950s. *Science*, 302(5648), pp. 1203-1206.

Curtis, T., S. Kvernmo, and P. Bjerregaard, In review: Changing living conditions, lifestyle and health. *International Journal of Circumpolar Health.*

Davis, C.H., L. Yonghong, J.R. McConnell, M.M. Frey, and E. Hanna, 2005: Snowfall-driven growth in Antarctic Ice Sheet mitigates recent sea-level rise. *Science*

De Angelis, H., and P. Skvarca, 2003: Glacier surge after ice shelf collapse. *Science*, 299(5612), pp. 1560-1562.

de la Mare, W.K., 1997: Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. *Nature*, 389, pp. 57-60.

DeFabo, E., In review: Arctic stratoshperic ozone depletion and increased UVB radiation: Potential impacts to human health. *International Journal for Circumpolar Health*, In review

Dietrich, R.A., 1981: *Alaskan Wildlife Diseases.* Institute of Arctic Biology, University of Alaska, Fairbanks, Fairbanks, Alaska, ???pp.

Domack, E., D. Duran, A. Leventer, S. Ishman, S. Doane, S. McCallum, D. Amblas, J. Ring, R. Gilbert, and M. Prentice, 2005: Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. *Nature*, 436(7051), pp. 681-685.

Domack, E.W., A. Leventer, S. Root, J. Ring, E. Williams, D. Carlson, E. Hirshorn, W. Wright, R. Gilbert, and G. Burr, 2003: Marine sedimentary record of natural environmental variability. In: *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives. Antarctic Research Series, 79*. AGU, Washington, DC, pp. 61-68.

Doran, P.T., J.C. Priscu, W. Berry Lyons, J.E. Walsh, A.G. Fountain, D.M. McKnight, D.L.

Moorhead, R.A. Virginia, D.H. Wall, G.D. Clow, C.H. Fritsen, C.P. McKay, and A.N. Parsons, 2002: Antarctic climate cooling and terrestrial ecosystem response. *Nature*, 415, pp. 517-520.

Downey, D., and Fenge, T., 2003: *Northern Lights Against POPs: Combatting Toxic Threats in the Arctic.* McGill-Queen's University Press, 347ppp.

Drinkwater, K., 2002: A review of the role of climate variability in the decline of Northern cod. *American Fisheries Society Symposium*, 32, pp. 113-130.

Duhaime, G., 2004: Economic Systems. In: *The Arctic Human Development Report*. Stefansson Arctic Institute, Akureyri. Iceland, pp. 69-84.

Dye, D.G., 2002: Variability and trends in the annual snow-cover cycle in Northern Hemisphere land areas, 1972-2000. *Hydrological Processes*, 16(15), pp. 3065-3077.

Dyurgerov, M.B., and C.L. Carter, 2004: Observational evidence of increases in freshwater inflow to the Arctic Ocean. *Arctic, Antarctic, and Alpine Research*, 36(1), pp. 117-122.

Eagles, P.F.J., 2004: *Trends affecting tourism in protected areas* Working Papers of the Finnish Forest Research Institute 2.

Edwards, M., and A.J. Richardson, 2004: Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, 430(7002), pp. 881-884.

Eugster, W., W.R. Rouse, R.A. Pielke, J.P. McFadden, D.D. Baldocchi, T.G.F. Kittel, F.S. Chapin III, G.E. Liston, P.L. Vidale, E. Vaganov, and S. Chambers, 2000: Land-atmosphere energy exchange in arctic tundra and boreal forest: available data and feedbacks to climate. *Global Change Biology*, 6 (Suppl. 1), pp. 84-115.

Flato, G.M., 2004: Sea-ice and its response to CO2 forcing as simulated by global climate models. *Clim. Dyn.*, 23(3-4), pp. 229-241.

Foley, J.A., J.E. Kutzbach, M.T. Coe, and S. Levis, 1994: Feedbacks between climate and boreal forests during the Holocene epoch. *Nature*, 371, pp. 52-54.

Forbes, D.L., 2005: Coastal erosion. In: *Encyclopedia of the Arctic*. Routledge, New York and London, pp. 391-393.

Fowbert, J.A., and R. Smith, 1994: Rapid population increases in native vascular plants in the Argentine Islands, Antarctic Peninsula. *Arc. Alpine Res.*, 26, pp. 290-296.

Fox, A.J., and A.P.R. Cooper, 1998: Climate-change indicators from archival aerial photography of the Antarctic Peninsula. *Ann. Glaciol.*, 27, pp. 636-642.

Fraser, W.R., and E.E. Hoffmann, 2003: A predator's perspective on causal links between climate change, physical forcing and ecosystem response. *Marine Ecology Progress Series*, 265, pp. 1-15.

Freeman, M., 1996: Identity, health and social order. In: *Human ecology and health: adaptation to a changing world.* Gothenburg Universitty, Gothenburg, Sweden, pp. 57-71.

Freeman, M.M.R., 2000: *Endangered Peoples of the Arctic.* Greenwood Press, Connecticut, xix + 278pppp.

Frenot, Y., S.L. Chown, J. Whinam, P.M. Selkirk, P. Convey, M. Skotnicki, and D.M. Bergstrom, 2005: Biological invasions in the Antarctic: extent, impacts and implications. *Biol. Rev.*, 80(1), pp. 45-72.

Friborg, T., H. Soegaard, T.R. Christensen, C.R. Lloyd, and N.S. Panikov, 2003: Siberian Wetlands: Where a sink is a source. *Geophysical Research Letters*, 30(21), pp. 2129.

Furgal, C., and T. Curtis, In review: Arctic food security and climate change: implications for Arctic communities. *International Journal of Circumpolar Health*

Furgal, C., D. Martin, and P. Gosselin, 2002.: Climate change in Nunavik and Labrador: Lessons from Inuit Knowledge. In: *The Earth is Faster Now: Indigenous Observations on Arctic Environmental Change*. Arcus, Washington, DC, pp. 266-300.

George, J., Huntington, HP., Brewster, K., Eicken, H., Norton, DW., Glenn, R., 2004: Observsations on shorefast ice dynamics in Arctic Alaska and the responses of the Inupiat hunting community. *Arctic*, 57(4), pp. 363-374.

Georgievsky, V.Y., I.A. Shiklomanov, and A.L. Shalygin, 2003: *Possible changes of water resources and water regimes in the Lena Basin due to global climate warming.*

Gibson, J.J., T.D. Prowse, and D.L. Peters, 2005: Evaluating climate change impacts in a regulated river system: the case of water level variability in Great Slave Lake. *Hydrological Processes*

Gray, A., 1995: The indigenous movement in Asia. In: *Indigenous Peoples of Asia*. Association for Asian Studies, Inc, Ann Arbor, USA

Gregory, J.M., P. Huybrechts, and S.C.B. Raper, 2004: Threatened loss of the Greenland ice-sheet. *Nature*, 428(616)

Gribchatov, U., 2004: *New disaster in Yakutia: climatic change*. *Yakutsk today.* Yakutsk.

Hamilton, L.C., B.C. Brown and R.O. Rasmussen, 2003: West Greenland's cod-to-shrimp transition: local dimensions of climate change. *Arctic*, 56(3), pp. 271-282.

Handmer, J.W., S. Dovers and T.E. Downing, 1999: Societal vulnerability to climate change and variability. *Mitigation and Adaptation Strategies for Climate Change*, 4, pp. 267-281.

Harris, C., D. Vonder Mühll, K. Isaksen, W. Haeberli, J.L. Sollid, L. King, P. Holmlund, F. Dramis, M. Guglielmin, and D. Palacios, 2003: Warming permafrost in European mountains. *Glob. Planet. Change*, 39, pp. 215-225.

Harris, L., 1990: *Independent Review of the State of the Northern Cod Stock: Final Report of the Northern Cod Review Panel.* Department of Supply and Services of the Government of Canada., Ottawa, Canada, ???pp.

Hassi, J., Rytkonen, M., Kotaniemi, J., and H. Rintimaki, In review: Impacts of cold climate on human heat balance, performance, illnesses and injuries in circumpolar areas. *International Journal of Circumpolar Health*, In review

Henttonen, H., and H. Wallgren 2001: Small rodent dynamics and communities in the birch forest zone of northern Fennoscandia. In: *Nordic mountain birch forest ecosystem*. UNESCO Man and Biosphere Series, UNESCO, Paris and Parthenon Publishing Group, New York and London, Man and the Biosphere Series, pp. 261-278.

Hild, C., and V. Stordhal, 2004: *Human health and well-being.* Steffanson Arctic Institute, Akureyri, Iceland.

Hinkel, K.M., F.E. Nelson, A.F. Klene, and J.H. Bell, 2003: The urban heat island in winter at Barrow, Alaska. *Int. J. Climatol.*, 23(15), pp. 1889-1905.

Hinzman, L.D., N.D. Bettez, W. Bolton, R,, F.S. Chapin, M.B. Dyurgerov, C.L. Fastie, B. Griffithy, R. Hollister, D,, A. Hope, H. Huntington, A.M. Jensen, G.J. Jia, T. Jorgenson, D.L. Kane, D.R. Klein, G. Kofinas, A.H. Lynch, A.H. Lloyd, A.D. McGuire, F.E. Nelson, M. Nolan, W.C. Oechel, T.E. Osterkamp, C.H. Racine, V.E. Romanovsky, R.S. Stone, D.A. Stow, M. Sturm, C.E. Tweedie, G.L. Vourlitis, M.D. Walker, D.A. Walker, P.J. Webber, J. Welker, K.S. Winker, and K. Yoshikawa, 2004: Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Clim. Change*, pp. 1-48.

Hobbie, J.E., B.J. Peterson, N. Bettez, L. Deegan, J. O’Brien, G.W. Kling, and G.W. Kipphut, 1999: Impact of global change on biogeochemistry and ecosystems of arctic Alaska freshwaters. *Polar Research*, 18, pp. 207-214.

Høgda, K.A., S.R. Karlsen, and H. Tømmervik, In press: Changes in growing season in Fennoscandia 1982-1999. In: *Arctic-Alpine Ecosystems and People in a Changing Environment*. Springer-Verlag, pp. 10.

Holloway, G., and T. Sou, 2002: Has Arctic sea ice rapidly thinned? *Journal of Climate*, 15(13), pp. 1691-1701.

Hughes-Hanks, J.M., L.G. Rickard, C. Panuska, J.R. Saucier, T.M. O'Hara, R.M. Rolland, and L. Dehn, In press: Prevalence of Cryptosporidium spp. and Giardia spp. in Five Marine Mammal Species. *Journal of Parasitology*, In press

Huisink, M., J.J.W. De Moor, C. Kasse, and T. Virtanen, 2002: Factors influencing periglacial fluvial morphology in the northern European Russian tundra and taiga. *Earth Surface Processes and*

Landforms, 27, pp. 1223-1235.

Huntington, H., 1998: Observations on the utility if the semi-directive interview for documenting traditional ecological knowledge. *Arctic*, 51(3), pp. 237-242.

Huntington, H., T.V. Callaghan, S. Fox, and I. Krupnik, 2004: Matching traditional and scientific observations to detect environmental change: a discussion on arctic terrestrial ecosystems. *Ambio Special Report (Tundra-Taiga Treeline Research)*, 13, pp. 18-23.

Huntington, H., G. Weller, E. Bush, T.V. Callaghan, V.M. Kattsov, and M. Nuttall, 2005a: Chapter 1: An introduction to the Arctic Climate Impact Assessment. In: *Arctic Climate Impact Assessment (ACIA)*. Cambridge University Press, Cambridge UK., pp. (pre-release version).

Huntington, H.P., 1992: *Wildlife Management and Subsistence Hunting in Alaska*. Belhaven Press, London, UK, xvii + 177pp.pp.

Huntington, H.P., S. Fox, I. Krupnik, and F. Berkes, 2005b: Chapter 3: The Changing Arctic: Indigenous Perspectives. In: *Arctic Climate Impacts Assessment (ACIA)*. Cambridge University Press, Cambridge, UK, pp. (pre-release version).

ICES, 2005: *Report of the Northwest Working Group (NWWG) on 26 April – 5 May, 2005, ICES Headquarters, Copenhagen*. International Council for the Exploration of the Sea, Copenhagen, Denmark, 615pp.

Instanes, A., O. Anisimov, L. Brigham, D. Goering, B. Ladanyi, J.O. Larsen, and L.N. Khrustalev, 2005: Chapter 16: Infrastructure: Buildings, Support Systems, and Industrial Facilities. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

Jensen, A.S., 1926: Indberetning av S/S Dana's praktisk videndskabelige fiskeriundersøgelser ved Vestgrønland i 1925. *Beretninger og Kundgørelser vedr. Styrelsen af Grønland*, 2, pp. 291-315.

Jensen, A.S., 1939: Concerning a change of climate during recent decades in the Arctic and Subarctic regions, from Greenland in the west to Eurasia in the east, and contemporary biological and physical changes. *Det. Kgl. Danske Videnskabernes Selskab. Biologiske Medd.*, 14(8), pp. 1-77.

Jernsletten, J.-L., and K. Klokov, 2002: *Sustainable Reindeer Husbandry*. University of Tromsoe, Tromsoe.

Johansson, T., N. Malmer, and T.R. Christensen, Submitted: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing. *XXX*

Johnson, D., C.D. Campbell, D. Gwynn-Jones, J.A. Lee, and T.V. Callaghan, 2002: Arctic soil microorganisms respond more to long-term ozone depletion than to atmospheric CO2. *Nature*, 416, pp. 82-83.

Jones, C.D., and D.C. Ramm, 2004: The commercial harvest of krill in the southwest Atlantic before and during the CCAMLR 2000 Survey. *Deep-Sea Research Part II -Topical Studies in Oceanography*, 51, pp. 1421-1434.

Juday, G.P., V. Barber, P. Duffy, H. Linderholm, S. Rupp, S. Sparrow, E. Vaganov, and J. Yarie, In press: Forests, Land Management and agriculture. In: *Arctic Climate Impact Assessment*. Cambridge University Press

Kaplan, J.O., N.H. Bigelow, I.C. Prentice, S.P. Harrison, P.J. Bartlein, T.R. Christensen, W. Cramer, N.V. Matveyeva, A.D. McGuire, D.F. Murray, V.Y. Razzhivin, B. Smith, D.A. Walker, P.M. Anderson, A.A. Andreev, L.B. Brubaker, M.E. Edwards, and A.V. Lozhkin, 2003: Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections. *Journal of Geophysical Research*, 108(D19), pp. 8171, doi:10.1029/2002JD002559.

Kattsov, V.M., J.E. Walsh, W.L. Chapman, V.A. Govorkova, T.V. Pavlova, and X. Zhang, Submitted: Simulation and projection of Arctic freshwater budget components by the IPCC AR4 global climate models. *Journal of Hydrometeorology*

Kawachi, I., B.P. Kennedy, and R. Glas, 1999: Social capital and self-rated health: A contextual analysis. In: *The society and population health reader: Income, inequality and health.* New Press, New York, pp. 236-248.

Khrustalev, L.N., 2000: On the necessity of accounting for the effect of changing climate in permafrost engineering. In: *Geocryological Hazards*. Kruk Publishers, Moscow

King, J.C., 2003: Antarctic Peninsula climate variability and its causes as revealed by analysis of instrumental records. In: *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives. Antarctic Research Series, 79*. AGU, Washington, DC, pp. 17-30.

Klein, D., 1989: Subsistence hunting. In: *Wildlife production systems: economic utilisation of wild ungulates*. Cambridge University Press, Cambridge, pp. 96-111.

Klein, D., L.M. Baskin, L.S. Bogoslovskaya, K. Danell, A. Gunn, D.B. Irons, G.P. Kofinas, K.M. Kovacs, M. Magomedova, R.H. Meehan, D.E. Russell, and P. Valkenburg, 2005: Chapter 11: Management and conservation of wildlife in a changing Arctic. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

Kofinas, G., G. Osherenko, D. Klein, and B. Forbes, 2000: Research planning in the face of change: the human role in reindeer/caribou systems. *Polar Research*, 19, pp. 3-22.

Korhola, A., S. Sorvari, M. Rautio, P.G. Appleby, J.A. Dearing, Y. Hu, N. Rose, A. Lami, and N.G. Cameron, 2002: A multi-proxy analysis of climate impacts on recent ontogeny of subarctic Lake Sannajärvi in Finnish Lapland. *Journal of Paleolimnology*, 1, pp. 59-77.

Koshida, G., and W. Avis, 1998: *Canada Country Study: Impacts and adaptation climate variability and change. Vol 7: Sectoral Questions.* Environment Canada, Ottawa, ON.

Kovats, R.S., B. Menne, A.J. McMichael, C. Corvalan, and R. Bertollini, 2000: *Climate change and human health: Impact and adaptation.* World Health Organization, Geneva, Switzerland, 48pp.

Krabill, W., W. Abdalati, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel, 2000: Greenland ice sheet: high-elevation balance peripheral thinning. *Science*, 289, pp. 428-430.

Kraemer, L., J. Berner, and C. Furgal, In review: The potential impact of climate change on human exposure to contaminants in the Arctic. *International Journal for Circumpolar Health*

Krupnik, I., and D. Jolly, 2002a: In: *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*. ARCUS, Washington, D.C., pp. 384.

Krupnik, I., and D. Jolly, 2002b: *The Earth is Faster Now: Indigenous observations of Arctic environmental change.* Arctic Research Consortium of the United States, Fairbanks, Alaska., 384pp.

Krupnik, I.a.J., D., 1993: *Arctic Adaptations: Native Whalers and Reindeer Herders of Northern Eurasia.* University Press of New England, xvii+355ppp.

Kuhnlein, H.V., O. Receveur, and H.M. Chan, 2001: Traditional food systems research with Canadian Indigenous Peoples. *International Journal of Circumpolar Health*, 60(2), pp. 112-122.

Kutz, S.J., E.P. Hoberg, J. Nishi, and L. Polley, 2002: Development of the muskox lungworm *Umingmakstrongylus pallikuukensis* (Protostrongylidae), in gastropods in the Arctic. *Canadian Journal of Zoology*, 80, pp. 1977-1985.

Lafortune, V., Furgal, C., Drouin, J., Annanack, T., Einish, N., Etidloie, B., Qiisiq, M., Tookalook, P., and the Communities of Kangiqsujuaq, Umiujaq, Kangiqsualujjuaq and Kawawachikamach, 2004: *Climate Change in Northern Québec: Access to Land and Resource Issues.* Kativik Regional Government, Kuujjuaq, Nunavik.

Langdon, S.J., 1995: increments, ranges and thresholds: human population responses to climate change in northern Alaska. In: *Human ecology and climate change: people and resources in the far north.* Taylor and Francis, Washington, DC, pp. 139-154.

Lantuit, H., and W. Pollard, 2003: Remotely sensed evidence of enhanced erosion during the twentieth century on Herschel Island, Yukon Territory. *Berichte zur Polar- und*

Meeresforschung, 443, pp. 54-59.

Lemke, P., R. Jiawen, R. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R. Thomas, and T. Zhang, In press: Chapter 4: Observations: changes in snow, ice and frozen ground. In: *Science of climate change: Fourth Assessment Report IPCC WG I*. Cambridge University Press, Cambridge

Lesack, L.F.W., P. Marsh, and R.E. Hecky, 1998: Spatial and temporal dynamics of major solute chemistry along Mackenzie Delta lakes. *Limnology and Oceanography*, 43(7), pp. 1530-1543.

Lewis, E.L., J. E.P., P. Lemke, T.D. Prowse, and P. Wadhams, 2000: *The Freshwater Budget of the Arctic Ocean*. Kluwer Academic Publishers, Dordrecht, Netherlands, 623pp.

Lilly, G.R., P.A. Shelton, J. Brattey, N. Cadigan, B.P. Healey, E.F. Murphy, D. Stanbury, and N. Chen, 2003: *An assessment of the cod stock in NAFO Divisions 2J+3KL in February 2003*. Department of Fisheries and Oceans Stock Assessment Secretariat.

Lilly, G.R., P.A. Shelton, J. Brattey, N.G. Cadigan, E.F. Murphy, and D.E. Stansbury, 2000: *An assessment of the cod stock in NAFO division 2J + 3KL*. Fisheries and Oceans Science Canada.

Lindgern, E., and R. Gustafson, 2001: Tick-borne encephalitis in Sweden and climate change. *Lancet*, 358(9275), pp. 16-18.

Lloyd, A.H., T.S. Rupp, C.L. Fastie, and A.M. Starfield, 2003: Patterns and dynamics of treeline advance on the Seward Peninsula, Alaska. *Journal of Geophysical Research*, 107(8161), pp. 8110.

Loeng, H., B. K, E. Carmack, S. Denisenko, K. Drinkwater, B. Hansen, K. Kovacs, P. Livingston, F. McLaughlin, and E. Sakshaug, 2005: Chapter 9: Marine Systems. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

Macdonald, R., T. Harner, J. Fyfe, H. Loeng, and T. Weingartner, 2003: Influence of global change on contaminant pathways to, within and from the Arctic. In: *ANAO Assessment 2002. Arctic Monitoring and Assessment Programme*. Oslo, Norway

Malmer, N., T. Johansson, M. Olsrud, and T.R. Christensen, In press: Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian sub-arctic mire over 30 years. *Global Change Biology*

Marsh, P., and L.F.W. Lesack, 1996: The hydrologic regime of perched lakes in the Mackenzie Delta: Potential responses to climate change. *Limnology and Oceanography*, 41(5), pp. 849-856.

Marsh, P., L.F.W. Lesack, and A. Roberts, 1999: Lake sedimentation in the Mackenzie Delta, NWT. *Hydrological Processes*, 13, pp. 2519-2536.

Marshall, G.J., V. Lagun, and T.A. Lachlan-Cope, 2002: Changes in Antarctic Peninsula tropospheric temperatures: A synthesis of observations and reanalysis data. *Int. J. Climatol.*, 22(3), pp. 291-310.

Marshall, G.J., P.A. Stott, J. Turner, W.M. Connolley, J.C. King, and T.A. Lachlan-Cope, 2004: Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophysical Research Letters*, 31, L14205, pp. doi: 10.1029/2004GL019952.

Martin, D., D. Belanger, P. Gosselin, J. Brazeau, C. Furgal., and S. Dery, 2005: *Climate change, drinking water, and human health in Nunavik: Adaptation Strategies. Final report submitted to the Canadian Climate Change Action Fund, Natural Resources Canada*. CHUL Research Institute, Ste-Foy, Quebec.

McCarthy, J., and M. Long Martello, 2005: Chapter 17: Climate Change in the Context of Multiple Stressors and Resilience. In: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, UK

McClelland, J.W., R.M. Holmes, and B.J. Peterson, 2004: Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *Journal of Geophysical Research*, 109(D18102)

McGuire, A.D., I. Chapin, F. S., C. Wirth, M. Apps, J. Bhatti, T.V. Callaghan, T.R. Christensen, J.S.

Clein, M. Fukuda, T. Maximov, A. Onuchin, A. Shvidenko, and E. Vaganov, In Press: *Responses of high latitude ecosystems to global change: potential consequences for the climate system.*

McGuire, A.D., J.S. Clein, J.M. Melillo, D.W. Kicklighter, R.A. Meier, C.J. Vorosmarty, and M.C. Serreze, 2000: Modeling carbon responses of tundra ecosystems to historical and projected climate: Sensitivity of pan-arctic carbon storage to temporal and spatial variation in climate. *Global Change Biology*, 6 (Suppl. 1), pp. 141-159.

Messner, T., In review: Environmental variables and the risk of disease. *International Journal for Circumpolar Health*, In review

Miller, J.R., and G.L. Russell, 1992: The impact of global warming on river runoff. *Journal of Geophysical Research*, 97, pp. 2757-2764.

Miller, J.R., and G.L. Russell, 2000: Projected impact of climate change on the freshwater and salt budgets of the Arctic Ocean by a global climate model. *Geophysical Research Letters*, 27, pp. 1183-1186.

Mokhov, I.I., V.A. Semenov, and V.C. Khone, 2003: Estimates of possible regional hydrologic regime changes in the 21st century based on global climate models. *Izvestiya, Atmospheric and Oceanic Physics*, 39, pp. 130-144.

Murphy, E.J., A. Clarke, C. Symon, and J. Priddle, 1995: Temporal variation in Antarctic sea-ice: analysis of a long term fast ice record from the South Orkney Islands. *Deep.Sea.Res.*, 42, pp. 1045-1062.

Nayha, S., In review: Environmental temperature and mortality. *International Journal of Circumpolar Health*, In review

Nelson, F.E., 2003: (Un)frozen in time. *Science*, 299(5613), pp. 1673-1675.

Nelson, F.E., O.A. Anisimov, and N.I. Shiklomanov, 2001: Subsidence risk from thawing permafrost. *Nature*(410), pp. 889-890.

Nemani, R.R., C.D. Keeling, H. Hashimoto, W.M. Jolly, S.C. Piper, C.J. Tucker, R.B. Myneni, and S.W. Running, 2003: Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 300, pp. 1560-1563.

Nickels, S., C. Furgal, J. Castelden, P. Moss-Davies, M. Buell, B. Armstrong, D. Dillon, and F. R., 2002: Putting the Human Face on Climate Change Through Community Workshops. In: *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*. ARCUS, Washington, DC, pp. 300-344.

Nikiforov, S.L., N.N. Dunaev, S.A. Ogorodov, and A.B. Artemyev, 2003: Chapter 1: Physical geographic characteristics. In: *The Pechora Sea: integrated research*. MOPE, Moscow, Russia, pp. 502 In Russian.

Nilsen, H., E. Utsi, and K.H. Bonaa, 1999: Dietary and nutrient intake of a Saami population living in traditional reindeer herding areas of North Norway: comparisons with a group of Norwegians. *International Journal of Circumpolar Health*, 58, pp. 120-133.

Nuttall, M., 2000a: *The Arctic is changing.* Stefansson Arctic Institute, http:/www.thearctic.ispp.

Nuttall, M., 2000b: Indigenous peoples, self-determination, and the Arctic environment. In: *The Arctic: Environment, People, Policy*. Harwood Academic Publishers, pp. 377-409.

Nuttall, M., F. Berkes, B. Forbes, G. Kofinas, T. Vlassova, and G. Wenzel, 2005: Chapter 12: Hunting, Herding, Fishing and Gathering: Indigenous Peoples and Renewable Resource Use in the Arctic. In: *Arctic Climate Impacts Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

O'Driscoll, R.L., D.C. Schneider, G.A. Rose, and G.R. Lilly, 2000: Potential contact statistics for measuring scale-dependent spatial pattern and association: an example of northern cod (Gadus morhua) and capelin (Mallotus villosus). *Canadian Journal of Fisheries and Aquatic Sciences*, 57, pp. 1355-1368.

Oechel, W.C., G.L. Vourlitis, S.J. Hastings, R.C. Zulueta, L. Hinzman, and D. Kane, 2000:

Acclimation of ecosystem CO2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature*, 406, pp. 978-981.

Ogorodov, S.A., 2003: Coastal dynamics in the Pechora Sea under technogenic impact. *Berichte zur Polar- und Meeresforschung*, 443, pp. 74-80.

Paine, R., 1994: *Herds of the Tundra: a portrait of Saami reindeer pastoralism.* Smithsonian Institution Press, Washington.

Parkinson, A., Butler, J., In review: Impact of climate change on infectious diseases in the Arctic. *International Journal for Circumpolar Health*

Parkinson, C.L., 2002: Trends in the length of the Southern Ocean sea ice season, 1979-1999. *Ann. Glaciol.*, 34, pp. 435-440.

Paterson, A.M., A.A. Betts-Piper, J.P. Smol, and B.A. Zeeb, 2003: Diatom and chrysophyte algal response to long-term PCB contamination from a point-source in northern Labrador, Canada. *Water, Air and Soil Pollution*, 145, pp. 377-393.

Pavlov, A.V., and N.G. Moskalenko, 2002: The thermal regime of soils in the north of Western Siberia. *Permafrost Periglacial Process.*, 13(1), pp. 43-51.

Pavlov, P., J.I. Svendsen, and S. Indrelid, 2001: Human presence in the European Arctic nearly 40,000 years ago. *Nature*, 413, pp. 64-67.

Payne, A.J., A. Vieli, A. Shepherd, D.J. Wingham, and E. Rignot, 2004: Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters*, 31(L23401), pp. doi:10.1029/204GL021284.

Peck, L.S., 2005: Prospects for surviving climate change in Antarctic aquatic species. *Frontiers of Zoology*, 2(9), pp. doi 10.1186/1742-9994-2-9.

Peters, D.L., T.D. Prowse, A. Pietroniro, and R. Leconte, In press: Establishing the flood hydrology of the Peace-Athabasca delta, Northern Canada. *Hydrological Processes*

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vorosmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov, and S. Rahmstorf, 2002: Increasing river discharge to the Arctic Ocean. *Science*, 298, pp. 2172-2173.

Polyakov, I.V., G.V. Alekseev, R.V. Bekryaev, U. Bhatt, R.L. Colony, M.A. Johnson, V.P. Karklin, A.P. Makshtas, D. Walsh, and A.V. Yulin, 2002: Observationally based assessment of polar amplification of global warming. *Geophysical Research Letters*, 29(18), pp. art. no.-1878.

Pritchard, H., and D.G. Vaughan, in prep: Acceleration of glaciers on the Antarctic Peninsula as a result of climate warming.

Prowse, T.D., 2001: River-ice ecology: Part B) Biological aspects. *Journal of Cold Regions Engineering5*, 15, pp. 17-33.

Prowse, T.D., and S. Beltaos, 2002: Climatic control of river-ice hydrology: a review. *Hydrological Processes*, 16, pp. 805-822.

Prowse, T.D., and B.R. Bonsal, 2004: Historical trends in river-ice break-up: A review. *Nordic Hydrology*, 35(4), pp. 281-293.

Prowse, T.D., and J.M. Culp, 2003: Ice breakup: a neglected factor in river ecology. *Canadian Journal of Civil Engineering*, 30, pp. 128-144.

Prowse, T.D., D.L. Peters, S. Beltaos, A. Pietroniro, L. Romolo, J. Töyrä, and R. Leconte, 2002: Restoring ice-jam floodwater to a drying delta ecosystem. *Water International*, 27(1), pp. 58-69.

Prowse, T.D., F.J. Wrona, and G. Power, 2004: Threats to Water Availability in Canada. *NWRI Scientific Assessment Report No. 3.*, pp. 9-18.

Prowse, T.D., F.J. Wrona, J. Reist, and L. Levesque, in prep.: General features of the Arctic relevant to freshwater ecosystems. *Hydrobiologia (special issue from ACIA Scientific Report)*

Pudsey, C.J., and J. Evans, 2001: First survey of Antarctic sub-ice shelf sediments reveals mid-Holocene ice shelf retreat. *Geology*, 29(9), pp. 787-790.

Quayle, W.C., L.S. Peck, H. Peat, J.C. Ellis-Evans, and P.R. Harrigan, 2002: Extreme responses to climate change in Antarctic lakes. *Science*, 295(5555), pp. 645-645.

Rachold, V., M.N. Grigoriev, F.E. Aré, S. Solomon, E. Reimnitz, H. Kassens, and M. Antonov, 2000: Coastal erosion vs. riverine sediment discharge in the Arctic shelf seas. *Geologisches Rundschau (International Journal of Earth Sciences)*, 89, pp. 450-460.

Raisanen, J., 2001: CO2-induced climate change in CMIP2 experiments: Quantification of agreement and role of internal variability. *Journal of Climate*, 14(9), pp. 2088-2104.

Rasumov, S.O., 2001: Thermoerosion modelling of ice-rich Arctic coast in stationary climatic conditions. *Kriosfera Zemli*, 5(4), pp. 50-58 (in Russian).

Reist, J., J.B. King, R., M. Power, and J.B. Dempson, in prep-a: Potential effects of climate change on arctic anadromous fisheries. *Hydrobiologia*

Reist, J., M. Power, J.B. Dempson, J. King, R. Beamish, H. Lehtonen, and R. Tallman, in prep-b: Potential effects of climate change on arctic freshwater fisheries. *Hydrobiologia*

Reist, J.D., M. Power, J.B. Dempson, R. Beamish, J. King, F.J. Wrona, and T.D. Prowse, in prep-c: General effects of climate change on arctic fishes and fish populations. *Hydrobiologia*

Richardson, A.J., and D.S. Schoeman, 2004: Climate impact on ecosystems in the northeast Atlantic. *Science*, 305, pp. 1609-1612.

Riebesell, U., I. Zondervan, B. Rost, P.D. Tortell, R.E. Zeebe, and M. F.M.M., 2000: Reduced calcification of marine plankton in response to increased atmospheric CO2. *Nature*, 407, pp. 364-367.

Riedlinger, D., 2001a: *Community-based assessments of change: Contributions of Inuvialuit knowledge to understanding climate change in the Canadian Arctic*. Masters, University of Manitoba, Manitoba, Canada.

Riedlinger, D., and Berkes, F., 2001b: Contributions of traditional knowledge to understanding climate change in the Canadian Arctic. *Polar Record*, 37(203), pp. 315-328.

Rignot, E., G. Casassa, S. Gogineni, P. Kanagaratnam, W. Krabill, H. Pritchard, A. Rivera, R. Thomas, and D. Vaughan, 2005: Recent ice loss from the Fleming and other glaciers,Wordie Bay, West Antarctic Peninsula. *Geophysical Research Letters*, 32(L07502), pp. doi:10.1029/2004GL021947.

Robinson, S.A., J. Wasley, and T. A., 2003: Living on the edge - plants and global change in continental and maritime Antarctica. *Global Change Biology*, 9, pp. 1681-1717.

Romanovsky, V.E., M. Burgess, S. Smith, K.Yoshikawa, and J. Brown, 2002: Permafrost temperature records: Indicators of climate change. *EOS,Transactions, American Geophysical Union*, 83, pp. 589-594.

Rose, G.A., 2004: Reconciling overfishing and climate change with stock dynamics of Atlantic cod (Gadus morhua) over 500 years. *Canadian Journal of Fisheries and Aquatic Sciences*, 61, pp. 1553-1557.

Rose, G.A., B. de Young, D.W. Kulka, S.V. Goddard, and G.L. Fletcher, 2000: Distribution shifts and overfishing the northern cod (Gadus morhua): a view from the ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, 57, pp. 644-664.

Rose, G.A., and D.W. Kulka, 1999: Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (Gadus morhua) declined. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(1), pp. 118-127.

Rose, G.A., and R.L. O'Driscoll, 2002: Capelin are good for cod: can Newfoundland cod stocks recover without capelin? *ICES Journal of Marine Science*, 5938, pp. 1026.

Roura, R., 2004: Monitoring and remediation of hydrocarbon contamination at the former site of Greenpeace's World Park Base, Cape Evans, Ross Island, Antarctica. *Polar Research*, 40(212), pp. 51-67.

Royal Society, 2005: *Ocean acidification due to increasing atmospheric carbon dioxide.* The Royal Society, London, UK, 60pp.

Ruhland, K.M., A. Priesnitz, and J.P. Smol, 2003: Paleolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian Arctic treeline. *Arct. Antarct. Alp. Res.*, 35, pp. 110-123.

Ruhland, K.M., and J.P. Smol, 2002: Freshwater diatoms from the Canadian arctic treeline and development of Paleolimnological inference models. *Journal of Phycology*, 38, pp. 429-264.

Russell, D.E., G. Kofinas, and B. Griffith, 2002: *Barren-ground caribou calving ground workshop.* Canadian Wildlife Services, Ottawa.

Sakshaug, E., 2003: Primary and secondary production in Arctic Seas. In: *The Organic Carbon Cycle in the Arctic Ocean*. Springer, Berlin, pp. 57-81.

Sarmiento, J.L., T.M.C. Hughes, R.J. Stouffer, and S. Manabe, 1998: Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature*, 393(6682), pp. 245-249.

Scambos, T.A., J.A. Bohlander, C.A. Shuman, and P. Skvarca, 2004: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. *Geophysical Research Letters*, 31(18), pp. L18402.

Seebacher, F., W. Davison, C.J. Lowe, and C.E. Franklin, 2005: The falsification of the thermal specialization paradigm: compensation for elevated temperatures in Antarctic fishes. *Bio. Lett.*, 1, pp. 151-154.

Serreze, M.C., D.H. Bromwich, M.P. Clark, A.J. Etringer, T. Zhang, and R. Lammers, 2003: Large-scale hydro-climatology of the terrestrial Arctic drainage system. *Journal of Geophysical Research*, 108(D2)

Shepherd, A., D.J. Wingham, and E. Rignot, 2004: Warm ocean is eroding West Antarctic Ice Sheet. *Geophysical Research Letters*, 31(L23402), pp. doi:10.1029\2004GL021106.

Shiklomanov, A.I., 1994: Influence of anthropogenic changes in global climate on the Yenisey River runoff. *Meterology and Hydrology*, 2, pp. 84-93 (in Russian).

Shiklomanov, I.A., A.I. Shiklomanov, R.B. Lammers, B.J. Peterson, and C.J. Vorosmarty, 2000: The dynamics of river water inflow to the Arctic Ocean. In: *The Freshwater Budget of the Arctic Ocean*. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 281-296.

Sigurdsson, O., 2002: Glacier variations 1930-1960, 1960-1990 and 1999-2000. *Jokull*, 51, pp. 79-86.

Sirotenko, O.D., H.V. Abashina, and V.N. Pavlova, 1997: Sensitivity of the Russian agriculture to changes in climate, CO2 and tropospheric ozone concentrations and soil fertility. *Clim. Change*, 36(1-2), pp. 217-232.

Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J.O. Kaplan, S. Levis, W. Lucht, M.T. Sykes, K. Thonicke, and S. Venevsky, 2003: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, 9, pp. 161-185.

Slayback, D.A., J.E. Pinzon, S.O. Los, and C.J. Tucker, 2003: Northern hemisphere photosynthetic trends 1982-99. *Global Change Biology*, 9(1), pp. 1-15.

Smith, L.C., G.M. MacDonald, A.A. Velichko, D.W. Beilman, O.K. Borisova, D.E. Frey, K.V. Kremenetski, and Y. Sheng, 2004a: Siberian peatlands a net carbon sink and global methan source since the early Holocene. *Science*, 303, pp. 353-356.

Smith, L.C., Y. Sheng, G.M. MacDonald, and L.D. Hinzman, 2005: Disappearing Arctic Lakes. *Science*, 308, pp. 1429.

Smith, N.V., S.S. Saatchi, and J.T. Randerson, 2004b: Trends in high northern latitude soil freeze and thaw cycles from 1988 to 2002. *Journal of Geophysical Research*, 109, pp. D12101.

Smith, O.P., 2002: Coastal erosion in Alaska. *Berichte zur Polar- und Meeresforschung*, 413, pp. 65-68.

Smith, R.C., W.R. Fraser, S.E. Stammerjohn, and M. Vernet, 2003: Palmer long-term ecological research on the Antarctic marine ecosystem. In: *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives. Antarctic Research Series, 79*. AGU, Washington, DC, pp. 131-144.

Snape, I., M.J. Riddle, D.M. Filler, and P.J. Williams, 2003: Contaminants in freezing ground and associated ecosystems: key issues at the beginning of the new millenium. *Polar Record*, 39(211), pp. 291-300.

Solomon, S.M., 2005: Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, northwest territories, Canada. *Geomarine Letters*, 25, pp. 127-137.

Stieglitz, M., S.J. Dery, V.E. Romanovsky, and T.E. Osterkamp, 2003: The role of snow cover in the warming of arctic permafrost. *Geophysical Research Letters*, 30(13), pp. art. no.-1721.

Stone, J.O., G.A. Balco, D.E. Sugden, M.W. Caffee, L.C. Sass III, S.G. Cowdery, and C. Siddoway, 2003: Holocene deglaciation of Marie Byrd Land, West Antarctica. *Science*, 299, pp. 99-102.

Strathdee, A.T., J.S. Bale, W.C. Block, S.J. Coulson, I.D. Hodkinson, and N. Webb, 1993: Effects of temperature on a field population of Acyrthosiphon svalbardicum (Hemiptera: Aphidae) on Spitsbergen. *Oecologia*, 96, pp. 457-465.

Stroud, D.A., N.C. Davidson, R. West, D.A. Scott, L. Haanstra, O. Thorup, B. Ganter, S. Delany, and o.b.o.t.I.W.S. Group), 2004: Status of migratory Wader population in Africa and Western Eurasia in the 1990's.

Sturm, M., C. Racine, and K. Tape, 2001: Increasing shrub abundance in the Arctic. *Nature*, 411, pp. 546-547.

Thomas, G., and P.R. Rowntree, 1992: The boreal forests and climate. *Quarterly Journal of the Royal Meteorological Society*, 118, pp. 469-497.

Thompson, D.W.J., and S. Solomon, 2002: Interpretation of recent Southern Hemisphere climate change. *Science*, 296, pp. 895-899.

Thorpe, N., N. Hakongak, S. Eyegetok, and the Kitikmeot Elders, 2001: *Thunder on the Tundra: Inuit Qaujimajatuqangit of the Bathurst Caribou.* Generation Printing, Vancouver.

Tuck, G.N., T. Polacheck, J.P. Croxall, and H. Weimerskirch, 2001: Modelling the impact of fishery by-catches on albatross populations. *Journal of Applied Ecology*, 38(6), pp. 1182-1196.

Tucker, W.B., J.W. Weatherly, D.T. Eppler, L.D. Farmer, and D.L. Bentley, 2001: Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s. *Geophysical Research Letters*, 28(14), pp. 2851-2854.

Turchin, P., and G.O. Batzli, 2001: Availability of food and population dynamics of arvicoline rodents. *Ecology*, 82, pp. 1521-1534.

Turner, J., S.R. Colwell, G.J. Marshall, T.A. Lachlan-Cope, A.M. Carleton, P.D. Jones, V. Lagun, P.A. Reid, and S. Iagovkina, 2005: Antarctic climate change during the last 50 years. *Int. J. Climatol.*, 25(3), pp. 279-294.

Tutubalina, O.V., and W.G. Rees, 2001: Vegetation degradation in a permafrost region as seen from space: Noril'sk (1961-1999). *Cold Regions Science and Technology*, 32(2-3), pp. 191-203.

U.S. Arctic Research Commission Permafrost Task Force, 2003: *Permafrost, and Impacts on Civil Infrastructure.* Arctic Research Commission, Arlington, VA, 62 + vipp.

United States Environmental Protection Agency, 1997: *Need for American Indian and Alaska Native Water Systems*, www.epa.gov/docs/ogwdw000/needs/97tribal.pdf.

Usher, M.B., and *e. al.*, 2005: Principles of conserving the Arctic's Biodiversity. In: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge

van den Broeke, M., and N.P.M. van Lipzig, 2003: Response of wintertime antarctic temperatures to the Antarctic Oscillation: results from a regional climate model. In: *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives. Antarctic Research Series, 79*. AGU, Washington, DC, pp. 43-58.

Van Wijk, M.T., K.E. Clemmensen, G.R. Shaver, M. Williams, T.V. Callaghan, F.S. Chapin III, J.H.C. Cornelissen, L. Gough, S.E. Hobbie, S. Jonasson, J.A. Lee, A. Michelsen, M.C. Press, S.J. Richardson, and H. Rueth, 2003: Long term ecosystem level experiments at Toolik Lake, Alaska and at Abisko, Northern Sweden: generalisations and differences in ecosystem and plant type responses to global change. *Global Change Biology*, 10, pp. 105-123.

Vandenberghe, J., 2001: A typology of Pleistocene cold-based rivers. *Quaternary International*, 79, pp. 111-121.

Vandenberghe, J., 2002: The relation between climate and river processes, landforms and deposits during the Quaternary. *Quaternary International*, 91, pp. 17-23.

Vandenberghe, J., and M. Huisink, 2003: High-latitude fluvial morphology: the example of the Usa river, northern Russia. In: *Paleohydrology: understanding global change*. Wiley, Chichester, pp. 49-58.

Vasilieva, I., 2004: *Climate, thawing permafrost, and buildings in the Northern lands*. *Expert - Siberia.* Yakutsk, pp. 2nd October 2004.

Vaughan, D.G., in press: Recent trends in melting conditions on the Antarctic Peninsula and their implications for ice-sheet mass balance. *Arct. Antarct. Alp. Res.*

Vaughan, D.G., G.J. Marshall, W.M. Connolley, C.L. Parkinson, R. Mulvaney, D.A. Hodgson, J.C. King, C.J. Pudsey, and J. Turner, 2003: Recent rapid regional climate warming on the Antarctic Peninsula. *Clim. Change*, 60, pp. 243-274.

Vilhjálmsson, H., 1997: Climatic variations and some examples of their effects on the marine ecology of Icelandic and Greenland waters, in particular during the present century. *Rit Fiskideildar*, 15(1), pp. 7-29.

Vilhjálmsson, H., A. Håkon Hoel, S. Agnarsson, R. Arnason, J.E. Carscadden, A. Eide, D. Fluharty, G. Hønneland, G. Hvingel, J. Jakobsson, G. Lilly, O. Nakken, V. Radchenko, S. Ramstad, W. Schrank, N. Vestergaard, and T. Wilderbuer, 2005: Chapter 13: Fisheries and Aquaculture. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

Wadhams, P., and N.R. Davis, 2000: Further evidence of ice thinning in the Arctic Ocean. *Geophysical Research Letters*, 27(24), pp. 3973-3975.

Walker, M., H. Wahren, L. Ahlquist, J. Alatolo, S. Bret-Harte, M. Calef, T.V. Callaghan, A. Carroll, C. Copass, H. Epstein, G. Henry, R. Hollister, I.S. Jonsdottír, J. Klein, B. Magnusson, U. Molau, S. Oberbauer, S. Rewa, C. Robinson, G. Shaver, K. Suding, A. Tolvanen, Ø. Totland, P.L. Turner, C. Tweedie, P. Webber, and P.A. Wookey, In Press: Tundra Plant Community Response to Experimental Warming: Sensitivity in a Rapidly Changing Environment. *Proceedings of the National Academy of Sciences*

Walsh, J.E., O. Anisimov, J.O.M. Hagen, T. Jakobsson, J. Oerlemans, T.D. Prowse, V. Romanovsky, N. Savelieva, M. Serreze, I. Shiklomanov, and S. Solomon, 2005: Chapter 6: Cryosphere and Hydrology. In: *Arctic Climate Impacts Assessment, ACIA*. Cambridge University Press, Cambridge, UK, pp. (pre-release version).

Walsh, J.J., D.A. Dieterle, and J. Lenes, 2001: A numerical analysis of carbon dynamics of the Southern Ocean phytoplankton community: the roles of light and grazing in effecting both sequestration of atmospheric CO2 and food availability to larval krill. *Deep-Sea Res. Part I-Oceanogr. Res. Pap.*, 48(1), pp. 1-48.

Walters, C., and J.-J. Maguire, 1996: Lessons for stock assessment from the northern cod collapse. *Reviews in Fish Biology*, 6, pp. 125-137.

Warren, J., Berner, J., Curtis, J., In press: Climate change and human health: infrastructure impacts to small remote communities in the North. *International Journal of Circumpolar Health*

Watt-Cloutier, S., 2004: *Presentation to the Senate Committee on Commerce, Science and Transportation. September 15, 2004* Inuit Circumpolar Conference, Washington, DC.

Weatherhead, B., A. Tanskanen, A. Stevermer, S.B. Andersen, A. Arola, J. Austin, G. Bernhard, H. Browman, V. Fioletov, V. Grewe, J. Herman, W. Josefsson, A. Kylling, E. Kyrö, A. Lindfors, D. Shindell, P. Taalas, and T. D., 2005: Chapter 5: Ozone and Ultraviolet Radiation. In: *Arctic Climate Impact Assessment, ACIA*. Cambridge University Press, Cambridge, pp. (pre-release version).

White, A., M.G.R. Cannel, and A.D. Friend, 2000: The high-latitude terrestrial carbon sink: a model analysis. *Global Change Biology*, 6, pp. 227-245.

World Commission on Dams, 2000: *Introduction to Global Change.* Secretariat of the World Commission on Dams, Cape Town, South Africa.

Wrona, F.J., T.D. Prowse, J. Reist, R. Beamish, J.J. Gibson, J. Hobbie, E. Jeppesen, J. King, G. Koeck, A. Korhola, L. Lévesque, R. Macdonald, M. Power, V. Skvortsov, and W. Vincent, 2005a: Chapter 8: Freshwater ecosystems and Fisheries. In: *Arctic Climate Impact Assessment, ACIA.* Cambridge University Press, Cambridge, UK, pp. (pre-release version).

Wrona, F.J., T.D. Prowse, J.D. Reist, L. Levesque, J. Hobbie, and W. Vincent, 2005b: Impacts of climate variability/change on hydro-ecology of arctic lotic ecosystems. *Hydrobiologia*

Yang, D., B. Ye and A. Shiklomanov,, 2004: Discharge characteristics and changes over the Ob River watershed in Siberia. *Journal of Hydrometeorology*, 5, pp. 595-610.

Yang, D., D.L. Kane, L.D. Hinzman, X. Zhang, T. Zhang, and H. Ye, 2002: Siberian Lena River hydrologic regime and recent change. *Journal of Geophysical Research*, 107(D3)

Yang, D., B. Ye, and D.L. Kane, 2004: Streamflow changes over Siberian Yenisei River basin. *Journal of Hydrology*, 296, pp. 59-80.

Yoccoz, N.G., and R.A. Ims, 1999: Demography of small mammals in cold regions: The importance of environmental variability. *Ecological Bulletins*, 47, pp. 137-144.

Yu, Y., G.A. Maykut, and D.A. Rothrock, 2004: Changes in the thickness distribution of Arctic sea ice between 1958-1970 and 1993-1997. *J. Geophys. Res.-Oceans*, 109(C8), pp. art. no.-C08004.

Zernova, L., 2003: *Has the frost cancelled the predicted global warming? The City.* St. Petersburg, Russia, pp. 14-15.

Zhang, X., and J.E. Walsh, Submitted: Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations. *Journal of Climate*

Zwally, H.J., J.C. Comiso, C.L. Parkinson, D.J. Cavalieri, and P. Gloersen, 2002: Variability of Antarctic sea ice 1979-1998. *J. Geophys. Res.-Oceans*, 107(C5), pp. art. no.-3041.