IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review

Chapter 15: Polar Regions

Coordinating Lead Authors
Oleg A. Anisimov (Russia), 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), James D. Reist (Canada), Torben R. Christensen (Sweden), Mark Nuttall (Canada / UK), Donald Forbes (Canada), James Berner (USA)

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

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Executive summary

Many climate-induced changes that were anticipated in the Third Assessment Report (Anisimov *et al.*, 2001) have now been documented. This validation, together with improved models, new data and increasing use of indigenous and local knowledge, has increased our confidence in projecting future changes in the polar regions. Model projections 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 the impacts forecast for many other regions. Awareness of this has already led to the preparation of a uniquely detailed assessment of the impacts of climate change in the Arctic (ACIA, 2005), however, the complexity of response in biological and human systems, and the fact that these systems are subject to additive multiple stressors, means that future impacts remain difficult to predict. Changes on the Antarctic Peninsula and sub-Antarctic islands have also been rapid and similar dramatic impacts are expected. Evidence of ongoing change from the rest of the Antarctic continent is, however, less conclusive and here prediction of the future change and its impacts is difficult. For both polar regions, economic impacts are especially difficult to address due to the dearth of available information.

Key findings:

- Substantial environmental impacts of climate change show profound regional differences both within and between the polar regions [very high confidence]. However, areas in both the Arctic and Antarctic regions have shown the most rapid rates of warming in recent years and continue to be extremely vulnerable to climate change [very high confidence]. The impacts of future climate change in the polar regions will produce feedbacks that in the next hundred years will have globally significant consequences [medium to high Confidence].
- There is a documented increase in the overall greenness of the Arctic, an increase in biological productivity, a change in species ranges (e.g., shifts from tundra to shrublands), some changes in position of the tree-line, and changes in the ranges and abundance of some animal species [high confidence]. Results from models and experiments indicate that such changes in biodiversity and vegetation zone relocation will continue [high Confidence].
- There has been a measured change in composition and range of plants and animals on and around the Antarctic Peninsula and sub-Antarctic islands as a response to climate change (especially, increasing temperature and changing precipitation) [very high confidence]. Such climate changes are likely to continue and to produce increasingly complex responses, as the disturbance to ecosystems increases [high Confidence].
- The combined discharge of Eurasian rivers draining into the Arctic Ocean shows an increase since the 1930s largely consistent with increased precipitation although changes to cryospheric processes (snowmelt and permafrost thaw) are also modifying routing and seasonality of flow [very high confidence]. The continuation of hydrologic and cryospheric changes will have significant regional impacts on freshwater, riparian and near-shore marine systems [high confidence].
- The retreat of Arctic sea ice over recent decades (reaching new summer minima since the TAR) has led to improved marine access, increased coastal wave action, changes in coastal ecology/biological production, together with adverse effects on many ice-dependent marine mammals [high confidence]. Continued loss of sea ice will have human costs and benefits and create issues of national sovereignty [high confidence].
- Reductions in freshwater ice will affect lake/river ecology and biological production, and will require changes in waterborne transportation [high confidence]. For many stakeholders, economic benefits may accrue, but some activities and livelihoods may be adversely affected [high confidence].
- Ice volume continues to decrease in the glaciers of the Arctic and sub-Arctic, as do parts of the

ice sheets of Antarctica and Greenland [very high confidence]. Beyond the impact on global sea level, a continued loss of glaciers will have local impacts, such as increased iceberg hazards and hydropower potential, and newly exposed ice-free ground [high confidence].

- Although earlier claims of a substantial mid-20th Century reduction of sea-ice extent around Antarctica are now questioned, a newly documented decline in krill abundance, together with an increase in salp (a pelagic tunicate) abundance, are due to recent regional reductions in the extent of Antarctic sea ice. Any further decline in krill will adversely impact higher predators [high confidence].
- Continued warming of the northern polar oceans is likely to further impact community composition and the biomass of phytoplankton, sea-ice algae and zooplankton [high confidence]. Evidence also exists of emergence of southern species where Arctic Species used to exist (e.g., Arctic Cod being replaced by Capelin in Hudson Bay). The impact of climate change on higher predators and fisheries will be regionally specific, some beneficial and some detrimental [high confidence].
- Changes in the frequency, type and timing of precipitation will increase contaminant capture in the Arctic. Combined with changes in the timing and rate of melt/thaw of snow-cover, floating ice and permafrost, these will increase contaminant loading to freshwater systems [medium confidence]. Increased loadings will more than offset the reductions expected in global emissions of contaminants [medium confidence].
- In both the Arctic and Antarctic, the pole-ward 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 [high confidence]. In the Arctic, current levels of biodiversity imply specific vulnerabilities and animal-transmitted diseases are moving north [high confidence].
- Many Arctic human communities are already being required to adapt to climate change, and the resilience that Indigenous Peoples have exhibited to environmental change for thousands of years is now being tested [high confidence]. Communities need to adapt to climate changes in their local environment, through such things as changes in resource and wildlife management regimes, and shifts in personal activities (e.g., hunting) [high confidence]. In addition to climate change, multiple stressors, together with external and internal social, cultural, economic and political forces challenge this adaptive ability [high confidence].
- Across the Arctic, shifts in vegetation, changes in abundance of wetlands and wetting/drying of soils are occurring [high confidence]. If these changes continue, they will have major impacts on surface albedo and the exchange of greenhouse gases [very high confidence]. Recent models predict a decrease in albedo due to changing vegetation and that the tundra will be a small sink for carbon [low confidence], however, increased methane emissions mean that overall the tundra contributes to climate warming [medium Confidence].
- Warming and thawing of permafrost will have a detrimental impact on many Arctic structures, including critical community infrastructure [very high confidence]. Substantial investments will be needed to adapt or relocate communities and structures in response to these changes [high confidence].
- A less severe climate in the Arctic will produce economic benefits for some stakeholders [Medium confidence]. The benefits will depend on particular local conditions, but in places will include reduced heating costs, increasing agricultural and forestry opportunities, more navigable northern sea routes and marine access to resources [medium confidence].

15.1 Summary of Knowledge Assessed in the TAR

This chapter builds on the IPCC Working Group, Third Assessment Report (in particular, Chapter 16; Anisimov *et al.*, 2001). That report summarised the climatic changes that have been observed in the polar regions over the 20th Century (See Fig. 15.1, for overview and place names used in this chapter), the impacts those changes had on the environment, and the likely impact of projected climate change in the future. Except where stated, the following summarises the key findings of that assessment to which "very-high confidence" or "high confidence" was attached.

Climatic change in the 20th Century was different in the Arctic and Antarctic and led to different environmental impacts:

- In the Arctic, extensive land areas showed a warming trend in air temperature of up to 5°C, and there was a slight warming over sea ice. Arctic sea ice had thinned and its extent decreased. Atlantic water flowing into Arctic Ocean had warmed, and the mixed layer in the Beaufort Sea had become less saline. Regions underlain by permafrost had reduced in extent, and warming of ground had been observed in many areas. There had been a decrease in spring snow extent over Eurasia. Many observations of environmental change in the Arctic showed trends consistent with warming predicted by GCMs.
- There had been a marked warming in the Antarctic Peninsula over the last half-century. [Elsewhere warming was not ubiquitous]. There was no overall change in Antarctic sea ice extent over in the period 1973-1996.

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

- Increased melting of Arctic glaciers and the Greenland ice sheet was expected, while the Antarctic ice sheet was expected to thicken due to increased precipitation. There was considered to be a small risk that the West Antarctic and Greenland ice sheets will retreat in coming centuries. It was considered that cryospheric changes will lead to sea level rise.
- Projected warming was expected to expose more bare ground on the Antarctic Peninsula and cause changes in the cryosphere and terrestrial biology.
- Climate change was expected to produce long-term, perhaps irreversible, changes in the physical environment and ecology of the Southern Ocean.
- There was expected to be a substantial loss of sea ice at both poles.
- Reduction of the area underlain by the near-surface permafrost, and thickening of the seasonally thawed layer above permafrost (active layer) were expected over large areas, leading to altered landscapes over much of the Arctic and sub-Arctic, ultimately with damage to existing human infrastructure.
- The hydrology of the Arctic was considered particularly susceptible to warming, with a shift to a runoff regime with less seasonal variation. A concern that this, and other factors, could result in a weakening of the global thermohaline circulation was given "medium-confidence".
- Warming was expected to increase biological production in the Arctic, but only "medium-confidence" could be attached to the projections about how this would affect particular species.
- It was expected that climate change, when combined with other stresses, will affect human communities in the Arctic, with particularly disruptive impacts on indigenous peoples following traditional lifestyles. For some Arctic communities economic costs and benefits were expected to result from climate change.

Climate change will affect key polar drivers of further climate change:

- Warming was expected to 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.

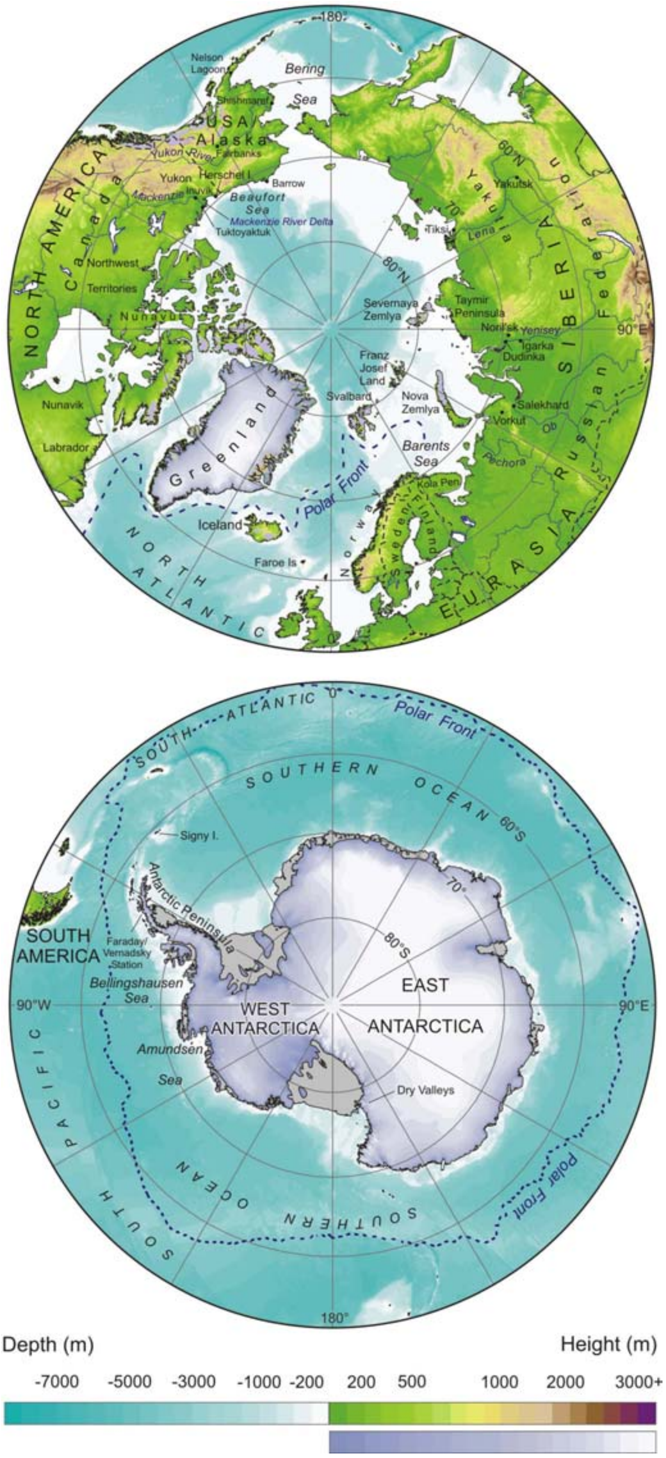

***Figure 15.1**: Location maps of the North and South Polar regions including place names used in the text. The topography of glaciated and non-glaciated terrain are shown using different shading schemes. The Polar Fronts shown are intended to give an approximate location for the extent of cold polar waters, but are in places, open to interpretation and potential fluctuations. (This and other maps drawn by Peter Fretwell, British Antarctic Survey).*

- It was suggested with "medium-confidence" that the oceanic thermohaline circulation could slow down because of increased runoff from Arctic rivers, greater increases in precipitation than evaporation, greater glacial melt and changes in the seasonal formation and melt of sea ice.
- It was suggested with "medium-confidence" that climate change will increase the contribution of

Arctic tundra to greenhouse gases, at least initially, and that the Southern Ocean's uptake of CO_2 emissions would decline.

15.2 Current sensitivity/vulnerability

15.2.1 Climate, environment and socio-economic state

Arctic

For several decades, surface air temperatures in the Arctic have warmed at approximately twice the global rate (McBean *et al.*, 2005). The areally-averaged warming north of 60°N has been 1-2°C since a temperature minimum in the 1960s and 1970s. In the marine Arctic, the 20th-Century temperature record is marked by strong low-frequency (multi-decadal) variations (Polyakov *et al.*, 2002). Serreze and Francis (2006) have discussed the attribution of recent changes in terms of natural variability and anthropogenic forcing, concluding that a substantial portion of the recent variability is circulation-driven, and that the Arctic is in the early stages of a manifestation of the greenhouse signature.

The most recent (1980-present) Arctic warming is strongest in spring and winter, and smallest in autumn; it is strongest over interior portions of northern Asia and north-western North America (McBean *et al.*, 2005). The latter regions, together with the Antarctic Peninsula, are the most rapidly warming areas of the globe over the past several decades (Turner *et al.*, Submitted). The North Atlantic sub-polar seas show little warming during the same time period, probably because of their intimate connection with the cold, deep waters. Temperatures in the upper troposphere and stratosphere of the Arctic have cooled in recent decades, consistent with increases of greenhouse gases and with decreases in stratospheric ozone since 1979 (Weatherhead *et al.*, 2005).

Precipitation in the Arctic shows signs of an increase over the past century, although the trends are small (about 1% per decade), highly variable in space, and highly uncertain because of deficiencies in the precipitation network (McBean *et al.*, 2005). There is no evidence of systematic increases of intense storms in the Arctic (Atkinson, 2005) although coastal vulnerability to storms is increasing with the retreat of sea ice (See 15.4.7). Little is known about areally-averaged precipitation over Greenland. The discharge of Eurasian rivers draining into the Arctic Ocean shows an irregular increase since the 1930s (Peterson *et al.*, 2002), generally consistent with changes temperature and the large-scale atmospheric circulation.

Reductions of Arctic sea ice and glaciers (IPCC, In prep-a), 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 recent (1980s-present) warming of permafrost in nearly all areas for which measurements are available (Romanovsky *et al.*, 2002; Walsh *et al.*, 2005) are consistent with the recent changes of Arctic surface air temperatures. Although there is visual evidence of permafrost degradation (IPCC, In prep-a), long-term 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 the Normalised Difference Vegetation Index (NDVI - a measure of photosynthetically active biomass) over much of the Arctic (Slayback *et al.*, 2003). This 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. Broader ecosystem impacts of climate change in the polar regions and elsewhere are summarized by Walther *et al.* (2002).

Recent analysis of airborne data (Krabill *et al.*, 2004), satellite data (Howat *et al.*, 2005; Luckman *et al.*, 2006; Rignot and Kanagaratnam, 2006) and seismic data (Ekstrom *et al.*, 2006) indicate thinning around the periphery of Greenland ice sheet, where summer melt has increased during the past 20 years (Abdalati and Steffen, 2001; Walsh *et al.*, 2005), while there is evidence of thickening in the interior (Johannessen *et al.*, 2005).

The Arctic is now home to approximately 4 million residents (Bogoyavlenskiy, 2004). Migration into the Arctic during the 20th Century has resulted in a change of demographics such that Indigenous Peoples are now 10% of the entire population. This influx has brought 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 remains generally sparse (Bogoyavlenskiy, 2004), with nomadic peoples still significant in some countries. However, on average, two-thirds of the Arctic population lives in settlements of more than 5 000 people. Indigenous residents have been, in most regions, encouraged to become permanent residents in fixed locations and this has had a predominantly negative effect on subsistence activities and some aspects of community health. At the same time, northern residents have experienced an increase in access to treated water supplies, sewage disposal, health care facilities and services, and improved transportation infrastructure which has increased access to such things as outside market food items (Hild and Stordhal, 2004). In general, the Arctic has a young, rapidly growing population with higher birth rates than their national averages, and rising but lower than national average life-expectancy. This is particularly true for indigenous populations in these regions however some exceptions exist as in the Russian north, where population and life-expectancy has decreased since 1990 (Einarsson, 2004).

Political and administrative regimes in Arctic regions vary between countries. In particular, indigenous groups have different levels of self-determination and autonomy. Some regions (e.g. Nunavut, Canada and Greenland) now have formalized 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 resource management, also vary between regions. Nowadays, large-scale resource extraction initiatives and/or forms of social support play significant roles in the economies of many communities. Despite these changes, aspects of subsistence and pastoral livelihoods remain important.

Regardless of its small number of dispersed inhabitants, the Arctic has become increasingly important in global politics and economies. For example, the deleterious effects on the health of Arctic residents of contaminants produced in other parts of the world has led to finalising of international agreements such as the Stockholm Convention on Persistent Organic Pollutants (Downey and Fenge, 2003).

Antarctic

Direct measurements reveal considerable spatial variability in temperature trends in Antarctica. All meteorological stations on the Antarctic Peninsula show strong and significant warming over the last 50 years (See box, 15.6.3). However, of the other long-term (>30 years) mean annual temperature records available, 12 show warming, while seven show cooling; although 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 continent-wide “polar amplification” in Antarctica. In some areas where cooling has occurred, such as the area around Amundsen-Scott Station at the South Pole, there is no evidence of directly attributable impacts, but elsewhere, cooling has caused clear local impacts. For example, in the Dry Valleys, a 6-9 % reduction in primary production in lakes and a >10 % per year decline in soil invertebrates has been observed (Doran *et al.*, 2002). Although the impacts are less certain, precipitation has also declined on sub-Antarctic islands (Bergstrom and Chown, 1999).

Recent changes in Antarctic sea-ice extent are discussed in detail elsewhere (IPCC, In prep-a), but evidence highlighted in the TAR (Anisimov *et al.*, 2001) gleaned from records of whaling activities (de la Mare, 1997) is no longer considered reliable (Ackley *et al.*, 2003). So for the period before satellite observation only direct local observations (e.g. Murphy *et al.*, 1995) and proxies (e.g. Curran *et al.*, 2003) are available. For the satellite period (1978-present) there has been no ubiquitous trend in Antarctic sea ice duration, but there have been strong regional trends (Fig. 15.3). Sea-ice duration in the Ross Sea has increased, while in the Bellingshausen and Amundsen seas it has decreased, with high statistical significance in each case (Parkinson, 2002; Zwally *et al.*, 2002). This pattern strongly reflects trends in atmospheric temperature at nearby climate stations (Vaughan *et al.*, 2003).

Increasing atmospheric concentrations are leading to an increased uptake of CO_2 by the oceans and as a consequence seawater is becoming more acidic (Royal Society, 2005). 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 Southern Ocean and contribute to the draw-down of atmospheric CO_2 to the deep ocean. Experimental studies (Riebesell *et al.*, 2000) indicate that elevated CO_2 concentration reduce draw-down of CO_2 compared to the production of organic matter. Increasing acidification leads to changes in the chemistry of the oceans which reduce their ability to absorb CO_2 from the atmosphere (Royal Society, 2005).

The community composition 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). Climate models indicate that stratification in the Southern Ocean is likely to increase as a consequence of increased precipitation (Sarmiento *et al.*, 1998). Since the draw-down of CO_2 and the rate of new production, which is actually lower with diatoms than with *Phaeocystis*, the increased stratification would lead to diminished draw-down to the deep ocean (Arrigo *et al.*, 1999).

Fishing and tourism are the only economic activities in the Antarctic at present. Over 20,000 tourists now visit Antarctica each year and the industry is growing. Fishing is, however, the only large-scale exploitation of resources. Since 1982, Antarctic fisheries have been regulated by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). 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 (*Dissostichus eleginoides*) is of concern because it could act alongside climate change to undermine sustainable management of stocks (Bialek, 2003). Furthermore, those fishing illegally often use techniques that cause the death of by-catch species; for example, albatross and petrels are under threat as they are drowned in large numbers following their taking bait being used in long-line fishing (Tuck *et al.*, 2001).

15.2.2 Vulnerability and adaptive capacity

Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of stress; whereas, adaptive capacity, or resilience, is an ability to adjust to stress, to realise opportunities or to cope with consequences (McCarthy, 2005b).

15.2.2.1 Terrestrial and marine ecosystems

Many polar 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 (for example, Callaghan *et al.*, 2005b; Peck *et al.*, 2006). Other species require specific conditions, for example winter snow cover, or a particular timing of food availability, for breeding and feeding (Mehlum, 1999; Peck *et al.*, 2006). Thus many species face multiple, concurrent human-induced stresses (including increased UV-B radiation, increasing contaminant loads, habitat loss and fragmentation), that will add to impacts of climate change (Walther *et al.*, 2002; McCarthy, 2005a).

Plants and animals in the polar regions are vulnerable to attacks from pests (Juday *et al.*, 2005) and parasites (Albon *et al.*, 2002; Kutz *et al.*, 2002) that develop faster and are more prolific in warmer and moister conditions. Many terrestrial polar ecosystems are vulnerable because biodiversity is low in general, and redundancy within trophic levels and some species groups is particularly low (Matveyeva and Y. Chernov, 2000). Loss of a keystone species (e.g., lemmings; Turchin and Batzli, 2001) could have cascading effects.

Arctic. In the Arctic, 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 adaptive capacity of current Arctic ecosystems is small because their extent is likely to be reduced substantially by compression between the general northwards expansion of forest, the current coastline and longer term flooding of northern coastal wetlands as sea level increases, and also as habitat is lost to land use (Fig. 15.2). General vulnerability and lack of adaptive capacity of Arctic species and ecosystems to warming is likely, as in the past, to lead to relocation rather than rapid adaptation (Fig. 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.

The extensive sea-ice cover, high water column and sediment primary production and close pelagic - benthic coupling of the Bering Sea have been found to be changing as air and seawater temperatures increase. A change from Arctic to sub-Arctic conditions is happening with a northward movement of the pelagic-dominated marine ecosystem that was previously confined to the south-eastern Bering Sea. Thus communities consisting of organisms such as bottom- feeding birds and marine mammals are being replaced by communities dominated by pelagic fish. Changes in the ice conditions to brash and thin ice has affected subsistence and commercial harvests (Grebmeier *et al.*, 2006).

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), and yield ~7 M tonnes per year, provide about $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 following traditional lifestyles (Vilhjálmsson *et al.*, 2005).

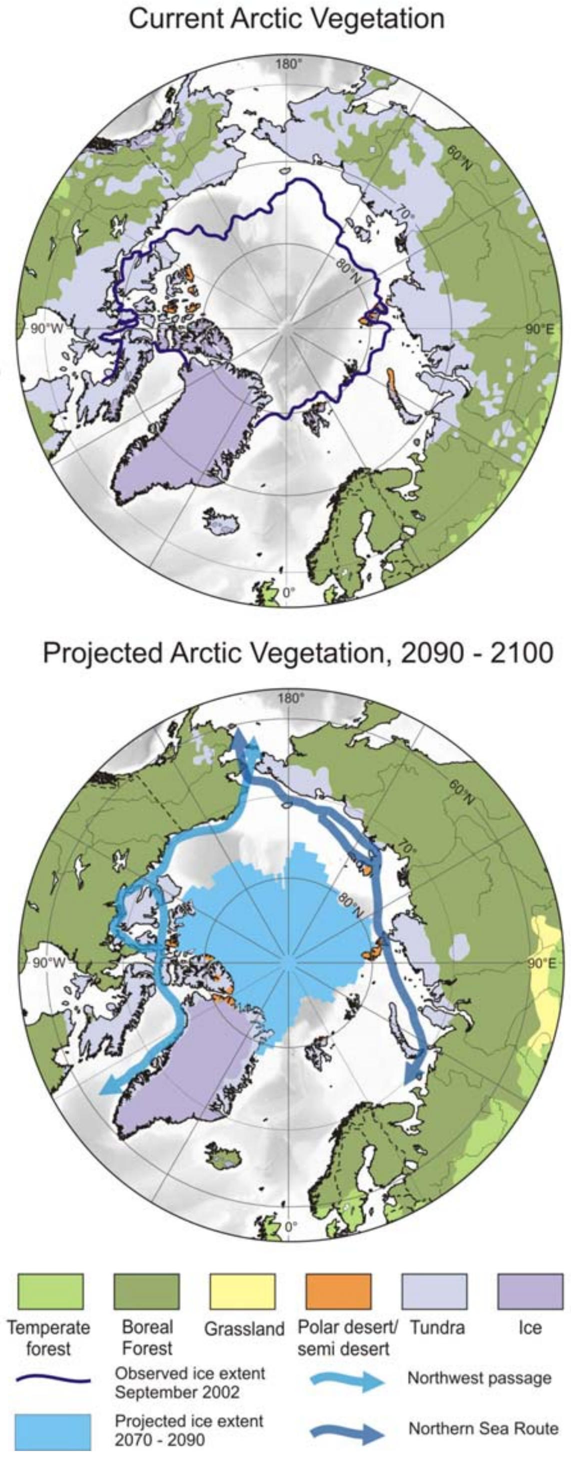

Figure 15.2: *Present and projected vegetation and sea-ice extent for Arctic and neighbouring regions. Vegetation maps based on floristic surveys (top) and projected vegetation for 2090-2100, predicted by the LPJ Dynamic Vegetation Model driven by the HadCM2 climate model (bottom) modified from (Kaplan 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. Also shown observed minimum sea ice extent for and projected sea-ice extent, together with potential new/improved sea routes (redrawn from, Instanes et al., 2005; redrawn from, Walsh et al., 2005).*

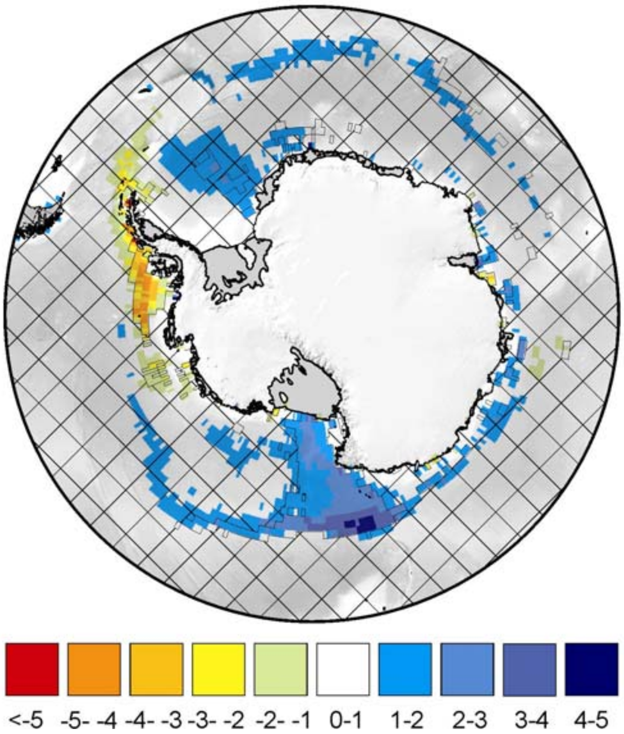

Figure 15.3: *Changes in Antarctic sea-ice duration in days per year, for the period 1978-2004, after Parkinson (Parkinson, 2002). Hatched areas show where trends are not significant at the 95 % level. (Data for figure provided by W.M. Connolley, British Antarctic Survey).*

Recent studies reveal that sea surface warming in the northeast Atlantic is accompanied by increasing abundance of the largest phytoplankton in cooler regions and their decreasing abundance in warmer regions (Richardson and Schoeman, 2004). In addition, the seasonal cycles of activities of marine micro-organisms and invertebrates and differences in the way components of pelagic communities respond to change, are leading to the activities of prey species and their predators becoming out of step. Continued warming is therefore likely to impact on the community composition and the numbers of primary and secondary producers with consequential stresses on higher trophic levels. This will impact economically important species, primarily fish, and dependent predators such as marine mammals and seabirds (Edwards and Richardson, 2004).

Antarctic

Substantial evidence indicates major regional changes in Antarctic terrestrial and marine ecosystems, in areas that have experienced warming. Increasing abundance of shallow water sponges and their predators, declining abundances of krill, Adelie and Emperor penguins and Weddell seals have all been recorded (Ainley *et al.*, 2005). Only two species of native flowering plant, the Antarctic pearlwort (*Colobanthus quitensis*) and the Antarctic hair grass (*Deschampsia antarctica*) currently occur on the Antarctic continent with similar distributions. Their increased abundance and distribution was ascribed to the increasing summer temperatures (Fowbert and Smith, 1994). 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 and water and nutrient availability changes (Robinson *et al.*, 2003).

The marked reduction reported in the biomass of Antarctic krill (*Euphausia superba*) and an increase in the abundance of salps (principally *Salpa thompsoni*), a pelagic tunicate, may be related to regional changes in sea ice conditions (Atkinson *et al.*, 2004). This change may also underlie the late-20th Century changes in the demography of krill predators (marine mammals and seabirds) 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 negative impacts on the local biota such as a decline in the number and size of *Sphagnum* moss beds (Whinam and Copson, 2006). On these islands, increasing human activities and increasing temperatures are combining to promote successful invasions of non-indigenous species (Bergstrom and Chown, 1999).

15.2.2.2 Freshwater systems

Arctic

Climate variability/change has historically had and will continue to have impacts on Arctic freshwater resources. First-order impacts (e.g., changes to the snow/ice/water budget) play a significant role in important global climate processes, through feedbacks (e.g., changes to radiative feedbacks, stability of the oceanic stratification and thermohaline circulation, and carbon/methane source-sink status). Cascading effects have important consequences for the vulnerability of freshwater systems, as measured by their ecological or human resource value.

From an ecological perspective, the degree of vulnerability to many higher order impacts (e.g., changes in aquatic geochemistry, habitat availability/quality, biodiversity) are related to gradual and/or abrupt threshold transitions such as those associated with water-phase changes (e.g., complete loss of ice cover) or coupled bio-chemical responses (e.g., precipitous declines in dissolved oxygen related to lake productivity) (Wrona *et al.*, 2005). Historically, Arctic freshwater ecosystems have responded to large variations in climate over long transitional periods (e.g., Ruhland and Smol, 2002; Ruhland *et al.*, 2003), but in the next century, the combination of high-magnitude events and rapid rates of change will probably exceed the ability of the biota and their associated ecosystems to adapt (Wrona *et al.*, in press-b). This will result in significant changes and both positive and negative impacts. It is projected, however, that overall the negative will very likely outweigh the positive, implying that freshwater systems are highly vulnerable to climate change (Wrona *et al.*, 2005).

From a human-use perspective, potential adaptation measures are extremely diverse, ranging from measures to facilitate modified use of the resource (e.g., changes in ice-road construction practices, altered hydro-electric and drinking-water distribution strategies and shifts in harvesting strategies), to adaptation strategies to deal with increased/decreased freshwater hazards (e.g., protective structures to reduce flood risks or increase floods for aquatic systems (Prowse *et al.*, 2002); changes to more land-based travel to avoid increasingly hazardous ice). Difficulties in pursuing adaptation strategies may be greatest for those who place strong cultural and social importance on traditional uses of freshwater resources (Huntington *et al.*, 2005b; Nuttall *et al.*, 2005).

Antarctic

Antarctic freshwater systems are fewer and smaller than those in the Arctic, but are no less vulnerable to climate change. The microbial communities inhabiting these systems are likely to be modified by changing nutrient regimes, contaminants and introductions of species better able to cope with the changing conditions. A drop in air temperature of 0.7 ºC per decade late in the 20th Century in the Dry Valleys led to a 6 to 9% drop in primary production in the lakes of the area (Doran *et al.*, 2002). In marked contrast, summer air temperature on the maritime sub-Antarctic Signy Island increased by 1 ºC over the last 50 years, and over the period 1980-1995, water temperature in the lakes rose several times faster than the air temperature – this is one of the fastest responses to regional climate change in the southern hemisphere yet documented (Quayle *et al.*, 2002). As a consequence, the annual period open water has extended by up to 4 weeks. In addition, the area of perennial ice cover on Signy Island has decreased by about 45% since 1951, and the associated change in microbial and geochemical processes has lead to increased amounts of organic and inorganic nutrients entering the lakes. Finally, there has been an explosion in the population of fur seals (*Arctocephalus gazella*) on the island due to decreased ice-cover and increased area available for resting and moulting. This increase in seals is leading to dramatic eutrophication of some lakes (Quayle *et al.*, 2003). Primary and bacterial production and the concentration of phytoplankton and bacteria are increasing and changes in the microbial community composition are likely. Similar vulnerabilities are expected to exist in other polar freshwater environments.

15.2.2.3 Permafrost

Permafrost, defined as sub-surface 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, and in the small areas of Antarctica without permanent ice-cover. The physical processes of climate-permafrost interactions and observations of permafrost change are discussed elsewhere (IPCC, In prep-a), here we focus on the observed and projected changes of permafrost, and impacts they may have on natural and human systems in the Arctic.

Observational data are limited, but precise measurements in boreholes indicate that permafrost temperatures in the Arctic increased markedly during the last 50 years (Romanovsky *et al.*, 2002), with rapid warming in Alaska (Hinzman *et al.*, 2005), Canada (Beilman *et al.*, 2001), Europe (Harris *et al.*, 2003), and Siberia (Pavlov and Moskalenko, 2002). Short-term and localized warming associated with the removal of snowcover (Stieglitz *et al.*, 2003) and feedbacks associated with increased vegetation productivity (Sturm *et al.*, 2001; Anisimov and Belolutskaia, 2004; Chapin III *et al.*, 2005b) are, however, important considerations that must be taken into account.

In the context of the future climate change there are two key concerns associated with the thawing of permafrost: the detrimental impact on the infrastructure built upon it, particularly on ice-rich soils, 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 permanent populations, for the most part, the only residents are staff at scientific stations and summer-only visitors. While there are some areas of particular sensitivity, where climate change might require facilities to be abandoned, from a global perspective these can be viewed as logistical issues only to the organisations concerned.

In contrast, the archaeological record shows that humans have existed in the Arctic for thousands of years (Pavlov *et al.*, 2001). Arctic Indigenous Peoples have historically lived with a high degree of environmental variability and the capacity to adapt has been part of their cultures (Balikci, 1968; Langdon, 1995).

Previously, many Arctic peoples practised seasonal movements between settlements, and/or seasonally between activities (e.g., farming to fishing), and the semi-nomadic and nomadic following of game animals and herding. Today, most Arctic residents live in permanent communities, many of which exist in low-lying exposed coastal areas. Despite the socio-economic changes taking place, many Arctic communities retain a strong relationship with the land and sea, with community economies that are a combination of subsistence and cash economies, in some cases strongly associated with mineral, hydrocarbon and resource development (Duhaime, 2004). The vulnerable nature of Arctic communities, and particularly coastal indigenous communities, to climate change arises 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 state of social, cultural, economic and political change taking place in these regions.

Communities are already adapting to local environmental changes (Krupnik and Jolly, 2002b; Nickels *et al.*, 2002) through wildlife management regimes, and changes in individual behaviours (i.e. shifts in times and locations of particular activities) and they retain great capacity to adapt. This is related to flexibility in economic organization, detailed local knowledge and wide ranging skill sets, and the sharing mechanisms and social networks which provide support among individuals and groups in times of need (Berkes and Jolly, 2001). However, for some Arctic peoples, movement into permanent communities' limits adaptive capacity as more sedentary lifestyles minimize mobility and increased participation in wage economy jobs decreased the number of individuals to provide foods from the local environment. 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, resource management regimes, political, legal and conservation interests and globalisation all affect, constrain or reduce the abilities of Arctic communities to adapt to climate change (Nuttall *et al.*, 2005). Trends in modernity within communities also affect adaptive capacity in both positive and negative ways. Increased access to outside markets and new technologies improves the ability to develop resources and a local economic base, however, increased time spent in wage earning employment reduces time on the land observing and developing knowledge of the environment required to adapt. This underscores the reality that climate change is but one of several interrelated problems affecting Arctic communities and livelihoods today (Chapin III *et al.*, 2005a).

In some cases, indigenous peoples may consider adaptation strategies as unacceptable as they impact critical aspects of traditions and cultures. For example, the Inuit Circumpolar Conference has framed the issue of climate change in a submission to the United States Senate as an infringement on human rights because it restricts access to basic human needs as seen by Inuit and will lead to the loss of culture and identity (Watt-Cloutier, 2004). Currently we do not know where these thresholds exist or what the limits are to adaptive capacity for Arctic populations.

15.3 Assumptions about future trends

15.3.1 Key regional impacts with importance to the global system

We expect many regional impacts of climate change in the polar regions, however, climate change in the polar regions may also have global implications through the following processes and feedbacks:

- **Reflectivity of Snow and Ice:** Snow, ice and sea ice, play vital roles in the global climate system, through albedo and insulation effects. For example, warming already seems to be leading to more rapid disappearance of snow and sea ice cover in some areas (e.g., Siberia, Alaska), and the consequent changes of albedo and energy balance may be leading to further climate change (e.g., Holland and Bitz, 2003).
- **Cryospheric retreat, freshwater Runoff, Sea Level, and Ocean Circulation:** Retreat of mountain glaciers in the Arctic and more rapid melting of the edges of the Greenland Ice Sheet (Section 15.2.1), together with observed increases in river runoff (Peterson *et al.*, 2002), the major contributor, will alter the freshwater budget of the Arctic Ocean. Further changes are expected and could influence ocean circulation with global impacts (IPCC, In prep-b).
- **Arctic terrestrial carbon flux:** Although models project that Arctic terrestrial ecosystems and the active layer will be a small sink for carbon within the next century, uncertainty is high. It is

possible that increased emissions of methane and carbon from thawing permafrost will lead to positive climate forcing (Sitch *et al.*, in press)

- **Migrating species:** Species that seasonally migrate from lower latitudes to polar regions, rely on the existence of specific polar habitats, and if those habitats are compromised the effects will be felt in communities and food-webs far beyond the polar regions. These habitats may be compromised by direct or consequential climate change impacts, but also by multiple stressors (e.g., land-use changes, hunting regulations).
- **Methane hydrates:** Significant amounts of methane hydrates are contained in sediments, especially on Arctic continental shelves. As these areas warm, this methane may be released, adding to the greenhouse gas concentration in the atmosphere. 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 carbon flux:** Climate models indicate that stratification of the Southern Ocean will change. This could change the community structure of primary producers and alter rates of draw-down of atmospheric CO_2 and its transport to the deep ocean.

15.3.2 Projected atmospheric changes

The areally-averaged warming is projected to range from about 2°C to about 9°C, depending on the model and forcing scenario. The projected 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, although regions such as the Canadian Archipelago are not well resolved.

In contrast to the unanimity of the models in predicting a north-polar amplification of warming, there are differences among the model projections concerning polar amplification in the Antarctic, especially over the continent (Parkinson, 2004). However, in several simulations, the warming is amplified over a narrow Southern Ocean band from which sea ice retreats.

Global precipitation is projected to increase during the 21st Century by about 10% to about 20% in the A1B scenario of the IPCC AR4 simulations. However, spatial patterns of the precipitation increase in the Arctic vary among the models. Similar results have emerged from the IPCC AR4 simulations (Kattsov *et al.*, in press). In addition, the partitioning among snow and rain will change in a warmer climate, affecting snow loads on structures. The difference between precipitation and evapotranspiration (P-E), which over multiyear timescales is approximately equivalent to runoff (river discharge), is also projected to increase over the course of the 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. Additional information on projected changes is presented elsewhere (IPCC, In prep-c).

15.3.3 Projected changes in the oceans

A new study (Zhang and Walsh, in press) based on the IPCC AR4 model simulations, projected mean reductions of annually averaged sea ice area by 2080-2100 of 31%, 33% and 22% under the A2, A1B and B1 scenarios, respectively (See Fig. 15.2). A consistent model result is that the sea ice loss is greater in summer than in winter, so the multiyear sea-ice coverage decreases by a greater percentage than does first-year ice, which actually increases in many models. The loss of summer sea ice will change the moisture supply to northern coastal regions and will likely impact the calving rates of glaciers that are now surrounded by sea ice for much of the year.

A definite shortcoming exhibited in several models is too little sea ice around Antarctica in the present climate, even during winter (Parkinson *et al.*, Submitted). Predictions for 21st-Century range from complete loss to a slight increase in Antarctic sea ice (Arzel *et al.*, 2006). 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).

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 (IPCC, In prep-d), point to a freshening of the ocean surface in northern high latitudes. However, the projected changes of ice discharge (calving rates) are not available from the IPCC simulations, since the ice-sheet discharge is not explicitly included in coupled global models.

The hydrography of the polar oceans in both hemispheres, however, varies substantially among models in the control and greenhouse simulations. For example, the fluxes in the Antarctic Circumpolar Current (ACC), 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 on land

Arctic

Seasonal snow-cover on land is highly variable but is, nevertheless, important in its effect on ground beneath and on local climate, as a result of a change in albedo and insulation of the ground. 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), 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 insulation of permafrost for the timing of spring melt-water pulses, transport and agricultural opportunities (Anisimov *et al.*, 2005a). The projected warming also implies a continuation of recent trends toward later freeze-up and earlier break-up of river and lake ice (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 (IPCC, In prep-b). Recent changes in the Greenland ice sheet have, however, been somewhat complex. The colder interior has thickened as a result of recently high precipitation rates, while the coastal zone has been thinning so that overall the ice sheet is growing in height (Krabill *et al.*, 2000; Johannessen *et al.*, 2005). The coastal thinning appears to be a response to recent increases in summer melt (Abdalati and Steffen, 2001), and acceleration of many coastal glaciers (Krabill *et al.*, 2004; Howat *et al.*, 2005; Ekstrom *et al.*, 2006; Luckman *et al.*, 2006; Rignot and Kanagaratnam, 2006).

Warming, thawing and decrease in areal extent of terrain underlain by permafrost are expected in response to climatic change in the 21st century (Sazonova *et al.*, 2004; Euskirchen *et al.*, in press; 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 decrease during the 21st Century, largely due to the thawing of the southern zone of sporadic and discontinuous permafrost but also due to increasing patchiness in areas that currently have continuous permafrost (Anisimov and Belolutskaia, 2004). Projected changes of the depth of seasonal thawing (base of the active layer) are uniform neither in either space nor in time. In the next three decades, active layer depths are likely to be within 10%-15% of their present values over most of the permafrost area; by the middle of the century, the depth of seasonal thawing may increase on average by 15%-25%, and by 50% and more in the northernmost locations; and by 2080, it is likely to increase by 30%-50% and more over all permafrost areas (Anisimov and Belolutskaia, 2004). The impacts such changes may have on the engineering infrastructure built on permafrost, and the feedback to the global climate system through potential emission of greenhouse gases are discussed below (Sections 15.7.1 and 15.4.2.3).

Antarctica

Current and projected changes in the Antarctic ice sheet, is discussed in detail elsewhere (IPCC, In prep-a), and only are summarised here. Recent changes in volume of the Antarctic ice sheet are much better mapped and understood than they were in the TAR, but competing theories over the causes 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), while 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 a suggestion 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 as yet there are too few oceanographic measurements to confirm this interpretation. Indeed, there is 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 now clear evidence of ice-sheet change, have reinvigorated debate about whether we should expect a deglaciation of part of the West Antarctic ice sheet on century to millennial timescales (Vaughan, in press). Evidence from satellite altimetry data seems to indicate that the thickness of the East Antarctic ice sheet has increased over the last 12 years which might be related to increase in precipitation associated with climate change (Davis *et al.*, 2005), however, other analyses appear to contradict this finding (Zwally *et al.*, 2005; Velicogna and Wahr, 2006).

Permafrost in ice-free areas, seasonal snow cover, and lake-ice do exist but in such small areas that they are only discussed in respect to particular impacts.

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 further south. These include five of the world's largest river catchments, which act as major conduits transporting water, heat, sediment, nutrients, contaminants and biota into the Arctic. For these systems, it will be the basin-wide changes that will determine the Arctic impacts.

Historically, the largest changes to northern river systems have been produced by flow regulation, much of it occurring 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 (e.g., Shiklomanov *et al.*, 2000). In the case of North America, downstream effects of regulation have been difficult to identify because of the dampening effects on flow produced by storage-release effects of major lake systems (e.g., Gibson *et al.*, in press; Peters *et al.*, in press). The typical effect of regulation for hydroelectric production has been to decrease summer flow and increase winter flow, and thereby overall to reduce seasonal flow variability.

Over the last half century, flow from the major Eurasian rivers has increased by an average 2 km^3/yr

(Peterson *et al.*, 2002). Potential controlling factors such as permafrost thaw, 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. Uncertainty remains concerning the role of precipitation because of difficulties in quantifying trends in such a data-sparse region (Walsh *et al.*, 2005). Changes to inter-annual variations in runoff production from precipitation are possibly linked to permafrost thaw and related alterations to flow pathways (Serreze *et al.*, 2003; Berezovskaya *et al.*, 2005; Zhang *et al.*, 2005). 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 seasonal effects of hydro-electric regulation (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; Berezovskaya *et al.*, 2005). Although regulation has also obscured trends in the timing of major spring flows, 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. 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).

The Arctic contains numerous types of lentic (still-water) systems, ranging from shallow tundra ponds to large lakes. Seasonal shifts in flow, ice cover, precipitation/evapotranspiration and inputs of sediment and nutrients have all been identified as climate-related factors controlling their biodiversity, storage regime, and carbon-methane source-sink status (Wrona *et al.*, in press-b). A significant number of paleolimnogical records from lakes in the circumpolar Arctic have shown synchronous changes in biological community composition and sedimentological parameters associated with climate-driven regimes shifts in increasing mean annual and summer temperatures and corresponding changes in thermal stratification/stability and ice cover duration (e.g., Korhola *et al.*, 2002; Ruhland *et al.*, 2003; Pienitz *et al.*, 2004; Smol *et al.*, 2005)**.**

Permafrost plays a large role in the hydrology of lentic 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 Fig. 15.4, Smith *et al.*, 2005). The spatial pattern of lake disappearance strongly suggests that permafrost thawing is driving the changes.

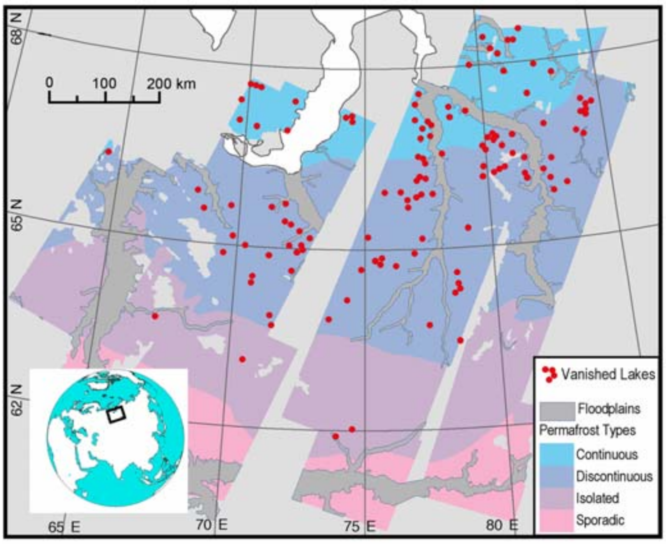

Figure 15.4: *Locations of Siberian lakes on various permafrost landscapes that have vanished after a three-decade period of rising soil and air temperatures (changes registered from satellite imagery from early 1970's to 1997-2004). The spatial pattern of lake disappearance suggests that permafrost thawing has driven the observed losses (Data and Figure from, Smith et al., 2005).*

15.4.1.2 Impacts on physical regime

Changes in Arctic freshwater systems will have numerous impacts on the physical regime of the Arctic, affecting in particular hydrologic extremes, global feedbacks and contaminant pathways. AOGCM-based hydrologic models have consistently also predicted increases in flow for the major Arctic river systems, with the largest increases during the cold season (Miller and Russell, 2000; Arora and Boer, 2001; Georgievsky *et al.*, 2003; Mokhov *et al.*, 2003). 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.*, 2005a). CO_2-induced reductions in transpiration might offset this, and have been suggested as being responsible for some 20th Century changes in global runoff (Gedney *et al.*, 2006).

Since Arctic river flow is the major component of the freshwater budget of the Arctic Ocean (Lewis *et al.*, 2000), it is important to the supply of freshwater to the North Atlantic and related effects on thermohaline circulation (IPCC, In prep-b). 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; Dowdeswell, 2006). The cumulative effect of these increasing freshwater supplies on thermohaline circulation remains unclear but is a critical area of concern (ACIA, 2005; IPCC, in prep-b).

Warming is also forecast to cause reductions in river- and lake-ice covers which will lead to changes in lake thermal structures, quality/quantity of under-ice habitat and effects on ice jamming and related flooding (Prowse *et al.*, in press-b). Specific to the latter, forecasts of earlier snowmelt freshets could create conditions more conducive to severe breakup events (Prowse and Beltaos, 2002) although a longer period of warming could also reduce severity (Smith, 2000). 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 press-b).

Projected changes of permafrost, vegetation and river-runoff may have noticeable impacts on river morphology, acting through destabilization of banks and slopes, increased erosion and sediment supply, and ultimately leading to the transformation between multi and single channel types. Geologic reconstructions and numerical simulations indicate that such transformations and also erosion events and flood risks occur especially at times of permafrost degradation (Bogaart and van Balen, 2000; Vandenberghe, 2002). Such changes are largely controlled by thresholds in sediment supply to the river and discharge (Vandenberghe, 2001). However, historical examples have shown that variability in flow regime is less important than variability in sediment supply which is especially determined by the vegetation cover (Huisink *et al.*, 2002; Vandenberghe and Huisink, 2003). Thus an increasingly denser vegetation cover may counter increased sediment discharge, which has been modelled to rise in Arctic rivers with both increases in air temperature and water discharge (Syvitski, 2002).

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). 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, runoff patterns and thermokarst drainage (Hinzman *et al.*, 2005) 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.

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; Prowse *et al.*, in press-a; Wrona *et al.*, in press-b). Ultimately the dispersal and geographical distribution patterns of aquatic species will be altered, particularly for fish (Reist *et al.*, in press-b). Extension of the ice-free season may lead to a decline in fish habitat availability and suitability, particularly affecting species such as lake trout that prefer colder waters (Hobbie *et al.*, 1999; Reist *et al.*, in press-a). 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).

Increased permafrost thawing and deepening of the active layer will increase nutrient, sediment and carbon loadings, enhancing microbial and higher trophic level productivity in nutrient-limited systems. As water-column Dissolved Organic Carbon (DOC) concentration increases, penetration of damaging UV radiation and photochemical processing of organic material would decline, although not as prominently in highly productive systems (Wrona *et al.*, in press-b). Enhanced sediment loadings will negatively affect benthic and fish-spawning habitats by increasing the biological oxygen demand and hypoxia/anoxia associated with sedimentation, and contribute to habitat loss through infilling (Reist *et al.*, in press-b; Wrona *et al.*, in press-a). Pond/wetland habitats will be affected through landscape-related nutrient enrichment; enhancing the biogeochemical processing of DOC and altering the generation and/or consumption of trace carbon-based gases. Enhanced decomposition of organic materials will increase the availability and loadings of new sources of DOC and possibly the emission of carbon dioxide. Whether freshwater systems will function as net carbon sinks or sources depends on the complex interactions among temperature, nutrient status and water levels (Frey and Smith, 2005; Flanagan *et al.*, in press). Initial permafrost thaw will form depressions for new wetlands and ponds interconnected by new drainage networks. This will allow for the dispersal and establishment of new aquatic communities in areas formerly dominated by terrestrial species (Wrona *et al.*, in press-b). As permafrost thaws further, surface waters will increasingly drain to groundwater systems leading to losses in freshwater habitat.

Southerly species presently limited by temperature/productivity constraints will likely colonize Arctic areas resulting in new assemblages. Many of these, particularly fishes, will likely out-compete or prey upon established Arctic species resulting in negative local effects on these (Reist *et al.*, in press-b). These southern emigrants to the Arctic will also bring with them new parasites and/or diseases to which Arctic species are not adapted, thereby increasing mortality (Wrona *et al.*, in press-b). Direct environmental change combined with indirect ecosystem shifts will significantly impact local faunas by reducing productivity, abundance, and biodiversity. Such effects will be most severe for freshwater fishes that rely entirely upon local aquatic ecosystems (Reist *et al.*, in press-a). Distributions of anadromous fish, which migrate up rivers from the sea to breed in fresh water, will probably shift as oceanic conditions and freshwater drainage patterns are affected (Reist *et al.*, in press-a) as will the geographic patterns of habitat use of migratory aquatic birds and mammals (Wrona *et al.*, 2005). Important northern fish species such as broad whitefish (*Coregonus nasus*), Arctic char (*Salvelinus alpinus*), inconnu (*Stenodus leucichthys*), Arctic grayling (*Thymallus arcticus*) and Arctic cisco (*Coregonus autumnalis*) will likely experience population reductions and extirpations (e.g., due to reproductive failures), contraction of geographic ranges in response to habitat impacts, and competition and predation from colonizing species (Reist *et al.*, in press-a; Reist *et al.*, in press-b).

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, mine tailings ponds, dams and impoundments for hydro-electric production (World Commission on Dams, 2000; Prowse *et al.*, 2004; Instanes *et al.*, 2005).

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 is considered to be a traditional practice, despite the fact that it poses a risk to human health via the transmission of water-borne diseases (e.g., 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 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 press-b). 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 press-b). 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 (Reist *et al.*, in press-b; Wrona *et al.*, in press-b)

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 and more have shaped current biodiversity, ecosystem extent, structure and function. Arctic species diversity is currently low partly because of past extinction events (FAUNMAP Working Group, 1996), and as a group, large mammals are in general more vulnerable to current change than in the past when the group contained many more species. Also, tundra ecosystem extent overall is now less than during the glacial period when extensive tundra-steppe ecosystems existed (Callaghan *et al.*, 2004). Modern habitat fragmentation (e.g., Nellemann *et al.*, 2001), 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 and this is related 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 (Elmhagen *et al.*, 2000); and moose, red fox, and some southern bird species have spread northwards (Hörnberg, 1995; Tannerfeldt *et al.*, 2002), although the specific role of climate change is unknown. Throughout the Arctic, many migrant bird populations have declined substantially (Stroud *et al.*, 2004) due to various causes including climate changes (Morrison *et al.*, 2001; Zöckler, 2005). Some populations of caribou/reindeer that are essential to the culture and subsistence of several Arctic peoples are currently in decline (Russell *et al.,* 2002; Chapin III *et al.*, 2005a). Formerly domesticated herds of Russian caribou/reindeer have been reduced over the last 10 years from 2 to 1 million (Baskin, 2000), mainly due to social and cultural factors, whereas some populations of wild reindeer have increased,. Icing events during warmer winters have impacted some high-Arctic ungulate populations (Aanes *et al.*, 2000; and references in, Callaghan *et al.*, 2004).

Aerial photographs show increased shrub abundance in Alaska in 70% of 200 locations (Sturm *et al.*, 2001). The tree-line has moved about 10 km northwards (2% of Alaskan tundra on the Seward Peninsula displaced by forest in the past 50 years, Lloyd *et al.*, 2003), and upwards (about 60 m in altitude in the 20th Century in sub-arctic Sweden, Dalen and Hofgaard, 2005) although bog growth has caused tree death in parts of the Russian European Arctic (Crawford *et al.*, 2003). However, such treeline changes are not unprecedented in the Holocene (MacDonald *et al.*, 2000; Esper and Schweingruber, 2004). Dry habitat vegetation in sub-Arctic Sweden has been partly displaced by wet habitat vegetation because of permafrost degradation in the discontinuous permafrost zone (Christensen *et al.*, 2004; Malmer *et al.*, 2005), up to 50% of peat plateau permafrost has thawed at 4 sites in the northern Canadian discontinuous permafrost zone (Beilman and Robinson, 2003; Malmer *et al.*, 2005) and Arctic ponds are disappearing in some areas where permafrost has thawed (Fig. 15.4, Stow *et al.*, 2004; Smith *et al.*, 2005).

Analyses of satellite images indicate that the length of growing season is increasing by 3 days per decade in Alaska and 1 day per decade in northern Eurasia (McDonald *et al.*, 2004; 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, compared with neighbouring areas (Høgda *et al.*, in press).

15.4.2.2 Projected changes in biodiversity, vegetation zones and productivity

Species richness will increase as relatively species-rich forest displaces tundra (Fig. 15.2, Callaghan *et al.*, 2004). Some species in isolated favourable microenvironments far north of their main 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. Likely rates of advance are uncertain: although tree-line advance of up to 25 km per year during the early Holocene have been recorded, rates of 2 km per year and less are more probable (Payette *et al.*, 2002; Callaghan *et al.*, 2005a). Trophic level structure is simple in the Arctic, and decreases in the abundance of keystone species are expected to lead to ecological cascades, i.e. knock-on effects for predators, food sources etc.. 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 while existing populations of weedy southern plant species that have already colonised some Arctic areas are likely to expand timing of bird migrations and migration routes are likely to change as appropriate Arctic habitats become less available (Callaghan *et al.*, 2005a; Usher *et al.*, 2005).

Warming experiments, that adequately reproduce natural summer warming impacts on ecosystems 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 initially (Walker *et al.*, 2006). 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 there were 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 processes (Callaghan *et al.*, 2004; Rinnan *et al.*, 2005).

Models project replacement of 11% (Sitch *et al.*, 2003), a "moderate" projection (See Fig. 15.2), to 50% (White *et al.*, 2000) of tundra by forest by 2100, although impacts of changing land use (e.g., Vlassova, 2002, suggests that 475,000 km2 of tree-line forest has been destroyed in Russia, thereby creating tundra-like ecosystems), hydrology and active layer depth 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). Large-scale forest fires and outbreaks of tree-killing insects that are triggered by warm weather are characteristic of the boreal forest (Juday *et al.*, 2005) and some forest tundra areas and are likely to increase. During the 1990s, the Kenai Peninsula of south-central Alaska experienced a massive outbreak of spruce bark beetle over 1.6 million ha with 10-20% tree mortality (Juday *et al.*, 2005). Also following recent climate warming, spruce budworm has reproduced further north reaching outbreak proportions in Alaska (Juday *et al.*, 2005) while autumn moth defoliation of mountain birch trees associated with warm winters in northern Fennoscandia has occurred over wide areas and is projected to increase (Callaghan *et al.*, 2005a).

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 III *et al.*, 2005a) and global climate (Bonan *et al.*, 1992; Thomas and Rowntree, 1992; Foley *et al.*, 1994; McGuire *et al.*, In Press).

Measurements show great spatial variability in the magnitude of sink or source status for carbon with no overall trend for the Arctic (Corradi *et al.*, 2005) whereas models suggest that overall, the Arctic is a small sink of about 20 g C m^{-2} yr^{-1} with a large spatial variance (standard deviation of 40 g C m^{-2} yr^{-1}) (McGuire *et al.*, 2000; Sitch *et al.*, 2003; Sitch *et al.*, in press), 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 III *et al.*, 2005a). They are, however, most likely a source of positive radiative forcing due to large methane emissions (Christensen *et al.*, Submitted); 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 projected 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 and increased active-layer depth (see section 15.3.4) will critically determine trace gas species composition and 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 6-10 M tons/year increase of methane emission from the Russian Arctic wetlands (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; Sitch *et al.*, Submitted), 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, are projected to 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 central Canadian boreal 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

Terrestrial resources are critical aspects of Arctic residents livelihoods, culture, traditions and health (Arctic Monitoring and Assessment Programme, 2003; Chapin III *et al.*, 2005a). Per capita consumption of wild foods by rural Alaskans is 465 g d^{-1} (16% land mammals, 10% plant products) and is valued at about $200 million; consumption by urban Alaskans is 60 g d^{-1}. 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). 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 III *et al.*, 2005a). 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). Wood, sod, peat, and coal are used locally as fuels throughout the north. Despite the significant role these resources represent to Arctic residents, ties to subsistence activities among Indigenous Peoples are deteriorating because of changes in lifestyles, cultural, social, economic and political factors (Chapin III *et al.*, 2005a). These ties are expected to continue decreasing as climate-driven changes in terrestrial ecosystems influence conditions for hunting, decreases in natural resources and loss of traditional knowledge. Together these shifts are making previously well-adapted Arctic peoples into "strangers in their own lands" (Berkes, 2002).

Agriculture in 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.*, 2005). The northern limit of agriculture 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 see 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 *et al.*, 2005).

15.4.3 Marine ecosystems and their services in the Arctic

15.4.3.1 Historical changes of marine ecosystems

Water temperatures in the North Atlantic have fluctuated over the last 200 years. The effects of these temperature variations have been profound, impacting plankton communities, larval drift, and the distribution and abundance of many fish stocks, including southern invaders and, especially, the commercially important cod and herring (Loeng *et al.*, 2005; Vilhjálmsson *et al.*, 2005), *(See 15.6).* These climatic impacts on fish stocks are superimposed on their massive over-exploitation.

15.4.3.2 Likely general effects of a warming ocean climate

Changing climatic conditions in Arctic and sub-Arctic oceans are driving changes in the biodiversity, distribution and productivity of marine biota, most obviously through the reduction of sea ice. The shifting distribution of crustacea (copepods and amhipods), adapted for life at the sea ice edge, and fish such as polar cod *(Boreogadus saida)* which forage on them, will move northward, and it is likely that their abundance will diminish. This is likely to have serious consequences for predators associated with sea ice including seals and polar bears *(Ursus maritimus)* (WG II, Chapter 2) as well as humans depending on them (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 fish stocks in Arctic and sub-Arctic seas; for example, cod *(Gadus morhua)* and herring *(Clupea harengus)* in the North Atlantic and walleye pollock *(Theragra chalcogramma)* in the Bering Sea, species that currently comprise ~70% of the total catch in these areas. However some coldwater species may lose habitat; for example, northern shrimp *(Pandalus borealis)*, king crab *(Paralithoides sp.)* and snow crab *(Chionoecetes opilio)* and possibly capelin *(Mallotus villosus)*.

15.4.3.3 Predicting future yields of commercial and forage stocks

Quantitative predictions of the responses of commercial and forage fish stocks to changes in ocean temperature are very difficult to make for the following reasons. Firstly, few models couple predictions of global warming to variations of oceanographic parameters. Secondly, although historical observations are the most valuable tool in predicting reactions of exploited and other stocks to changes in climate, exploitation has already altered stock sizes and basic biology/ecology, so that in future stocks cannot be expected to react exactly as they did during recorded history. Finally, management practices, including international agreements on harvesting joint stocks, will in many cases have just as much effect on yields as a climate change. This is especially true with regards to sub-Arctic stocks, for example cod around Iceland and in the Barents Sea (Fig. 15.5 c and d).

Increasing water temperatures will, however, lead to an increased risk of harmful algal blooms and increased occurrences of other marine pests and pollution, hazards that will be multiplied by increased shipping as Arctic sea ice is reduced (Loeng *et al.*, 2005; Vilhjálmsson *et al.*, 2005).

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

The complexity of potential responses is illustrated by the following examples where ocean temperature variability and fishing pressure have impacted the fish populations, but in each the balance of the stresses was different and the overall effect quite different.

Greenland/Iceland

For all practical purposes there were no Atlantic cod in Greenland waters in the latter half of the 19th Century (Jensen, 1926; Jensen, 1939; Buch *et al.*, 1994). But in the early 1920s, large numbers of juvenile cod drifted from Iceland to West Greenland and started a self-supporting stock at Greenland. Ocean temperature records, begun off W-Greenland in the 1870s, showed very cold conditions until a sudden warming began around 1920, reached a peak in the early 1930s and continued until they dropped suddenly in the late-1960s (Jensen, 1939; Buch *et al.*, 1994; Vilhjálmsson, 1997) (Fig. 15.5a).

Comparison of catches and temperature records shows that the occurrence of cod off Greenland depends principally on West Greenland water temperature (Horsted, 2000). The reappearance of cod off Greenland will likely depend on drift of juvenile cod from Iceland as it did in the 1920s. Although such drifts occurred in 2002 and 2005, the numbers were small as a consequence of the depleted spawning stock of Icelandic cod, which has not produced a strong year class for 20 years, even under the present warmer conditions (ICES, 2005).

Newfoundland/Labrador

Ambient temperatures mark the northern limit of the 'northern cod' stock (Drinkwater, 2005). Beginning in the 16th Century, annual catches increased to about 200 000 t by the early 1800s. Between 1920 and 1960 annual catches varied between about 300 and 400 000 t, then increased rapidly in the 1960s with massive overfishing peaking in 1968 at 810 000 t. Catches then dropped to about 170 000 t after 1977 due to changed fishing regulations (Rose, 2004). Total allowable catches were increased to over 250 000 t in the mid-to-late 1980s. After 1989 catches dropped sharply and a moratorium on fishing was imposed in 1992 (Fig. 15.5b).

In retrospect it is clear that over-fishing and mis-management continued after the implementation of changed regulations in 1977 (Walters and Maguire, 1996). However, decreased productivity in cod and declines in their primary food, capelin, unrelated to fishing, also occurred in the late 1980s and 1990s (Rose and O'Driscoll, 2002; Shelton *et al.*, 2006). In addition, a moratorium on hunting harp and hooded seals led to a rapid increase in their abundance and thus increased mortalities of their prey which includes cod (Lilly *et al.*, 2003). While a warming climate is likely to promote the recovery of the northern cod stock (Drinkwater, 2005), an increase in abundance of the main forage fish, capelin, and a decline in seal abundance are likely necessary for recovery to occur.

The northern cod situation demonstrates how fishing, climate change in marginal areas and other factors affecting marine ecosystems, may interact strongly at the extremes of the range of a species. On one hand, a lightly-exploited stock may show few drastic changes as climate and other factors change, but, on the other, as with northern cod, such changes may amplify the effects of overfishing, causing negative and sudden changes in vital survival rates and abundance, as well as distribution (Rose *et al.*, 2000; Rose, 2004; Drinkwater, 2005).

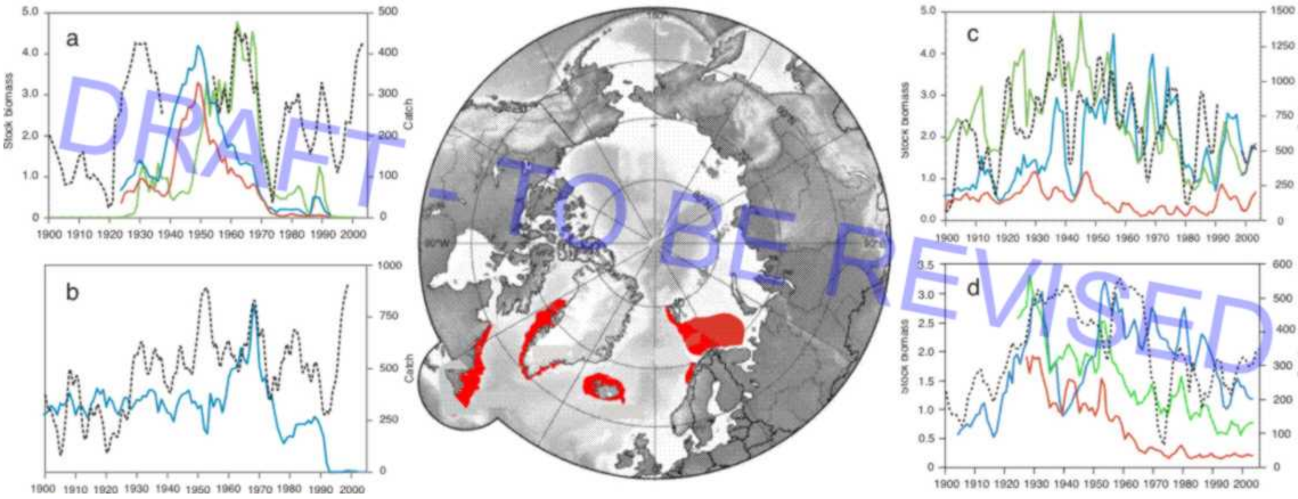

Figure 15.5: *The map shows the geographic distribution of four major cod stocks in Arctic and sub-Arctic waters in the North Atlantic. The graphs (a: West Greenland; b: Newfoundland/Labrador; c: Barents Sea and d: Iceland) show the developments of fishable stock (green line), catches (blue line) and temperature (black broken line) during the period 1900-2005. Data are from various official and published sources.*

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 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 t 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 was lost 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 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. And here it important to note, that the impact of changes these 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 forces acting on them (Hamilton, 2003). However, such impacts, on the health and well-being of Arctic residents are and will be tangible and ongoing. Recently, significant research has been conducted on the health and well-being of Indigenous populations in the Arctic and the role of the environmental change as a determinant of health; accordingly, this section puts more emphasis on these more vulnerable segments of the population.

15.4.6.1 Direct Impacts of climate on the health of Arctic residents

Direct impacts (injury and death) are expected to result, in part, from exposure to temperature extremes and weather events. Increases 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 are associated with short-term increases in respiratory and cardiovascular diseases (Kovats *et al.*, 2000). Messner (2005) saw an increased incidence of non-fatal heart attacks with increased temperature during the positive phase of the Arctic Oscillation (AO) in Sweden, but he related this to a potential disruption in physiological and behavioural adaptation which could cause an increase in the susceptibility to atherosclerotic diseases. Low temperatures and social stress have been related to "northern cardiomyopathia" identified in Northern Russia (Khasnullin *et al.*, 2000). Residents in some Arctic regions report respiratory stress associated with 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 *et al.*, 2005). An estimated 2000-3000 per year extra deaths occur in Finland during the cold season.

This excess winter mortality is much higher than from other common causes of death in the country (e.g., 400 per year from traffic accidents, 100-200 per year from heat). The prevalence of respiratory diseases among children in the Russian North is 1.5-2 times higher than the national average. Evidence (Nayha, 2005) suggests that warming in Arctic regions during the winter months will reduce excess winter mortality, primarily through a reduction in cardiovascular and respiratory deaths. Assuming that the standard of cold protection (including individual behavioural factors) does not deteriorate, a reduction in cold-related injuries is also likely (Nayha, 2005).

15.4.6.2 Indirect Impacts of climate on the health of Arctic residents

Climate warming and increased variability will have a series of more complex, indirect impacts on human-environment interactions in the Arctic (Warren *et al.*, 2005). Local and traditional knowledge in nearly all regions records increasingly uncharacteristic environmental conditions and extremes not experienced before in those regions (e.g. Krupnik and Jolly, 2002b). There is anecdotal evidence that an increase in injuries among northern residents associated with “strange” or changing environmental conditions, such as thinning and earlier break up of sea ice, are related to trends in climate (e.g. Lafortune, 2004).

Climate change in the Arctic during El Nino Southern Oscillation (ENSO) events has been associated with illness in marine mammals, birds, fish, and shellfish. A number of disease agents have been associated with these illnesses (e.g. botulism, Newcastle disease). It is likely that temperature changes arising from long-term climate change will be associated with an increased incidence of those diseases that can be transmitted to humans (Bradley *et al.*, 2005). The examples of tick-borne encephalitis (brain infection) in Sweden (Lindgern and Gustafson, 2001), and *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida)* and bowhead whales (*Balaena mysticetus)* in the Arctic Ocean are evidence of the potential (Hughes-Hanks *et al.*, in press). Many zoonotic diseases which currently exist in Arctic host species (e.g. tularemia in rabbits, muskrats and beaver, rabies in fox; Dietrich, 1981) spread via climate-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 are positively impacted by warming temperatures and may mean many new diseases appear in Arctic regions (Parkinson and Butler, 2005). Although the monitoring evidence might be biased by the sampling effort, one observed example of such a migration appears to be that of west Nile virus (See Fig. 15.6) – there are many other that could occur under future climate change projections.

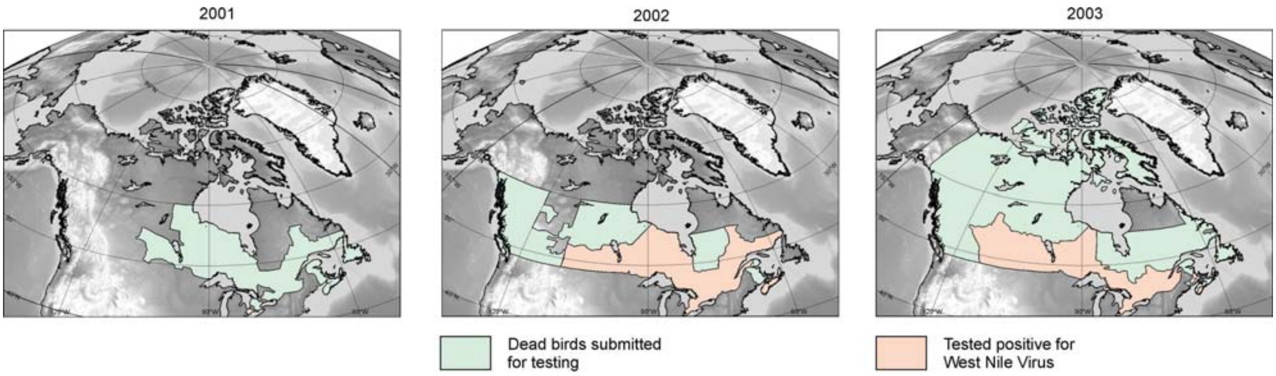

Figure 15.6: *The distribution of West Nile virus through Canada as detected in submitted bird species, between 2000-2003 (Redrawn from Warren et al., 2005).*

Subsistence food items from the local environment provide Arctic residents with cultural and economic benefits and contribute a significant proportion of daily requirements of several vitamins and essential elements to the diet (e.g. Blanchet *et al.*, 2000). Wild foods also comprise the greatest source of exposure to environmental contaminants. The uptake, transport and deposition behaviour of many of these chemicals is influenced by temperature, and therefore climate warming may indirectly influence human exposure (Kraemer *et al.*, In review). Through changes in accessibility and distribution of wildlife species, climate change in combination with other social, cultural, economic and political trends in Arctic communities, will likely influence the diet of circumpolar residents.

Transitions towards more market food items in Arctic indigenous diets to date have been associated with a rise in levels of cardiovascular diseases, diabetes, dental cavities, and obesity (Van Oostdam *et al.*, 2003). In many indigenous communities, these subsistence food systems are the basis of traditions, socio-economic and cultural well-being. Indigenous peoples maintain a strong connection to the environment through these activities in a way that distinguishes them from non-indigenous communities, and may indeed contribute to how specific peoples retain a fundamental identification to a particular area (Gray, 1995; Nuttall *et al.*, 2005).

While climate related changes threaten aspects of food security for some subsistence systems, increased temperatures and decreased sea-ice cover represent increased transport opportunities and access to market food items. Shifts in animal population movements also mean potential introduction of new food species to northern regions. These combined effects on Arctic food security, in addition to increased opportunities for agricultural and pastoral activities with decreased severity of winter and lengthened summer growing seasons make it difficult to predict how diets will change and impact health, even presupposing we have sufficient understanding of what local environments can provide and sustain. It is also clear that these impacts will be influenced not only by environmental change but also by economic, technological and political forces.

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, most seriously in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada). Community water sources may be subject to saltwater intrusion and increased contaminant levels. Quantities 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 and damaged infrastructure such as sewage lagoons, or inadequate hygiene, spreads sewage. However, treatment efficiencies in wastewater lagoons may also improve due to warmer water temperatures, delaying the need to expand natural wastewater treatment systems as local populations grow (Warren *et al.*, 2005).

The combined forces acting on Arctic communities and individuals today (Chapin III *et al.*, 2005a) have significant implications for the health and well-being of some residents (Curtis *et al.*, 2005). 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 resources resulting in altered access to subsistence 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 anxiety among individuals (Hamilton, 2003; Curtis *et al.*, 2005). However, in nearly all Arctic locations climate change is just one of many driving forces acting to transform Arctic communities today. These combined forces from inside and outside the community are influencing the acculturation process by influencing ways of living, and loss of 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 last 50 years has influenced all aspects of health in the Arctic, and this influence is highly likely to continue in the future. Climate change is likely going to drive rapid changes in communities by challenging individuals' and community's relationship with their local environment which has been the basis of Arctic peoples' identity, culture, social and physical well-being (Einarsson, 2004; Chapin III *et al.*, 2005a; Warren *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 change, climate, and lithology), and by features particular to the high-latitudes (low temperatures, ground ice, and sea ice). The most severe erosion problems affects infrastructure, and culturally important sites in areas of rising relative sea level, areas seasonally-free of sea ice and ice-rich permafrost terrain (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; e.g., Nikiforov *et al.*, 2003). Wave erosion and high summer air temperatures promote distinctive thermal and mechanical processes that promote 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). Communities located on resistant bedrock coasts and where glacio-isostatic rebound is occurring are less vulnerable to erosion.

Coastal instability may be further magnified by poorly adapted 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 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. This has led to abandonment and relocation of homes and other facilities (Instanes *et al.*, 2005) and may require relocation, despite a cultural aversion in the local communities to moving from traditional sites. Although clear 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 (Instanes *et al.*, 2005).

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).

15.5 Adaptation: practices, options and constraints

Circum-arctic nations contribute about 40% of global CO_2 emissions and the Arctic is an important source of fossil fuels. Although some residents may contribute only a very small portion of these emissions, there is a need to consider both mitigation and adaptation in polar regions in light of trends in resource development and modernization. The burden faced by Arctic residents is magnified by the projected amplification of climate change in polar regions and the potential for dramatic environmental impacts. As with other vulnerable regions of the world, human adaptation is critical, and particularly for those living in closest relationship with the local environment.

Historically, cultural adaptations and the ability of Arctic indigenous peoples to utilize their local resources have been associated with, or affected by, seasonal variation and changing ecological conditions. One of the hallmarks of successful adaptation 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 III *et al.*, in press). Historically, 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, 2005b), yet, in the future, such responses may be constrained by social, cultural, economic and political forces acting on communities externally and from within.

Detailed local knowledge and the social institutions in which this it exists are critical foundations of understanding 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 (e.g. amount and frequency of time spent on land or engaged in subsistence activities) so does the information it provides. Changes in local environments further challenge this knowledge and increases human vulnerability to climatic and social change.

Greater uncertainty and threats to food security stress the need for resilient and flexible resource procurement systems. Resilience and adaptability depends on ecosystem diversity as well as the institutional rules which govern social and economic systems (Adger, 2000). Innovative co-management of both renewable and non-renewable resources could support adaptive abilities via flexible management regimes while providing opportunities to enhance local economic benefits and ecological and societal resilience (Chapin III *et al.*, 2004).

Opportunities for adaptation exist within some changes already taking place. The arrival of new species (e.g., Babaluk *et al.*, 2000.; Huntington *et al.*, 2005a) and an increase in growing seasons and opportunities for high latitude agriculture provide chances to enhance resilience in local food systems. Increased ecotourism may increase incentives for protection of environmental areas. Taking advantage of these potentially positive impacts will, however, require institutional flexibility and forms of economic support.

Given the interconnected nature of Arctic ecosystems and human populations strategies are required that take a broad approach to support adaptation among a range of sectors. For example, policies that allow local people to practice subsistence activities within protected areas contribute to both biodiversity and cultural integrity (Chapin III *et al.*, 2005a). The creation and protection of critical areas such as parks, with flexible boundaries to compensate for changing climatic conditions, enhances conservation of wildlife and services provided by this land for human use (e.g. tourism and recreation) (Chapin III *et al.*, 2005a).

Although arctic communities show great resilience and ability to change in many regions, some responses have been compromised by socio-political change. The political, cultural and economic diversity that exists among Arctic regions today impacts how communities are affected by, and respond to, environmental change. Such diversity also means that local experiences of climate impacts and responses to climate variability and change may not be universal. Currently, little is known about how communities and individuals, indigenous or non-indigenous, differ in the way risks are perceived, or how use such aspects of their lives as harvesting strategies and other forms of resource procurement for mitigating negative change. 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 sensitive to drivers of change, even when sharing similar resources and ecological settings. Ultimately, an understanding of adaptation can only derive from a better understanding of social and economic vulnerability among all arctic residents (Handmer, 1999).

15.6 Case studies[1]

15.6.1 Cross-chapter case study - Traditional knowledge for adaptation

Among Arctic 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 Arctic indigenous knowledge that can be documented offers detailed information that adds to conventional science and environmental observations, as well as to a holistic understanding of environment, natural resources and culture (Huntington *et al.*, 2004). Thus there is an increasing awareness of the value of Arctic 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 of Inuit hunters to navigate new travel and hunting routes despite decreasing ice stability and safety (e.g. Lafortune, 2004); in the ability of many Indigenous groups to locate and hunt species such as geese and caribou that have shifted their migration times and routes and to begin to locate and hunt alternative species moving into the region (e.g. Krupnik and Jolly, 2002a; Nickels *et al.*, 2002; Huntington *et al.*, 2005a); the survival skills and ability to detect safe sea-ice and weather conditions when travelling in an environment with increasingly uncharacteristic weather and a dangerous near shore ice

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

environment (George *et al.*, 2004); or the knowledge and skills required to hunt marine species in open water later in the year versus off the ice in the early spring because of earlier sea-ice break up and changing sea-ice conditions (Community of Arctic Bay, 2005). These examples are indicative of the adaptive challenges being faced by residents of Arctic indigenous societies and the critical interactions between indigenous knowledge and adaptive capacity.

15.6.2 Cross-chapter case study – Mega-deltas

Numerous river deltas are located along the Arctic coast and the rivers that flow to it. Of particular importance are the mega-deltas of the Lena (44 x 10^3 km^2) and Mackenzie (9 x 10^3 km^2) rivers, fed by the largest Arctic rivers of Eurasia and North America, respectively. In contrast to non-polar mega-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 with warming 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, thawing of the permafrost and melting of the ground ice that currently consolidates deltaic material will induce hydrodynamic erosion on the delta front as well as along river banks. Thawing of permafrost on the delta plain will also lead to similar changes in other terrestrial environments, e.g., 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). Thaw subsidence may also affect the magnitude and frequency of delta flooding from spring flows and storm surges (Kokelj and Burn, 2005).

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 watershed (Peace-Athabasca Delta) indicates that a combination of thinner river ice and reduced spring runoff (due to greater winter rainfall and hence smaller snowpacks) will lead to decreased ice jam flooding (Beltaos *et al.*, in press). This change 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 is a rugged mountain chain generally more than 2000 m high, protruding out of the Antarctic continent towards South America and differing from most of Antarctica, by having a summer season during which considerable melt occurs at low elevations. Summer melt produces many isolated snow-free areas, which are habitats for simple biological communities of cryptogamic plants, microbes and invertebrates, and breeding grounds for marine mammals and birds. The Antarctic Peninsula 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.

Since records began, 50 years ago, mean annual temperatures on the Antarctic Peninsula have risen rapidly (>2.5 C at Faraday/Vernadsky Station, Turner *et al.*, 2005). On the west coast, warming has been much slower in summer than in winter or autumn, but has been sufficient to raise the number of positive-degree-days by 74% (Vaughan, 2006), and this increase in melt has caused the dramatic impacts on the Antarctic Peninsula environment, and its ecology.

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 snow and floating ice does not have a direct impact on global sea level, but 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 increases run-off of melt-water (Vaughan, 2006) will cause an increased in this contribution. If summer warming continues these effects will grow in coming decades.

Marine sediment cores show that ice shelves probably have not reached a similar minimum for at least 10 000 years (Domack *et al.*, 2005), but certainly not for 1000 years (Pudsey and Evans, 2001; Domack *et al.*, 2003). This suggests that the retreat is not simply due to cyclic variations in local climate, and that recent warming is unique on that timescale (Turner *et al.*, Submitted). The processes leading to the warming are not entirely clear; but warming, does appear to be correlated with atmospheric circulation (van den Broeke and van Lipzig, 2003), and is consistent with changes in circulation patterns (Southern Annular Mode) caused by anthropogenic influence (Marshall *et al.*, 2004). The winter warming on the west coast also appears to be related to persistent retreat of sea ice in the Bellingshausen Sea (Fig. 15.3, Parkinson, 2002), and warming of the nearby seas (Meredith and King, 2005). The spring depletion of ozone over Antarctica (the Antarctic Ozone Hole) has also been implicated (Thompson and Solomon, 2002) in driving circulation change, but this has also been disputed (Marshall *et al.*, 2004). Current GCMs do not, however, 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, which limits our ability to predict the future impacts.

Notwithstanding this uncertainty over the cause, continued warming (especially in the summer) would cause significant impacts; retreat of coastal ice and loss of snow cover, would result 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 stressors and their responses will be complex. For example, 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, as climatic barriers to alien species are eroded by climate amelioration and increasing human activity increases the opportunity for introduction. Furthermore, slow reproduction rates during rapid climate change may limit the possible relocation of native species. Such invasions have already occurred on many sub-Antarctic islands with detrimental consequences for native species (Frenot *et al.*, 2005).

Two decades of monitoring of the marine ecosystems west of the Antarctic Peninsula have revealed trends in all trophic levels, driven by reduced sea-ice duration and distribution. Although in some case, changes in primary production may also have been affected by changes in the supply of glacial melt (Smith *et al.*, 2003). Similarly, it is likely that altered sea ice cover 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, the main concern is for the loss of a unique landscape and biota. The rate of warming on the Antarctic Peninsula is, however, among of the highest seen anywhere on Earth in recent times, and is a dramatic reminder of the regionality to be expected in future, and the complexity of its impacts in an environment even where human influence is at a minimum.

15.7 Implications for sustainable development

15.7.1 Economic activity, infrastructure and sustainability in the Arctic

Because of its potential for settlement, thawing of ice-rich permafrost is a significant environmental hazard in northern high-latitudes, 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 (Instanes *et al.*, 2005), particularly the oil and gas extraction and transportation facilities (Hayley, 2004).

Deeper seasonal thawing and higher temperature of the frozen ground will stimulate destructive processes, particularly thermokarst formation, which may have detrimental impacts on infrastructure. Such risks have been evaluated using the "permafrost hazard" index (e.g., Nelson *et al.*, 2001; Anisimov and Belolutskaia, 2004; Anisimov and Lavrov, 2004; Smith and Burgess, 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 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, there are several large population centres (Yakutsk, Noril'sk, Vorkuta) and much of the Trans-Siberian and Baikal-Amur railways. Substantial investment will be 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 on permafrost of climate change, and of more localised human-induced changes (Nelson, 2003). Several scientific and media reports in recent years have suggested widespread damage to human infrastructure caused by thawing permafrost (e.g., Smith *et al.*, 2001; Couture *et al.*, 2003; Zernova, 2003; e.g., 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 is known and can be mistaken for an impact of climate change. Similarly, significant urban heat-island effects have been documented (e.g., Hinkel *et al.*, 2003) and may be important in local degradation of permafrost.

Urbanization has a confounding effect on our ability to assess the relation between climatic change and the effects of thawing permafrost on the built environment (Tutubalina and Rees, 2001). For example, in Fairbanks, Alaska, the Permafrost Technology Foundation has identified more than 350 structures affected by differential thaw settlement, although not all are attributable to climatic change. Inappropriate positioning and construction practices have continued as the suburbs of Fairbanks have grown. Experience here illustrates how thawing permafrost can affect the real estate industry. Once a structure has been identified as being affected by degrading permafrost it becomes almost unmarketable, as loans cannot be secured on it, with a devastating effect on individual lives.

The cost of rehabilitating community infrastructure damaged by widespread thawing of permafrost could be overwhelming (Couture *et al.*, 2000; Chartrand *et al.*, 2002; Couture *et al.*, 2002). 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 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). Costs of adaptation may, in part, be compensated by economic benefits, such as savings on building heating. Models based on cumulative winter degree-days predict up to 15% decline in the demand for heating energy in the populated parts of the Arctic and sub-Arctic and up to one month decrease in the duration of a period when heating is needed (Anisimov, 1999).

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, and Northern Sea Route will probably create new opportunities for cruise shipping. In some cases longer and warmer summers and less summer ice are already leading to such increases in the North American Arctic (Eagles, 2004).

Even without 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 climate change and its likely amplification in many Arctic areas, make this 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 (Fig. 15.2), and changing fish stock, ecosystem changes will provide many 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 an impact on sustainability, in some more or less predictable way. There does, however, 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) and a forum for circum-Arctic cooperation exists in the Arctic Council. This involves eight nations, and six indigenous people’s organizations and embraces the concept of sustainable development in its mandate. The Arctic Council, in partnership with the International Arctic Science Committee, is 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.

15.8 Key uncertainties

Detailed lists of uncertainties (ACIA, 2005) and research agendas (ICARP, 2005) have recently been developed by the Arctic research community, the key uncertainties listed below, summarise gaps in our understanding that specifically restrict our ability to make reasonable projections of the impact of climate change in the polar regions, and the importance of those changes on the Earth system.

We have insufficient understanding

- of how climate warming over Arctic landscapes, and polar continental shelves will alter the regional carbon balance, and to what extent this has global implications;
- of how the complex suite of cumulative and/or synergistic stressors (e.g., increasing human activities), operating separately or in concert with climate change, will modify or even magnify the effects of climate change in the polar regions;
- of the spatial variability in climate change within both polar regions, and specific sub-regions where change will be most dramatic, in particular, to predict whether rapid recent rates warming on the Antarctic Peninsula and sub-Antarctic islands and parts of the Arctic will be sustained, and whether loss of sea ice, seasonal snow-cover, and vegetation change will promote rapid local warming;
- of the social, cultural, economic and sovereignty consequences of climate change in the Arctic, and their significance within the broader framework of technological, cultural, and socio-economic changes that face Arctic human communities;
- of the thresholds, step-changes and non-linear effects in polar systems, particularly those associated with phase-changes produced by shrinking cryospheric components and those associated with natural and anthropogenic disturbance to ecosystems, that make modelling climate-change effects in polar regions extremely difficult;
- and of whether there are critical rates of change, or thresholds/tipping points above which the adaptation capacity of natural and human systems are exceeded.

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