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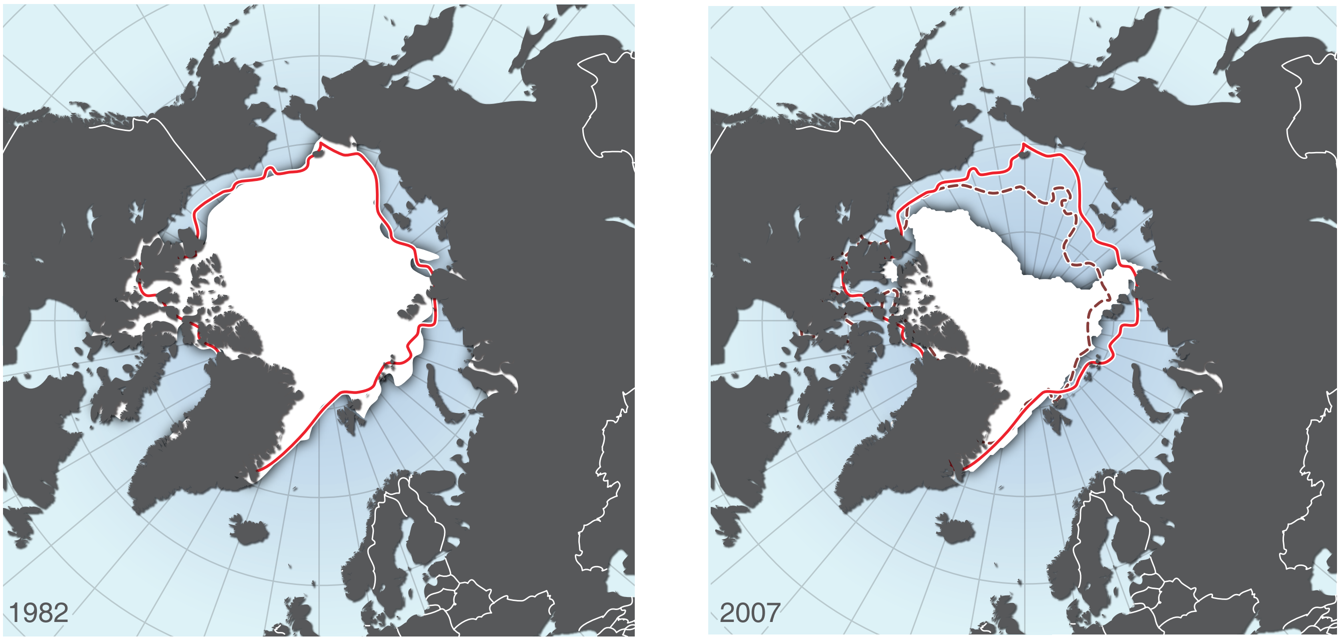
Arctic Climate Impact Science

an update since ACIA

Arctic sea ice minimum extent in September 1982. 2005 and 2007



Sources: Fetterer, F., and K. Knowles. 2002, updated 2004. Sea ice index. Boulder, CO: National Snow and Ice Data Center. Digital media. (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/ Accessed October 2007)

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Arctic Climate Impact Science — an update since ACIA

Contents

1. Conclusions: Arctic Climate Impacts since ACIA

Context

This report presents a wide-ranging review of arctic climate impact science published since the Arctic Climate Impact Assessment (ACIA) in 2005. It spans the width of subject areas, covering impacts on physical and biological systems, as well as on humanity. The report presents the scientific evidence for arctic climate change impacts in review sections, each of which targets a particular arctic system or cross-cutting arctic theme. A separate bullet-point section highlights what expert reviewers, authors, and editors rank as the most important findings.

One of the most significant scientific advances since the ACIA is the conclusion of the 4th Assessment Report of the Intergovernmental Panel on Climate Change that climate change is "highly likely" (with 90 per cent likelihood) human-made (IPCC 2007). This report can therefore now use this cognition as a basis from which to showcase the recent evidence for arctic climate impacts.

While human-made climate change is a global problem, by documenting the growing scientific evidence on arctic climate change impacts along with the projected and potential consequences of a changing Arctic for the globe, this report highlights the growing insight that the Arctic is not only one of the places on Earth that is most vulnerable to climate change, but also place where vulnerability is of urgent global relevance.

Main findings

When compared with the 2005 ACIA, this report, in summary, conveys three main messages.

1. Arctic climate change impact trends described in the ACIA continue throughout the Arctic. None of the trends outlined in 2005 were found to have reversed. Understanding of arctic climate change impacts improved for many of the systems studied, while for others the new findings foremost highlighted the evidence of the complex reasoning of impacts.

2. Change is occurring on all arctic system levels, impacting on physical systems such as atmosphere and oceans, sea ice and ice sheets, snow and permafrost, as well as on biological systems such as species and populations, food webs, ecosystem structure and function, and on human societies. It is the breadth of impacts across the report that is adding weight to the conclusion that there is hardly a component of the Arctic that is not showing signs of change.

3. For several key arctic systems, notably arctic sea ice and the Greenland Ice Sheet, recently observed changes are happening at rates significantly faster than predicted in previous expert assessments, notably ACIA and IPCC AR4, and therefore faster than accommodated for in climate models. While this primarily reflects the current limits of scientific understanding of the Arctic it also raises questions about the means and range of climate impact predictions that guide arctic and global mitigation and conservation approaches.

Most prominent changes.

In terms of the magnitude of impacts as well as their arctic and global significance the most prominent change described in this report is the recent severely accelerated melting of both the Greenland Ice Sheet and the arctic sea ice. Expert scientists now actively and openly discuss the possibility that both these systems are approaching, or may have already reached, their tipping point, at which time accelerating positive feedbacks are causing an even quicker melt.

The Greenland Ice Sheet.

With an ice volume of about 2.9 million km^3, the Greenland Ice Sheet has the potential to contribute much more to global sea-level rise than all of the other glaciers and ice caps combined (excluding the Antarctic Ice Sheet). If the entire Greenland Ice Sheet were to melt, sea level would rise by about 7.3 m (IPCC 2007), making its status a global concern. ACIA (which gave equal space to the Greenland Ice Sheet and other arctic glaciers) reoported, a net mass loss of the Greenland Ice Sheet was reported. Subsequent satellite findings (e.g. Chen et al. 2006, Velicogna & Wahr 2006, Rignot & Kanagaratnam 2006) have indicated that mass loss from the Greenland Ice Sheet is accelerating, with much greater mass losses over the last few years. This has led to speculations that the Greenland Ice Sheet will reach a tipping point, with accelerating positive feedback causing its ever-more rapid decline, and will contribute much more than previously estimated to global sea-level rise during the 21st century.

Two issues complicate this picture and currently make it impossible to predict the short or long term future of the Greenland Ice Sheet with confidence (Sheperd & Wingham 2007). First, data spans from such satellite studies are still relatively short (about one decade), making the long-term response of the ice sheet to global climate change difficult to assess. Second, dynamic responses of the ice sheet (i.e. increased glacier flow) to temperature changes, which are believed to have caused most of the recent accelerated ice loss, are not adequately simulated in existing ice sheet models.

For this reason, the IPCC excluded the uncertainties surrounding ice dynamics from estimates of increases in sea levels in their 4th Assessment Report, stating that understanding of these processes is too limited to provide a best estimate or upper boundary. This can lead the public to incorrectly believe that predicted sea level rise is moderate, and in fact, less than in the previous 3rd Assessment Report, which did include ice dynamic uncertainties for Greenland in its calculations of sea level rise

(Hansen 2007). Recent studies have used methods that do not require an estimation of the Greenland Ice Sheet's contribution to predict global sea level rise. Rahmstorf (2007) made use of semi-empirical methods and Rohling et al. (2008) used studies of past sea-level rise, both coming up with estimates of sea level rise far greater than those of the IPCC 4th Assessment Report.

Arctic Sea Ice.

The decreasing trend in extent of summer arctic sea ice has massively accelerated since publication of ACIA, with the two lowest years on record occurring in 2005 and 2007. In September 2007, the sea ice reached a low extent of 4.3 million km^2, or 39% less than its 1979-2000 mean, the lowest since satellite monitoring began in 1979 and also the lowest for the entire 20th century based on monitoring from ships and aircraft (NSIDC 2007). Although it is believed that cloud and wind conditions have contributed to the summer 2007 ice minimum, the primary factor for the 2007 low is understood to stem from arctic warming that reduced both the area and thickness of multi-year ice, making the remaining ice more prone to summer thaw (NSDIC 2007).

Nearly all models now predict enormous sea ice retreat this century, with a few respectable models predicting a nearly ice-free Arctic by mid-century. However, the recent acceleration in sea-ice retreat is not captured by most models. Many scientists now speculate that a “tipping point” could soon be reached, in which multiple positive feedback effects will send sea ice into a low from which it cannot recover—a process which is inadequately simulated in models. After the 2007 low in sea ice extent, scientists at the National Snow and Ice Data Center (NSIDC) speculated that an ice-free Arctic Ocean in summer could occur by 2030 (NSIDC 2007). And in a recent synthesis of model results with observations, Whelan et al. (2007) predicted that there will be no summer arctic sea ice by 2013.

There is evidence that some feedback effects are already occurring, and the events of summer 2007 are of particular concern in this respect. The extreme low in sea ice extent and thickness in summer 2007 resulted in more absorption of solar radiation, causing autumn freeze-up to progress slowly (NSIDC 2007). The winter 2007/2008 maximum of sea ice was slightly more than in recent years, but still below the 1979-2000 average. Because an unprecedented percentage of the ice is now thin new ice, experts believe that it is almost certain that sea ice extent in the summer of 2008 will also be well below average (NSDIC 2008).

Arctic sea ice is regarded as one of the first and clearest indicators of climate change in the Arctic (Meier et al. 2007). Melting of arctic sea ice will have not only global effects, through positive feedback to global warming from reduced ice albedo and effects on ocean circulation, but many regional implications for the Arctic as well. The potential for coastal erosion, effects on the livelihoods of indigenous peoples, effects on marine organisms, and increased marine transport and access to resources were all well documented in ACIA. At least one of these projected impacts became more of a reality in the summer of 2007, when the Northwest Passage was free of ice for the first time.

Policy implications

The increasing range, magnitude, and unexpected pace of arctic climate change impacts outlined in this report highlight the added risks that are emerging from an Arctic subject to climate change. Consequently, the conclusions drawn from this report prompt the following most urgent policy actions:

1. Mitigation. At this point, the radical impacts on important arctic systems are caused by global warming that is only half of what humanity is already committed to experience, and what according to current policies is considered to be "not dangerous" (IPCC 2007). Therefore, the dramatic impacts on the Arctic that are now being observed challenge the magnitude of the predicted impacts of climate change at both arctic and global levels. The Arctic is a key component of the Earth's climate system and with its responding to climate change faster than previously understood, there is a substantially heightened risk for arctic positive feedback mechanisms to contribute to faster and stronger global climate change than previously predicted.

2. Protecting the integrity of vulnerable arctic carbon pools. More potential for feedbacks to the Earth's climate system is held in store in the Arctic, in the form of carbon contained in permafrost soils and sediments. An unknown part of this vast pool is vulnerable to be released to the atmosphere as CO_2 or methane through climate change impacting on thermokarst formation, on the interactions of soil temperature and water conditions, as well as on vegetation. Even though this report provides only localised evidence of climate impacting on the permafrost carbon pool to date, the magnitude of the potential feedbacks in combination with a limited scientific understanding of the dynamics and thresholds defining this pool, is a matter of concern. No permafrost carbon dynamics are currently incorporated in climate models.

3. Managing ecosystems for resilience. Recent changes observed over a wide range of arctic ecosystems in response to climate change are affecting species distribution, composition, and population numbers, and through it food webs and human subsistence harvests and husbandry. Under these diverse pressures, the resilience of many arctic ecosystems appears severely stretched. However, despite considerable research demonstrating impacts on arctic ecosystem structure and processes, there remains a limited scientific basis for predictive forecasting of arctic socio-ecological systems dynamics in response to climate and other anthropogenic pressures. As these pressures increase, there is a real danger for arctic ecosystems to change beyond critical thresholds before an understanding of the changes can be achieved and concrete measures can be taken to avoid passing these thresholds. Precautionary management approaches that build ecosystem resilience are the appropriate and only tool available that can keep arctic ecosystems stable under diverse pressures.

Given the state of the Arctic as outlined in this report WWF concludes that conservation in the Arctic has reached a turning point. With the Arctic the stakes are global. The debate can no longer focus only on creating protected areas and allowing arctic ecosystems to find their balance. The magnitude of the physical and ecological changes in the Arctic creates an unprecedented challenge for governments, the corporate sector, community leaders and conservationists to reinforce the potential for natural systems to adapt, and to define a sustainable future for the people and ecosystems of the Arctic.

Addressing the root causes of climate change requires a global response. WWF's Arctic Network Initiative works to create the momentum for such a response. In answer to the challenges facing the arctic environment, WWF advocates a two-pronged strategy: first, reducing global emissions of greenhouse gases to levels that will avoid the continued warming of the Arctic and the anticipated resulting disruption of the global climate system and, second, simultaneously reducing the vulnerability of social and environmental systems of the Arctic by reducing immediate threats and building inherent resilience.

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2. Summary: Arctic Climate Impacts today

Atmosphere

- Confirmation by the IPCC (2007) of the oft-cited ACIA (2005) finding that temperatures in the Arctic have increased at almost twice the rate of the global mean over the past few decades. Further demonstration of the importance of feedback effects from the reduction of snow and ice cover in this ‘arctic amplification.

- Recent arctic surface air temperatures anomalies and associated sea-level pressure fields shown to have a different pattern than during other 20th century periods of warming, evidence of entering into a new and uncertain climate pattern.

- Increased certainty that recent warming in the Arctic (and globally) is influenced by human activities. (The ACIA had concluded that there was insufficient evidence to draw conclusions on this point.)

- Range of arctic warming projections from recent work remains close to the range of the ACIA model projections, and, as with the ACIA, warming is projected to be greater in autumn and winter.

- Trends to increased precipitation as described in the ACIA continue. Improved modelling of precipitation shows much greater increases in precipitation in the Arctic than the global mean.

Oceans

- Pronounced warming in Arctic Ocean peripheral seas particularly since 2000, with sea surface temperature anomalies in summer 2007 of up to 5°C, and possible regional interactions with sea ice decline.

- Large natural variability in Atlantic Meridional Overturning Circulation (MOC), but decadal trends are correlated with the Arctic Oscillation. The MOC is central to global ocean circulation and strongly influenced by the Arctic Ocean and surrounding seas.

- Advances in understanding mechanisms of potential MOC weakening –especially the importance of changes in the Labrador Sea. Findings are not yet conclusive due to a combination of high natural variability and lack of long-term observations.

- The ACIA reported that most models projected weakening, but no abrupt transitions, of the MOC during the 21st century and this is still the case.

Glaciers

- Further evidence of continued and accelerating glacier decline (worldwide and in the Arctic). Predictions of complete loss of glaciers in many areas in coming decades.

- Trend reversal for northern European glaciers. Glaciers were reported as gaining ice mass (Scandinavia) or no change in ice mass (Svalbard) in the ACIA. Recent studies show trends of ice loss for both Svalbard and Scandinavia.

- Particularly large ice loss from Alaskan glaciers – with a correspondingly large contribution to sea-level rise.

Greenland Ice Sheet

- Evidence of accelerating mass loss of ice from new satellite monitoring techniques -- considerably higher loss than predicted from models.

- Increased attention to the contribution of ice dynamics (mainly faster flow of glaciers) as the dominant mechanism of shrinking of the ice sheet, as opposed to changes in surface melting and runoff.

- Recognition that current models are not considering the mechanisms that dominate recent mass losses and that IPCC model projections are therefore unrealistically conservative. Recognition of the need to include dynamic, non-linear processes in modelling.

- Increasing trends in (1) surface melting and runoff and (2) snowfall approximately balanced out, resulting in little change in surface mass balance in the period 1958-2006.

- Estimates of contribution of mass loss from the Greenland Ice Sheet to sea level rise revised increasingly upwards
    - from 0.13 mm/yr (ACIA)
    - to 0.14 to 0.28 mm/yr in the period 1993-2003 (IPCC 2007)
    - to 0.5-0.6 mm/yr currently (estimates in recent research papers).

Sea Ice

- Marked acceleration of the decrease in arctic sea ice extent in recent years, with the 2007 minimum ice extent being 39% less than the 1979-2000 average. The decreasing trend in winter ice extent has also accelerated in recent years (becoming a significant trend in 2004).

- Reduction in thickness and age of ice – less extent of multi-year ice.

- Improved understanding of the relative contributions of natural fluctuations and radiative forcing from greenhouse gases in these changes in ice extent.

- Need for revision of the previous, conservative ACIA and IPCC projections on sea ice decline in the Arctic and awareness of the possibility of reaching (or having reached) a tipping point, leading to much faster disappearance of multi-year ice.

Snow Cover

- General decline in snow extent during the era of satellite measurements. Long-term decline in spring snow extent during the past 20 years compared to the previous 60 or so years (continuing the trend reported in ACIA).

- New and better projections for future changes in regional snow extent. While the overall trend is to decreasing snow cover, snowfall is projected to increase in some arctic areas.

- Quantification of impact of feedback from changes in snow albedo, showing that lengthening of the snow-free season has a major impact in accelerating local atmospheric heating.

River and Lake Ice

- Reduction in ice-cover duration, characterised especially by earlier spring break-ups, based on recent studies examining trends from the latter half of the 20th century at a regional or continental scale, mostly in North America.

- Increasing trend in occurrence of mid-winter break-up events of river ice, potential causes of severe flooding.

Permafrost

- Continuation of the permafrost warming trend identified in ACIA. Better information available for trends in many regions, including Siberia, Svalbard, Alaska and the Mackenzie Valley in Canada.

- Increasing evidence of changes in active layer thickness, though variability between years and locations is great. ACIA did not report changes in active layer thickness.

- Evidence of permafrost degradation and significant impacts on wetlands – drainage of thermokarst ponds in areas with discontinuous permafrost and, in continuous permafrost regions, creation of new water bodies by thermokarsting.

Projections show widespread disappearance of lakes and wetlands even in formerly continuous permafrost zones.

- More information on carbon stored in permafrost, showing that permafrost is as large a carbon reservoir as the atmosphere. Estimates of half of global permafrost stores of carbon in yedoma (a type of carbon-rich permafrost) in parts of Siberia. Yedoma is considered a globally significant potential source of carbon emissions in response to permafrost thaw.

- Evidence of a globally substantial source of atmospheric methane from thawing permafrost below thermokarst lakes in Siberia.

- Recognition of the need to incorporate permafrost (soil) carbon dynamics and feedback processes into climate change models.

Ecosystems

- Expanding research base since ACIA documenting impacts of climate change at species, community, and ecosystem level in marine, terrestrial, and freshwater systems.

- IPCC AR4 identifies sea ice biome as the marine ecosystem most likely to be especially affected by climate change (confirmation of ACIA). Confirmation by evidence of declining trends for a range of marine species of the sea ice biome, including some in the upper trophic levels (e.g., ringed seals, some populations of ivory gulls, grey whales).

- Work since the ACIA confirms the risks to polar bears from decline and earlier break-up of arctic sea ice, with a conservative model projecting a two-third loss of the current population by mid-century. Studies show impacts on body condition, size, and on behaviour in several regions. Changes at population level changes are often complicated by influence of harvest, but declines in two of 19 populations have been attributed to climate change. Population surveys have been undertaken in some regions to establish or improve baseline data.

- Increasing air and water temperatures and a reduction in sea ice have coincided with a major shift from an arctic to sub-arctic ecosystem in the last decade in the northern Bering Sea. Preliminary evidence for similar effects in Barents Sea and Laptev Sea with potential to decrease harvestable fish production.

- Evidence of treeline advance, and an increase in the abundance and extent of shrubs in tundra areas in many arctic regions attributable to climate change. Projections for this trend to continue. Evidence for both these vegetation shifts to contribute substantially to regional warming, through lower albedo.

- Photosynthetic activity (atmospheric CO2 uptake) increased for tundra vegetation, but decreased for boreal forest over the last 25 years.

- Recognition of large feedback potential of arctic terrestrial ecosystems to increase atmospheric concentrations of CO2 and methane. Findings show increased CO2 emissions from tundra soils under shrubs and increased methane emissions from thawing permafrost under thermokarst lakes. Projections are not yet conclusive mostly because of uncertainties in interactions with hydrological cycle. Recognition of the need to incorporate ecosystem carbon dynamics and feedback processes into climate change models.

- Shifts in species phenology with significant advances observed in plant growth and flowering, invertebrate emergence, and egg-laying in numerous bird species across different regions. Evidence from the high Arctic indicates that timing of ice and snowmelt is the most important factor for most ecological processes.

- Vegetation changes, ice crust formation due to freeze-thaw events, freezing rain, and collapse of under snow spaces are affecting the population dynamics of some key herbivores, including caribou, and predators.

- Evidence of arctic ponds and lakes becoming more productive and changing pH, with impacts on populations and diversity. High arctic pond ecosystems have desiccated due to increased evaporation.

Human Dimension

- Recognition of Health Impact Assessments as an approach to understanding health outcomes of climate change.

- Since the ACIA, the research community has prioritised exploring how existing policy structures and resource management regimes will interact with the down-scale impacts of climate change, and how the findings of human dimension research can inform new innovations in policy-making to affect more sustainable response strategies.

- Recognition of the need for locally- and regionally-scaled projects capable of detecting interactions between climate and other drivers of change, of identifying differently-impacted sub-groups (e.g. household, community), and of identifying the specific pathways by which change translates into localised impacts.

- Together, vulnerability, adaptation and resilience are the most frequently discussed analytical frameworks in human dimension climate change literature since 2004. However, they continue to be used without standardisation or cross-referencing across the literature, despite attempts to reconcile definitions and frameworks.

- Acknowledgement that an understanding of ecological processes is essential for effective adaptive governance. Studies argue for open collaboration in social-ecological research

- Suggestions for an approach to facilitating climate-change adaptation to be mainstreaming it within policy areas outside climate change, such as poverty alleviation, education, healthcare and sustainable development.

- Actively involving communities in the research process is seen as an important way in linking research to adaptation-friendly policy outcomes. Interventions to reduce vulnerability are regarded to be more successful if they are identified and developed in co-operation with local actors.

3. Atmosphere

Temperature

Recent changes in temperature

Temperatures in the Arctic have continued to increase in recent years at rates greater than the global average. Like ACIA (2005), the IPCC AR4 (2007) reported that surface air temperatures (SAT) in the Arctic have increased at almost twice the rate as the global mean over the past few decades. Annual surface air temperatures over land have been consistently above the 20th century average since the early 1990s; over the last decade, the temperatures have been about 1.0°C above the 20th century average (Overland *et al*. 2007b; Overland and Wang 2007) (Figure 3.1). According to the Goddard Institute for Space Studies (GISS) analysis, 2007 tied with 1998 as the second warmest year in the period of instrumental data beginning in 1880, behind the record warmth of 2005; the greatest warming occurred in the northern high latitudes and Arctic (Hansen *et al*. 2007; Hansen *et al*. 2006) (Figure 3.2).

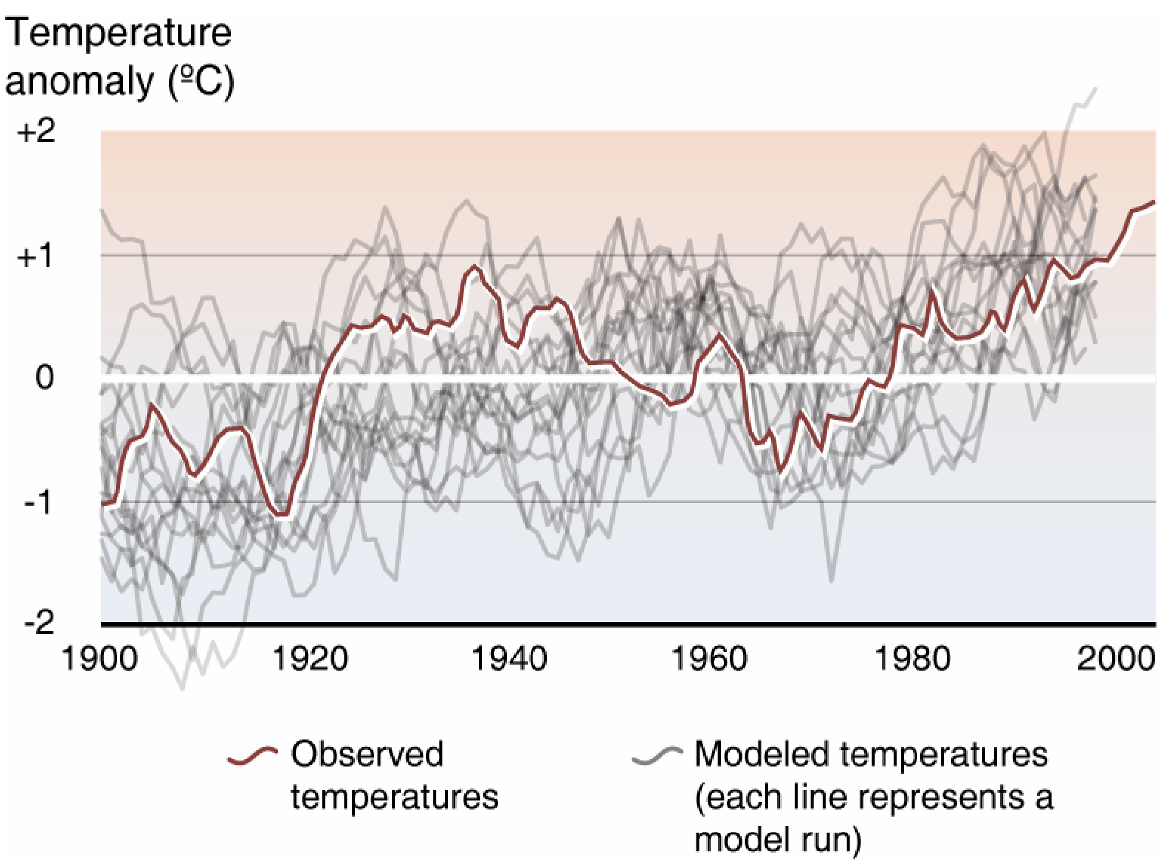

Figure 3.1 Arctic winter land surface temperatures in the 20th century, modelled and observed. Anomalies are relative to the average temperature over 1961-1990. Source:

UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library). Based on Wang et al. (2007).

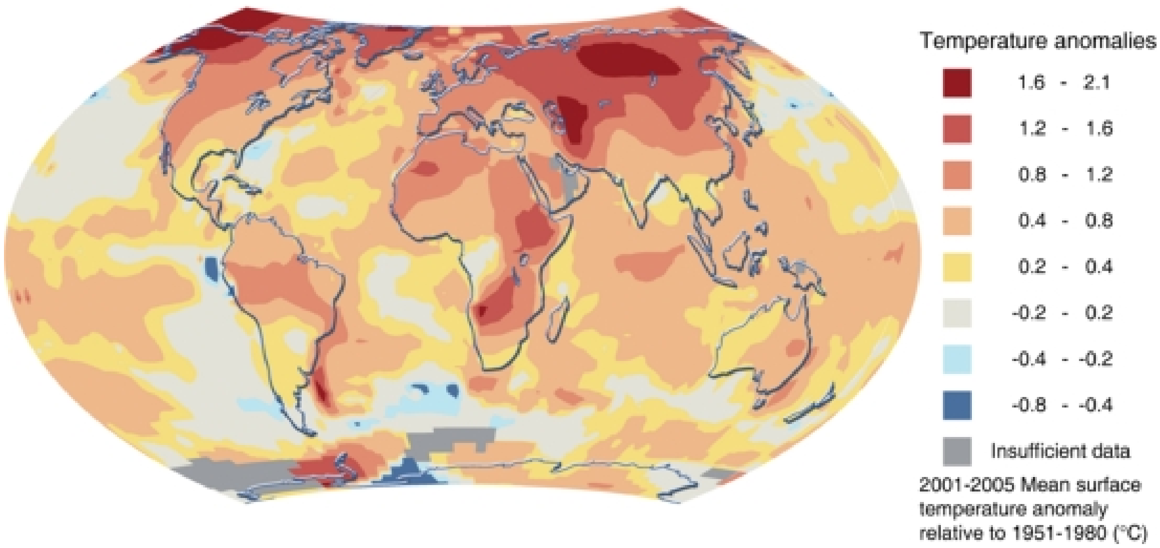

Figure 3.2 Increases in annual temperatures for 2001-2005 relative to 1951-1980, showing the greatest warming over land and at high latitudes in the Northern Hemisphere. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) Based on Hansen et al. (2006).

Patterns of recent temperature change

The recent surface air temperatures anomalies and associated sea-level pressure fields have a decidedly different pattern than other periods of warming during the 20th century (Overland and Wang 2007) (Figure 3.3). The two main atmospheric circulation patterns of the 20th century, the Pacific North American-like Pattern, which was in its positive phase during 1977-1987, and the Arctic Oscillation/Northern Annular Mode, which was in its positive phase during 1989-1995, contributed to warm anomalies in the Arctic primarily over their respective eastern and western hemisphere land areas during these periods (Overland and Wang 2005). In contrast, the recent warming period during 2000-2007 is characterised by Arctic-wide warming centralized over the Arctic Ocean; a dipole sea-level pressure (SLP) pattern over the Arctic with anomalous wind flow towards the central Arctic supports the above average temperatures through warm air advection (Overland and Wang 2007). The period from 1928–1935 also had a dipole structure in SLP, which contributed to Arctic-wide warm temperature anomalies in the first half of the 20th century (Overland and Wang 2005). The Arctic Oscillation index was negative in 2006, but positive in 2007, continuing the trend that began in the mid-1990s of relatively low values fluctuating between positive and negative. This is more consistent with the Arctic Oscillation index during the period from the 1950s to the 1980s, in contrast to the consistently positive phase from 1989-1995 (Overland *et al*. 2007a). The recent warm period thus represents a new and uncertain climate pattern (Overland *et al*. 2007b).

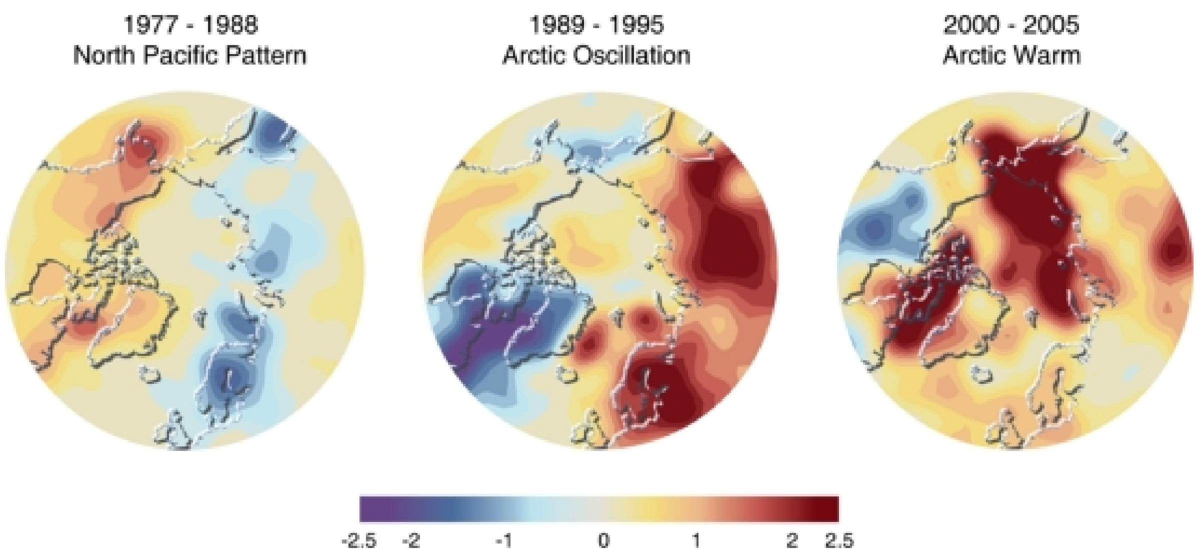

Figure 3.3. Recent Northern Hemisphere surface temperature anomalies averaged over periods with different dominant patterns of natural variability. The pattern of warm temperature anomalies in recent years (2000-2005) does not match either of the two previous climate patterns. (Source: UNEP/GRID-Arendal. 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) Based on J.E. Overland (2007), data from NOAA/ESRL. Climate composites. NOAA/ESRL Physical Sciences Division, Boulder, CO. http://www.cdc.noaa.gov/cgi-bin/Composites/ printpage.pl [Accessed 6 April 2007]

Drivers of temperature change

ACIA (2005) highlighted the fact that further study is needed to firmly conclude that the recent increase in Arctic temperatures is due to anthropogenic forcing rather than natural variability. Decadal and inter-annual variability are great in Arctic SAT due to high natural variability in the Arctic climate as well as to sparser data sets (ACIA 2005). The IPCC AR4 came out with the firmest pronouncement yet that it is *highly likely* (90% confidence) that humans have already contributed to a rise in global temperatures due to an increase in greenhouse gas forcing (IPCC 2007). Using 20 different atmosphere-ocean coupled global circulation models, Wang *et al*. (2007) demonstrated that the increase in winter land SAT at the end of 20th century can only be simulated by models when CO_2 and other greenhouse gases are added as an external forcing (Figure 3.1). In contrast, warming in the earlier part of the 20th century can be explained by natural variability as models can simulate these warm anomalies without any external forcing. This is consistent with the findings of an earlier study that used two coupled global circulation models (Johannessen *et al*. 2004).

Feedback effects from the reduction of snow and ice cover seem to have played a role in the 'Arctic amplification' phenomenon of global warming, as projected by global climate models in response to enhanced greenhouse gas forcing. Walsh (2007) demonstrated that surface albedo-temperature feedback has enhanced recent warming in two ways: first, the retreat of Arctic sea ice has created a footprint of enhanced warming during autumn and early winter in the periphery of the Arctic Ocean. Correspondingly, the large Arctic warm anomaly of 2007 is consistent with observations of record low Arctic sea ice cover in September of 2007 (Hansen *et al*. 2007). Comparison of observations with near-future model projections of Arctic SATs over land and ocean reveals that we are likely very near a threshold in which absorption of solar radiation during summer will limit ice growth during autumn and winter, thus leading to a substantial increase in surface air temperatures over the Arctic Ocean as projected by climate models (Serreze and Francis 2006). Second, earlier springtime disappearance of snow cover from northern land areas has enhanced the springtime heating of the surface by approximately 1 watt per square meter, consistent with the enhanced warming over northern land areas during spring (Walsh 2007). This is consistent with findings that a lengthening of the snow-free season in Alaska has increased local atmospheric heating by about 3 watts per square meter per decade (Chapin *et al*. 2005).

Changes to atmospheric and oceanic circulation, as well as cloud cover, may also cause amplification of global warming in the Arctic. Graversen *et al*. (2008) found that while snow and ice feedbacks are expected to affect temperatures primarily in the lower atmosphere, most warming in the Arctic in the 1980s and 1990s occurred well above the surface. Examination of the flow of energy into the Arctic using meteorological data points to changes in atmospheric heat transport as an important cause of the recent Arctic temperature amplification (Graversen *et al*. 2008).

Outlook

The five ACIA-designated models, using the A2 and B2 IPCC emissions scenarios, projected a 2.5°C increase by mid-century for the region north of 60°N (ACIA 2005). 7°C and 5°C increases were projected for the end of the 21st century for the A2 and B2 scenarios, respectively, which were double the global projections (ACIA 2005). Amplification of projected 21st-century warming in northern latitudes is also a consistent feature of all climate models used in the IPCC AR4 (2007). Consistent with ACIA, the projected annual mean warming in the Arctic exceeds the global mean warming by roughly a factor of two (IPCC, 2007). Although the rates of projected warming vary considerably among the models, a study of 14 models used in the IPCC AR4 shows that they all project an Arctic twenty-first-century warming that is largest in the autumn and winter, as projected in ACIA (Chapman and Walsh 2007). The winter warming in the central Arctic exceeds the global annual mean by a factor of four when averaged over the models (IPCC 2007). Using 12 IPCC models whose simulations best matched 20th century observations, Overland *et al*. (2007b) projected an increase in Arctic annual mean temperatures of 3°C by 2050. The projection of Arctic warming averaged for all models is 5°C, 5.9°C, and 3.4°C by the end of the century for the A1B, A2, and B1 scenarios, respectively (IPCC 2007).

Precipitation

Recent changes

Using six global land-area precipitation data sets, including the GHCN database employed by ACIA, the IPCC AR4 (2007) concluded that precipitation has generally increased over land north of 30°N from 1900 to 2005. In central and eastern North America, northern Europe, and northern Asia, precipitation has increased by 6 to 8% from 1900 to 2005 (IPCC 2007). This is consistent with the positive trend of 1.4% per decade from 1900 to 2005 for the Arctic (60°N to 90°N) reported in ACIA (2005). Since these regions all experience snowfall, part of the trend may arise from increases in the efficiency of measuring snowfall; however, the trends are supported by measured changes in streamflow (IPCC 2007, Groisman *et al*. 2004). The trend also extends across the North Atlantic, as evidenced by ocean freshening (Josey and Marsh 2005).

Outlook

Climate models appear to be less reliable in projecting climate variables other than temperature, such as precipitation or wind conditions (DeWeaver and Bitz 2006). However, there are some indications that the models used in the IPCC AR4 have improved in their simulation of Arctic precipitation compared to the previous generation of models used in the IPCC TAR (Kattsov *et al*. 2007). General increases in precipitation at high latitudes are very consistent and of a similar magnitude (per degree of warming) across IPCC AR4 models, with the increases strongly correlated to the projected warming. Percentage increases in the Arctic are much larger than the global mean precipitation (Kattsov *et al*. 2007). As projected in ACIA, relative increases are largest in the winter and smallest in the summer, consistent with the project warming and with observations up to present (IPCC 2007). There is substantial variation between models, but the monthly ensemble mean of the models used in the IPCC AR4 are within the range of observational datasets, which is an improvement over simulations used in ACIA (IPCC 2007).

Local changes in temperature and precipitation are largely dependent on changes in synoptic circulation patterns (IPCC 2007). Not all models accurately simulate changes in the frequency of occurrence of these patterns; of 15 global climate models evaluated, only 4 models were able to reproduce the key features of the Arctic synoptic climate as observed for the period of 1991-2000 (Cassano *et al*. 2007). Models generally indicate an increase in cyclonically dominated weather patterns over the 21st century in the Arctic, with the change in pressure patterns during winter favoring precipitation increases along the Canadian west coast, southeast Alaska and North Atlantic extending into Scandinavia (Cassano *et al*. 2007; Cassano *et al*. 2006). Groisman *et al*. (2005) reported that an increased probability of intense precipitation events can be expected in many extratropical regions.

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4. Oceans

Ocean temperature and salinity

Since 2000, conditions of the upper ocean in the central Arctic Ocean have relaxed back to those before the dramatic changes of the 1990s (Morison *et al*. 2006a). The change in the 1990s and the subsequent return to pre-1990s conditions seem to be correlated with the Arctic Oscillation (Morison *et al*. 2006a). Measurement of bottom pressure trends from 2002 to 2006 support a return to pre-1990s climatology over the whole Arctic Ocean (Morison *et al*. 2006b). However, preliminary data for 2007 shows a slowing in this rate of return (Proshutinsky and Morison 2007). Steele *et al*. (2008) found that warming in the Arctic Ocean peripheral seas has been pronounced since 1995, and particularly since 2000, with sea surface temperature anomalies in summer 2007 up to 5°C. The heat content in the Beaufort Gyre, the major reservoir of freshwater in the Arctic Ocean, has increased and the recent pronounced sea ice reduction in this region may have resulted from the increase in Pacific water heat content in this region (Shimada *et al*. 2006).

Ocean circulation in the Atlantic

The Atlantic Meridional Overturning Circulation (MOC) consists of a northward inflow of warm, saline upper-ocean waters from the low latitudes and a southward flow of cold, dense, deep waters from the high latitudes. The processes occurring in the Arctic Ocean and surrounding seas—the Nordic Seas and the Labrador Sea—are very important climatically as they affect the rate of deep-water formation in the North Atlantic, thereby influencing the Atlantic MOC (ACIA 2005; IPCC 2007). The Labrador Sea is generally considered to provide one-third of the North Atlantic Deep Water (NADW), while overflows from the Nordic Seas/Arctic Ocean across the Greenland-Scotland Ridge provide the remaining two-thirds (Hansen *et al*. 2004). ACIA (2005) reported that most climate models predict a weakening of the Atlantic MOC during the 21st century due to increased freshwater input in the Arctic. This weakening would have subsequent effects on Arctic climate. However, at the time of ACIA the observational evidence for a weakening in the MOC was uncertain (ACIA 2005). This is still the case, with recent findings particularly highlighting the large natural variability in ocean currents.

Based on measurements of heat flow from the years 1957, 1981, 1992, and 2004, Bryden *et al*. (2005) found a 30% reduction in the Atlantic MOC at 25°N between 1957 and 2004, although lack of supporting direct current measurements reduces confidence in this estimate. New measurements of currents recorded between the Bahamas and the Canary Islands at 26.5°N show that the strength of the Atlantic MOC fluctuates widely, with the previous findings of Bryden *et al*. 2005 fitting within the huge range of seasonal fluctuations (Cunningham *et al*. 2007). Additionally, in direct contrast, Knight *et al*. (2005)

and Latif *et al*. (2006) reported that the Atlantic MOC has increased in strength over the last several decades, based on ocean observations and model simulations.

It has been argued that early evidence for changes should be sought in the rates of overflow across the Greenland-Scotland Ridge (Hansen *et al*. 2004). Although freshening of the Nordic Seas has been observed over the last few decades (Curry and Mauritzen 2005), this negative influence on the overflow rates may be counteracted by the observed increase in salinity in the waters of the North Atlantic over the last 50 years (Boyer *et al*. 2007). In any case, there does not seem to have been a reduction in strength of the overflow. Overflow from the Denmark Strait, one of the main overflow branches, showed considerable interannual variability during a 4-year program of observations, without enough years of observation to discern long-term trends (Macrander *et al*. 2005). Based on a 10-year long series of measurements, Hansen and Østerhus (2007) also found large seasonal and interannual variability but no discernible long-term trend in the Faroe Bank Channel overflow, the other important overflow branch. On the other hand, convection in the Labrador Sea, the other major contributor to the NADW, has changed over the last decade (IPCC 2007). Climate modellers now predict that weakening of the Atlantic MOC will occur as a result of changes in the Labrador Sea, as opposed to changes in overflow rates (Hansen 2008).

Thus, findings are inconclusive partly because of the large natural variability observed in components of the Atlantic MOC and partly due to inadequate long-term observations. The models used in the IPCC 4AR show a reduction in the Atlantic MOC of up to 50% or more by the end of the 21st century, when forced with the SRES A1B scenario (IPCC 2007). Since the TAR, more coupled models have become available, and therefore the evolution of the Atlantic MOC can be more thoroughly assessed. The reduction in circulation is a result of the predicted increases in high-latitude temperature and precipitation, both of which make the high-latitude surface waters less dense and increase their stability (IPCC 2007). Based on these models, however, it is very unlikely that the MOC will undergo an abrupt shut-down during the 21st century (IPCC 2007).

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5. Glaciers, Ice Caps, and the Greenland Ice Sheet

Glaciers and ice caps

Recent studies have continued to document general glacier degradation in the Arctic and worldwide which has accelerated over the past two decades. Based on mass balance measurements of more than 300 glaciers, including glaciers in the Arctic, Kaser *et al*. (2006) estimated glaciers worldwide to have lost 219 ± 112 kg m^{-2} per year between 1961-1990, which more than doubled to a loss of 510 ± 101 kg m^{-2} per year between 2001-2004 (or 136 Gt/year from 1961-1990 and 354 Gt/year from 2001-2004, based on an area of glaciers and ice caps of 763 000 km^2). Since a step-wise change in climate would cause initial mass balance change followed by a return to zero values, these trends are indicative of ongoing changes in climatic conditions (Zemp *et al*. 2007).

Recent mass losses in the Arctic

ACIA (2005) reported a positive mass balance for Norwegian glaciers during the 1990s, attributed to increased precipitation due to a positive phase of the North Atlantic Oscillation, but subsequent negative mass balances. Recent publications have confirmed this trend reversal, reporting considerable retreat of Norwegian glaciers since 2000 (Nesje *et al*. 2008; Andreassen *et al*., 2005). While ACIA reported no significant mass changes in Svalbard glaciers, Haeberli *et al*. (2005) showed strong trends in ice loss over the past 40 years from two Svalbard glaciers. In 2002, a much-cited study reported large and accelerating mass loss from Alaskan glaciers, collectively contributing an equivalent sea-level rise of 0.27 mm per year, which was the largest glaciological contribution to sea-level rise yet measured (Arendt *et al*., 2002). A comprehensive survey of changes in the area and length of Alaskan glaciers by Molnia (2007) corresponds well to these findings, reporting that 98% of the glaciers surveyed are currently thinning and/or retreating. See Figure 5.1. for an overview of regional glacier changes in the Arctic.

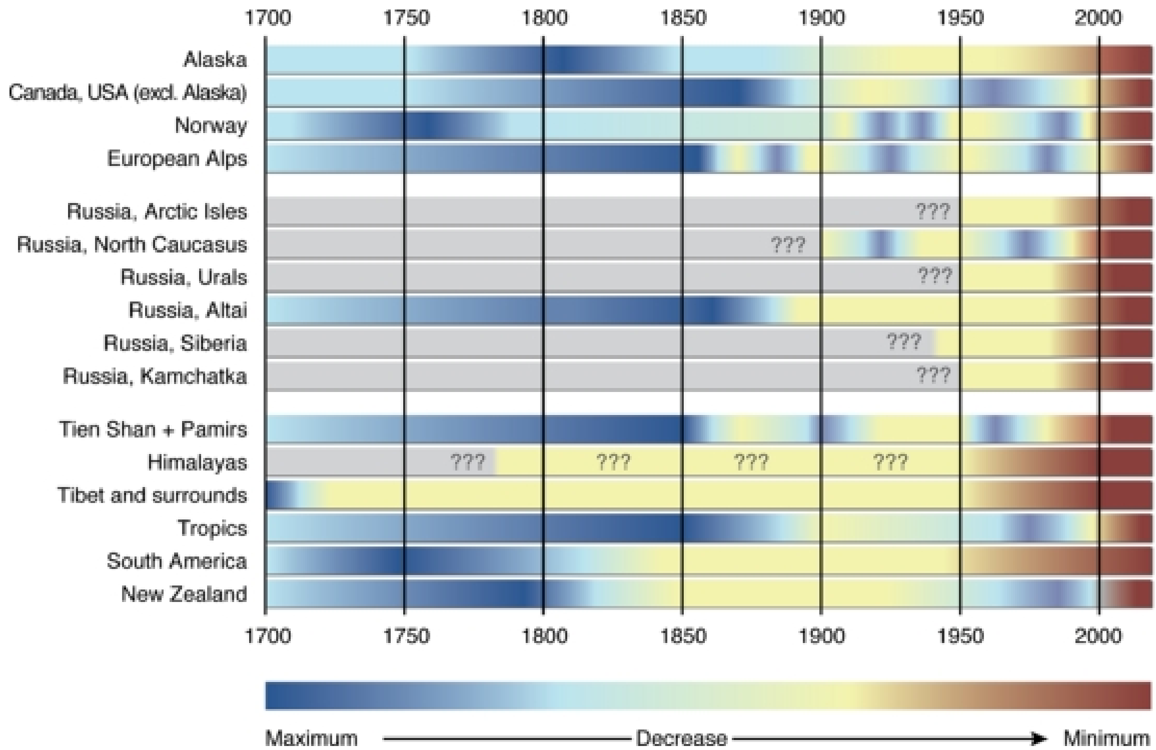

Figure 5.1 Overview of regional glacier changes since the end of the Little Ice Age (early 14th to mid 19th century). Source: UNEP/GRID-Arendal, 2007. (UNEP/GRID-Arendal Maps and Graphics Library). From Zemp and Haeberli (2007).

Outlook

Present climate scenarios indicate that the current trends of glacier mass loss are non-periodical in nature and may lead to complete loss of glaciers in many regions in coming decades (Zemp *et al*. 2007). The IPCC (2007) projected that, depending on the emission scenario, glaciers and ice caps will contribute from 7 to 17 cm of sea level rise between 1980-1999 and 2090-2099, making up about 29-38% of the total projected sea-level rise. A later study, taking into particular account the recent accelerations in ice loss and the importance of dynamic processes of ice loss, estimates that glaciers and ice caps, including those surrounding the ice sheets, will contribute 10-25 cm of sea level rise by 2100 (Meier *et al*. 2007). Although, apart from those in Alaska, glaciers in the Arctic are not among the highest in terms of mass loss per unit area, their large areas mean that they will be among the biggest contributors to sea-level rise (Romanovsky *et al*. 2007).

Greenland Ice Sheet

ACIA (2005) reported high-elevation balance of the Greenland Ice Sheet but considerable thinning around the coast, with a conservative estimate of net loss of ~50 km^3 per year. Since that time, satellite monitoring has improved understanding of the current mass balance of the ice sheet. Despite discrepancies between estimates and the short data spans, which mean results are considerably affected by year-to-year variability, findings in the last few years have confirmed net loss of mass from the Greenland Ice Sheet and showed that this mass loss is accelerating (IPCC 2007).

Evidence of accelerating mass loss

Some of the most convincing evidence for mass loss comes from the Gravity Recovery and Climate Experiment (GRACE) mission of gravity satellites launched in 2002. Measurements from GRACE show an ice mass loss of 239 ± 23 km^3 per year from the period April 2002 to November 2005 (Chen *et al*. 2006) or 248 ± 36 km^3 per year from April 2002 to April 2006 (Velicogna and Wahr 2006). This rate is three times larger than the rate of 80 ± 12 km^3 per year during the period 1997 to 2003, measured by airborne laser altimetry measurements (Krabill *et al*. 2004). GRACE measurements indicate that the acceleration in ice loss started in the spring/summer of 2004 and occurred almost entirely in southern Greenland (Chen *et al*. 2006; Velicogna and Wahr 2006). The rate of ice loss increased by 250 per cent between the periods April 2002 to April 2004 and May 2004 to April 2006 (Velicogna and Wahr 2006). An earlier analysis of the first two years of GRACE data had estimated an ice mass loss of 82 ± 28 km^3/year during 2002-2004 (Velicogna and Wahr 2005); the increase in later estimates of rate is due to improved filtering and estimation techniques for the data as well as to the acceleration of mass loss (Chen *et al*. 2006).

The gravity results agree remarkably well with a recent study using satellite radar interferometry data, which found that Greenland mass loss more than doubled between 1996 and 2005 from 90 km^3 per year to 220 km^3 per year (Rignot and Kanagaratnam 2006). In addition, this study found that glacier accelerations occurring in southern Greenland may be in the process of spreading northwards (Rignot and Kanagaratnam 2006). Laser altimeter measurements also show an acceleration in ice loss, with net mass loss more than doubling between the periods 1993/4-1998/9 and 1998/9-2004 (Thomas *et al*. 2006). Khan *et al*. (2007), studying elastic uplift in southeastern Greenland using GPS measurements, found an uplift of 3.5 cm between 2001 and 2006, with an acceleration in uplift since 2004 indicating an acceleration of ice loss since that time.

Mechanisms of ice loss

Until recently, it was thought that velocities of outlet glaciers and ice streams cannot change rapidly, and climate change was thought to impact primarily on snowfall and surface melting of the ice sheet (IPCC 2007). However, recent findings have pointed to changes in ice dynamics (enhanced glacier flow) rather than changes in surface balance (enhanced surface melting and runoff) as being the dominant mechanism of ice loss from the Greenland ice sheet, though the reasons for these changes are still not well understood.

Rignot and Kanagaratnam (2006) found that ice-flow speed of many outlet glaciers south of 72° N increased by up to 100% beginning in the late 1990s, contributing two-thirds of the observed mass loss during the last decade. Helheim and Kangerdlugssuaq, two of Greenland's largest glaciers, were observed to retreat more than 7 km in 3 years and 5 km during the winter of 2004 to 2005, respectively, concurrent with accelerated ice flow (Howat *et al*. 2005; Luckman *et al*. 2006). The two glaciers have partially slowed down since, indicating a re-equilibration after the perturbation in geometry (Howat *et al*. 2007). Jakobshavn Isbrae increased its speed to about 14 km per year after rapid thinning, and shows no signs of slowing down (Joughin *et al*. 2004). Khan *et al*. (2007) found that, of the uplift observed in southeast Greenland due to mass loss, most was as a result of ice dynamics rather than melt.

The long-term increase in the extent of summer surface melting from 1979-2002 noted in ACIA (see Steffen *et al*. 2004) has continued in recent years, with the summer of 2007 reaching a record high amount of melt. In the first study to extend the passive microwave time series of surface melting back to 1973, Mote (2007) reported that the amount of melt in summer 2007 was 60% more than the previous high in 1998. The amount of melt in 2007 is higher than one would expect based on the relationship between amount of melt and increases in summer temperature. This could indicate that the period of increased melt during 2002–2006 had some effect that would enhance melting in 2007, e.g. through a decrease in surface albedo (Mote 2007). The 2007 melt period was anomalously long, starting as many as 30 days earlier than the average from 1973-2007 and lasting as many as 50 days longer than the average depending on the location (Mote 2007) (Figure 7). In another analysis of satellite data, Tedesco *et al*. (2007) found that the 2007 melt index (length of melt season *x* area of melt) reached a record high in high-altitude areas, at 150% greater than the average from 1988-2006. At low altitudes, though not record breaking, the melt index was 30% greater than the average (Tedesco 2007).

The increasing trend in surface melting corresponds to a long-term increasing trend of 113.0 km^3 per year in meltwater runoff according to a 49-year surface mass balance series (Hanna *et al*. 2008, updated from Hanna *et al*. 2005). However, the surface mass balance time series also shows a significant increasing trend in precipitation (Hanna *et al*., 2008), consistent with recent reports from satellite data showing thickening of the ice sheet at high elevations (Thomas *et al*. 2006; Luthcke *et al*. 2006; Johannessen *et al*. 2005). These findings are consistent with expectations of increasing snowfall in a warming climate. The balance between increased accumulation in the interior of the ice sheet and increased runoff around the edges results in an insignificant trend in surface mass balance from 1958-2006 (Hanna *et al*. 2008).

Although the increases in runoff do not directly outweigh the increased accumulation, indications of net mass loss, mostly as a result of glacier speed-up, have lent support to the suggestion by Zwally *et al*. (2002) that drainage of surface melt water through crevasses and moulins to the base of the ice sheet may act as a lubricant to speed up glacial flow (Hanna *et al*. 2007). An increase in the frequency of glacier earthquakes in the last 5 years, particularly in the summer when surface melting is at its peak, acts as evidence of glacier acceleration and also supports the idea of basal lubrication (Ekstrom *et al*. 2006). Glacial speed-up may also be linked to reduction or loss of ice shelves, as seen in the speed-up of Jakobshavn Isbrae and Helheim glacier, implicating forcing from the ocean as the cause (Thomas *et al*. 2003; Joughin *et al*. 2004; Howat *et al*. 2005).

Contribution of the Greenland Ice Sheet to sea-level rise

ACIA (2005) suggested a contribution of the Greenland Ice Sheet to sea-level rise of 0.13 mm/year, corresponding to a conservative estimate of net ice loss. More recent estimates for the current contribution of the Greenland Ice Sheet to global sea-level rise are higher, corresponding to the observations of greater rates of mass loss. Rignot and Kanagaratnam (2006) estimated a contribution of 0.57 ± 0.1 mm/year in 2005, while Chen *et al*. (2006) suggested a contribution of about 0.54 mm/year during 2002-2005, based on their respective findings of mass loss. The IPCC (2007) reported that Greenland contributed 0.14 to 0.28 mm/year of sea level rise over the period 1993-2003. These contributions make up only a fraction of the current estimated sea-level rise of 3.1 mm/year (Nerem *et al*. 2006), with the remaining sea-level rise due to thermal expansion of ocean waters, contributions from glacier melt, and contributions from the Antarctic Ice Sheet.

Models and projections

The discrepancies between the rapid ice loss observed over the last five years and the ice loss predicted by models for this period have made it clear that existing ice sheet models do not realistically simulate the dynamic responses of the ice sheet that are apparently causing much of the ice loss (Bentley *et al*. 2007). The greatest modelling difficulty arises in simulating stresses at the base and seaward margin of the ice sheet (Vaughan and Arthern 2007). The IPCC (2007) projected a total sea-level rise from all contributing factors of 18-59 cm by the end of this century. However, due to the uncertainty in modelling changes in ice sheet flow, the IPCC (2007) took a conservative approach and excluded the full dynamic ice sheet responses from their projections. Instead, they included a constant dynamic contribution based on the contribution to sea level rise from increased ice flow from Greenland and Antarctica during 1993-2003. This constant results in, for example, a contribution of 3 cm from accelerated ice flow on both ice sheets by 2095 according to the warmest scenario (Rahmstorf 2007a). The upper bound of projected sea-level rise would increase by 10-20 cm if this contribution were instead to grow linearly with temperature change (IPCC 2007); more so if ice flow does not respond linearly to temperature change, for example, due to feedback effects.

Thus, the estimates provided by the IPCC for future ice-sheet related rises in sea level should be regarded as lower bounds (Bentley *et al*. 2007). Hansen (2007), for example, proposes that if temperatures continue to rise, ice loss from the ice sheets may begin to occur rapidly and non-linearly, fed by multiple positive feedback effects—and could reach a sea-level rise equivalent of several metres by the end of the century. Rignot and Kanagaratnam (2006) found a northward trend in the acceleration of outlet glaciers, indicating that the contribution of the Greenland ice sheet to sea-level rise will continue to increase. But it is not possible now to predict the future of the Greenland ice sheet with any confidence (Shepherd and Wingham 2007). Although recent observations of ice sheet change provide an opportunity for model validation, the uncertainties over the future of the ice sheet can be expected to persist into the future (Vaughan and Arthern 2007). Given the difficulties in modelling ice sheets, a semi-empirical method which correlates past changes in sea level with temperature change may be useful to predicting sea-level rise. Using such a method, Rahmstorf (2007b) predicted sea-level rise of 50-140 cm by 2100. Another indication of how conservative current models may be comes from looking at the rates of sea-level rise during the last interglacial period, when temperatures were similar to those predicted for the next 50 to 100 years. Rohling *et al*. (2008) found that average rates of sea-level rise were 1.6 m per century during that period, more than double the maximum estimate from the IPCC 4AR.

Arctic sea-level rise

Satellite observations and hydrographic observations, in agreement with climate models, show that sea level is not rising uniformly around the world. Along Arctic coastlines, sea level is rising, and this rise has accelerated in recent years. The rate of sea level rise along Arctic coastlines from 1954-1989 was approximately 1.9 mm/year, after correction for glacial isostatic adjustment, based on data from coastal stations (Proshutinsky and Morison 2007; Proshutinsky *et al*. 2004). Addition of 1990-2006 data from 9 stations in the Siberian Seas increases the estimated rate of sea level change, beginning in 1954, to 2.5 mm/year (Proshutinsky *et al*. 2004). This rate is comparable with the global sea-level rise of about 1.7 mm/year over the 20th century and 3 mm/year since 1993 (IPCC 2007). Although earlier sea-level rise in the Arctic correlates well with the Arctic Oscillation and sea-level pressure, since 1997 sea level has increased despite the more or less stable Arctic Oscillation and sea-level pressure. The recent sea-level rise in the Arctic is likely a result of decadal variability together with the influences of climate change (land ice melt and expansion of the water column due to increased water temperatures and decreased water salinity) (Proshutinsky and Morison 2007).

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6. Sea Ice

Sea ice extent

Decreases in Arctic sea ice extent have accelerated in recent years. The summers of 2002-2007 featured an unprecedented series of low sea-ice extent minima, with 2005 and 2007 marking the two lowest sea-ice extents since monitoring began. In 2005, the minimum sea-ice extent was 5.6 million km^2 (Richter-Menge et al., 2007). The minimum sea-ice extent in 2007 was 4.3 million km^2, 23% smaller than the previous record low in 2005 and 39% smaller than the long-term average from 1979-2000 (Richter-Menge et al., 2007). In September 2007 the Northwest Passage also completely opened for the first time since regular monitoring began (Figure 6.1) (NSIDC, 2007).

The immediate cause of the extreme low in September 2007 was an unusually strong high pressure centre over the central Arctic Ocean and a strong low over Siberia, which allowed lots of solar heat through the high pressure centre and also pumped warm air from the south between the high and the low (NSIDC, 2007). However, this is not thought to be the only factor contributing to the record minimum (Kerr, 2007).

The decreasing trend in maximum winter sea-ice extent has also accelerated in recent years, becoming significant in 2004 (Meier et al., 2005). The linear trend in sea ice extent over the period 1979-2007, updated since the 2007 summer minimum, is -2.9% per decade for March and -10.5% per decade for September (updated from Gerland et al., 2007).

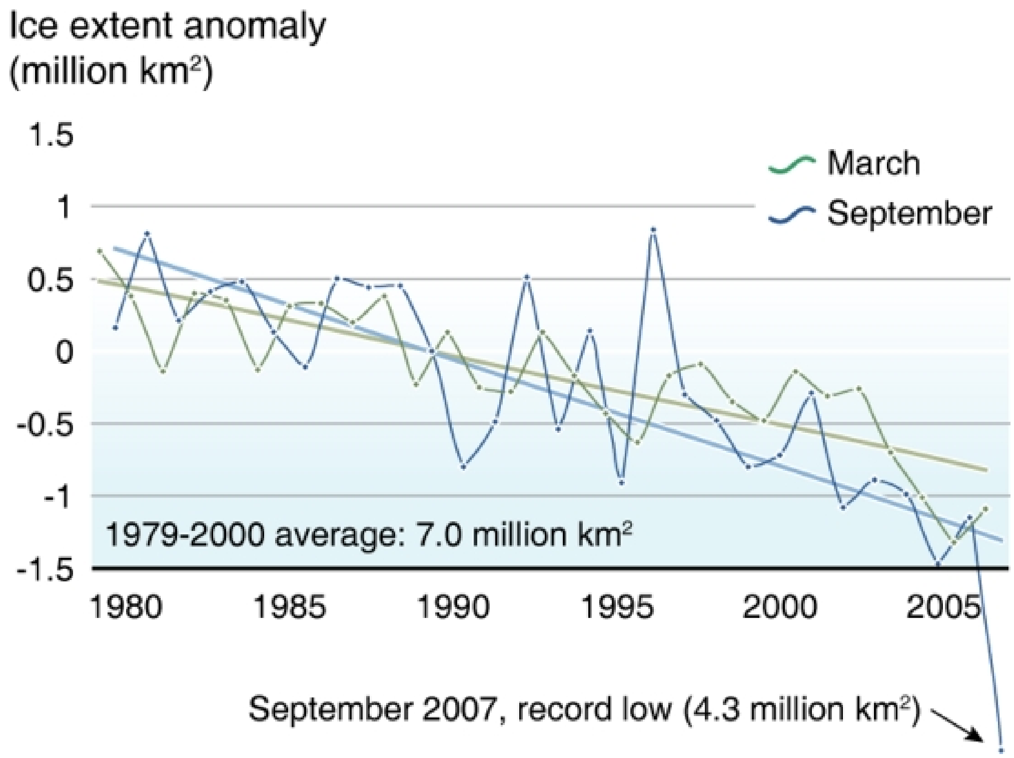

Figure 6.1 Anomalies in sea-ice extent compared to the 1979-2000 average of 7.0 million km^2 in September and 15 million km^2 in March. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library) From: National Snow and Ice Data Center (NSIDC), 2007. Sea Ice Index G02315. ftp://sidads.colorado.edu/DATASETS/NOAA/G02135 (accessed October 22, 2007)

The melt season of Arctic sea ice lengthened by about 2 weeks per decade from 1979 to 2005, corresponding to changes in sea-ice extent (Stroeve et al., 2006). The summer 2007 melt season followed this trend of earlier spring melt and later autumn freezing, with the five-day running minimum of ice extent occurring on September 16, 2007; from 1979 to 2000, the minimum usually occurred on September 12 (NSIDC, 2007).

Sea ice thickness and age (perennial and seasonal sea-ice)

Changes in sea-ice thickness are more difficult to assess than sea-ice extent as there is no comprehensive record of measurements (Gerland et al., 2007). Since the much-cited findings by Rothrock et al. (1999), other analyses of submarine sonar data have also shown decreases in thickness of sea ice (Yu et al., 2004). Based on submarine sonar data and physically based sea ice models, the IPCC (2007) concluded that it is very likely that sea ice thickness in the central Arctic Ocean has decreased by up to 1 m since the late 1980s, with most of the change occurring between the late 1980s and the late 1990s. In contrast, measurements of seasonal ice cover along the Canadian and Siberian coasts do not indicate any significant changes in thickness in recent decades

(Polyakov et al., 2003, Melling et al., 2005), although shorter-term monitoring off the coast of Svalbard showed thinner sea ice during the warmer-than-normal winters of 2005/2006 and 2006/2007 (Gerland et al., 2007). Satellite-based monitoring techniques using radar or laser altimetry have recently been introduced (Kwok et al., 2004), and are promising for future large-scale monitoring of sea ice thickness (see results from ICESat below).

Consistent with the decreases in overall sea-ice extent and sea-ice thickness, decreases in the area of thicker perennial (multi-year) ice have also been observed. Rigor and Wallace (2004) in fact found that the age of sea ice explains more than half of the variance in summer sea-ice extent. These decreases have accelerated in the last few years. A new technique using scatterometer data from the QuikSCAT satellite (QSCAT) suggests a precipitous decrease in the perennial ice extent in the last few years, for example showing a 23% loss between March 2005 and March 2007 (Nghiem and Neumann, 2007, Nghiem et al., 2007b, Nghiem et al., 2006). These findings are confirmed by simulations using drifting buoy data and satellite-derived ice concentration data, which also reveal a significant long-term decline in the relative amount of perennial ice in March ice cover from 1958-2006 (Nghiem et al., 2007a). The decreasing trend started in the early 1970s, when surface air temperatures began to increase Arctic-wide, and became more rapid in the 2000s.

In addition, results from a satellite-derived record of sea-ice combined with ice thickness estimates from the ICESat satellite show that the amount of the oldest and thickest ice within the remaining perennial ice pack has declined significantly (Maslanik et al., 2007). Ice with an age greater than 5 years covers 56 percent less of the Arctic Ocean than in the early 1980s, and the majority of the remaining perennial pack now consists of ice 2 to 3 years old. The younger and thinner ice is predisposed towards rapid, extensive, and persistent reductions in sea-ice extent. The end-of-winter extent of perennial ice in March 2007 was the smallest on record, consistent with the record low summer sea-ice extent in 2007 (Nghiem et al., 2007a).

Causes of decline

Earlier studies attributed changes in sea ice during the early 1990s to a strongly positive phase of the Arctic Oscillation (AO), a large-scale pattern of atmospheric variability (e.g. Rigor et al., 2002). However, the AO has been in a more neutral phase since the mid-1990s and yet changes in sea ice have accelerated since the turn of century. Rigor and Wallace (2004) argued that changes in surface winds associated with fluctuations in the AO dramatically decreased the extent of multi-year ice in 1989-1990, thereby setting the stage for the 2002 and 2003 sea-ice extent minima. But the extreme lows in ice extent in subsequent years have made it difficult to attribute the changes to natural variation in the atmosphere. Examination of models suggests that the ice loss is best viewed as a combination of the strong natural fluctuations in the ice-ocean-atmosphere system and radiative forcing from the increase in greenhouse gases (Serreze et al., 2007). Ogi and

Wallace (2007) found that the year-to-year variations in the summertime atmospheric circulation over the Arctic account for 42% of the year-to-year variability of sea-ice extent from 1979-2006. Stroeve et al. (2007) found that in computer models about half of the observed trend in September sea ice extent from 1979-2006 is caused by greenhouse gas forcing; the role of greenhouse gases may be more given that the models used probably fail to capture the full impact of increased greenhouse gases.

Feedbacks and tipping points

The idea of a sea ice “tipping point”, a point at which strong positive feedback effects will accelerate ice retreat and result in an era of thinner and less extensive sea ice, has been much discussed in the recent literature. Holland et al. (2006) and Winton (2006) showed through modeling that in theory such abrupt changes can occur, and are more likely to occur under higher greenhouse gas emissions scenarios. They found that, in the models, the abrupt changes occurred as a result of mechanisms such as more rapid retreat for a given melt rate as sea ice thins, the ice-albedo feedback, and rapid increases in ocean heat transport to the Arctic (Winton, 2006, Holland et al., 2006). There is evidence that these mechanisms for enhancing sea ice retreat are already occurring in reality. Decreasing trends in winter sea-ice extent have accelerated since 2002 and have now become significant (Meier et al., 2005), which may be the first indication of the ice-albedo feedback effect in action (Meier et al., 2007). Perovich et al. (2007) recently showed increasing absorption of solar heat by open Arctic waters since 1979 as summer ice retreated, suggesting that the ice-albedo feedback had been operating there. And, in a dynamic feedback effect, Nghiem et al. (2007b) found that thinner sea ice as a result of warming made it easier for winds to blow sea ice out of the Arctic Ocean, thus contributing to sea ice loss.

Based on model results, Lindsay and Zhang (2005) suggested that the late 1980s and early 1990s could be considered a tipping point, because, although sea ice thinning was also dependent on changes in air temperatures and the positive phase of the Arctic Oscillation, the thinning was predominantly influenced by the ice-albedo feedback at this time. Strong natural variability and patchiness in the observational record make assessment of the tipping point difficult (Holland et al., 2006). However, with the 2007 record low in summer minimum sea-ice extent, some scientists are starting to speculate that the tipping point has been reached (Kerr, 2007).

Outlook

The five ACIA-designated models all projected decreases in sea-ice extent during the 21st century, with one of the five models projecting an ice-free summer by 2100 (ACIA, 2005). Subsequent thinking tends toward faster loss of Arctic sea ice, with nearly all models predicting enormous sea-ice retreat this century. About half of the current climate models developed as part of the IPCC assessment report 4 (AR4) project a mainly ice-free Arctic Ocean in summer by 2100 (Gerland et al., 2007). The models used in the

AR4 predict rapid decreases in multiyear ice coverage and increases in seasonal (first year) ice area (Zhang and Walsh, 2006). However, models tend to underestimate the current loss of sea ice when compared to observations (Kerr, 2007). Stroeve et al. (2007) found that present summer minima levels are 30 years ahead of the mean model forecast from the IPCC AR4 models. Models probably lack some of the feedback mechanisms and internal processes that contribute to sea ice loss, such as the transport of heat from the sub-polar oceans to the Arctic waters (Stroeve et al., 2007, Kerr, 2007). Holland et al. (2006) reported findings from one climate model that did include such feedback mechanisms; it projected an ice-free summer by as early as 2040. The most extreme projection yet, made by a coupled ice-ocean model using data sets from 1979 to 2004, and thus thought to incorporate more of the internal sea ice processes, predicts that there will be no sea ice in summer by 2013 (Whelan et al., 2007).

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7. Snow

Snow-cover extent

ACIA reported a decrease of snow-cover extent in the Northern Hemisphere by several percent from 1972 to 2003, based on visible satellite data (ACIA, 2005). The trend was strongest in spring and summer (greater than 10%). Recent analyses of satellite data show a continuation of this trend, with snow cover decreasing in most regions, especially in the spring and summer. Visible satellite data from the NOAA weekly snow extent charts show a decrease in monthly snow-cover extent (SCE) in the Northern Hemisphere of 1.3% per decade from 1966 to 2005 (Barry *et al*. 2007). Both visible and passive microwave satellite data show a decreasing trend in SCE from 1979-2005 for every month except November and December, with the most significant decreasing trends during May to August (Brodzik *et al*. 2006; IPCC 2007). The IPCC (2007) show that March and April SCE for the Northern Hemisphere decreased by 7.5 ± 3.5% from 1922-2005, based on the station-derived snow cover index of Brown (2000) and, after 1972, the NOAA satellite data set (Figure 7.1).

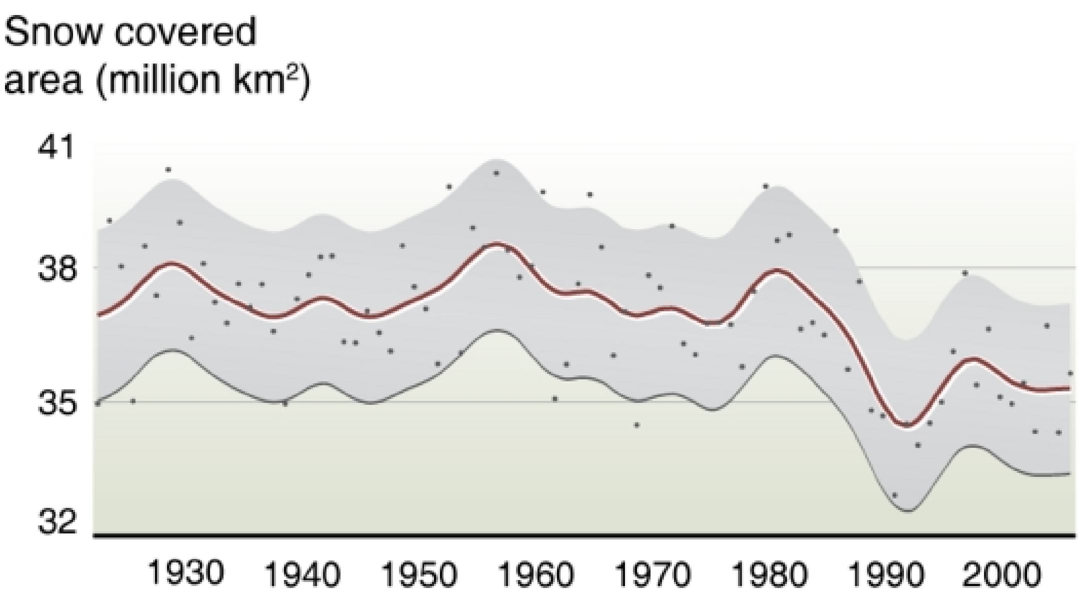

Figure 7.1 Northern Hemisphere snow-covered area (SCA) for the spring (March-April) from 1922-2005. Since the early 1920s, and especially since the late 1970s, SCA has declined in the spring. The linear trend shows a decrease in snow-covered area of 2.7 ± 1.5 × 106 km2 or 7.5 ± 3.5 %. The shaded fields in the figure represent the 5 to 95% range of the data. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) From IPCC (2007), updated from Brown (2000).

The years of 2006 and 2007 continued this trend, with Northern Hemisphere SCE below the long-term mean in every month of 2007 except December. Departures from the mean were as large as -3.0 million square kilometres in May, followed closely by June (-2.6) and April (-2.5) (Global-Snow-Lab 2007b). Overall spring (March-May) SCE was the 3rd lowest on record in 2007. Together with the lower than average extents in most of 2006, the twelve-month running means of Northern Hemisphere SCE were below the long-term mean throughout 2007. In fact, the negative 12-month anomaly at the end of 2007 was the lowest since the record lows of the satellite era were observed from 1988-1990 (Robinson 2008).

Snow depth

ACIA reported a long-term decrease in snow depth over Canada and European Russia, but a general increase elsewhere in Russia in agreement with the increase in precipitation noted in northern high latitudes (ACIA 2005). Subsequent findings have reported a long-term increase in both snow depth and duration in most of northern Eurasia (Kitaev *et al*. 2005a; Kohler *et al*. 2006; Heino *et al*. 2006). Kitaev *et al*. (2005b) reported that snow storage can be expected to decrease in the future in northern Eurasia as increasing air temperatures cause a change from solid to liquid precipitation.

Outlook

The five ACIA-designated models predicted decreases in Northern Hemisphere mean annual snow cover of 9-17% by 2071-2090 under the B2 scenario, with the largest reduction projected for spring and late autumn/early winter (ACIA 2005). Shallow snow cover at low elevations in temperate regions is the most sensitive to temperature fluctuations and hence most likely to decline with increasing temperatures (IPCC 2007). Higher temperatures will thus result in a poleward retreat of the snow margin, but also likely contribute to acceleration of the hydrological cycle and thus, in regions where temperatures remain below freezing, an increase in snowfall and possibly snow depth/snow water equivalent (ACIA, 2005). Ananicheva and Krenke (2005), for example, reported a rise in snow line of the North-Eastern Siberia mountains over the 20th century which was partly compensated by a rise in solid precipitation. In general snow coverage and snow amount is projected to decrease in the Northern Hemisphere, but in a few regions snow amount is projected to increase (IPCC 2007).

This effect can be seen in a simulation from a General Circulation Model (ECHAM5) which projects decreases of 60-80% in monthly maximum snow water equivalent over most middle latitudes by 2100, with the largest decreases projected over Europe, while increases are projected over the Canadian Arctic and Siberia (Barry *et al*. 2007) (Figure 7.2). Simulations from an Arctic hydrological model project that days of first and peak runoff will advance by as much as 25 days in the coming century, and project increases in runoff volume as a result of increases in temperature and precipitation (Pohl *et al*. 2007). The model also projects a large number of incidences of mid-winter snow melt, which will have large impacts on snow pack properties.

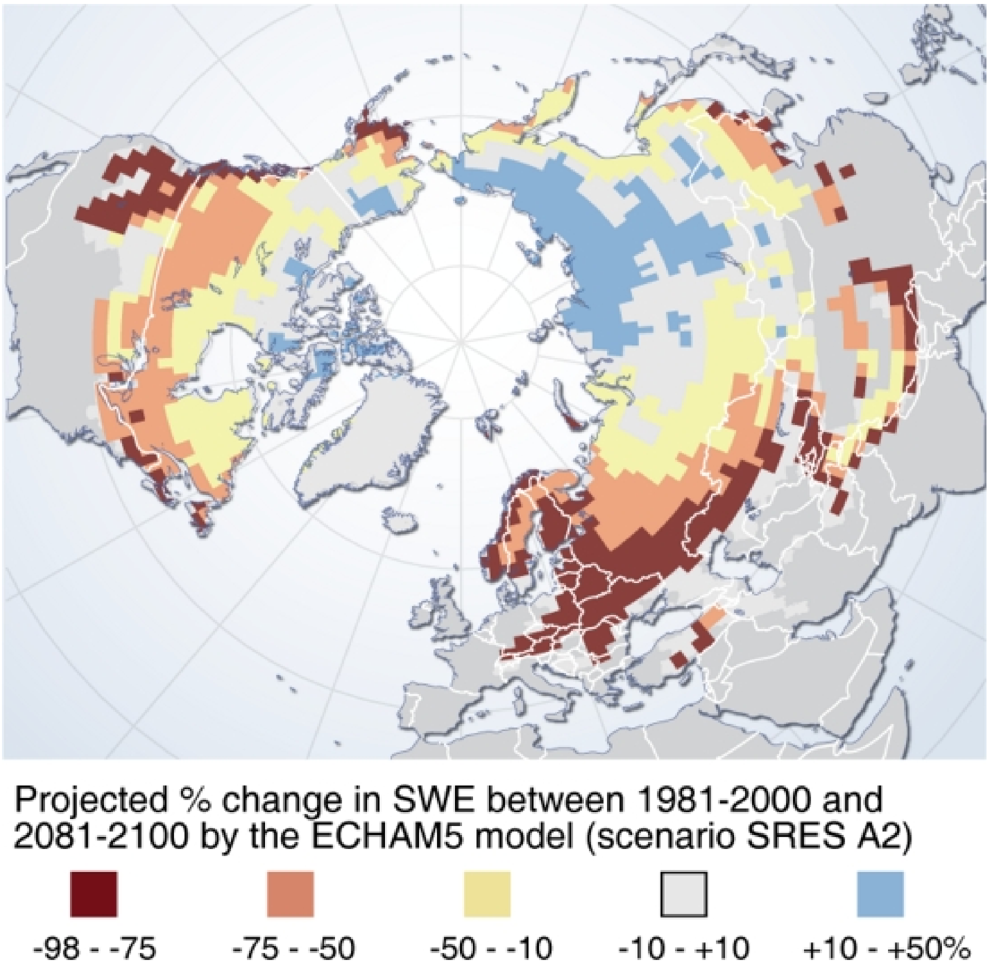

Figure 7.2 Using one specific climate change model (ECHAM5) and the SRES A2 emission scenario (RUN 2) the projected loss of snow amounts to decreases of 60–80% in monthly maximum snow water equivalent over most middle latitudes by the end of this century. Increases are projected in the Canadian Arctic and Siberia. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) Based on: R. Brown, Environment Canada; data from ESG (2007). WCRP CMIP3 Multi-Model Dataset. Earth System Grid. https://esg.llnl.gov:8443/ [Accessed February 2007]

Snow cover and albedo

Research findings since ACIA have quantified the contribution of feedback from changes in snow albedo to atmospheric warming. Chapin *et al*. (2005) found that a lengthening of the snow-free season in arctic Alaska over the last few decades, caused by terrestrial summer warming, has increased local atmospheric heating by about 3 watts/m^2/decade. This is similar in magnitude to the regional warming expected from the predicted doubling of atmospheric carbon dioxide in the next few decades (4.4 watts/m^2/decade). Across the entire Arctic region, feedback from changes in snow cover during 1970-2000 was simulated to have increased atmospheric heating by 0.9 watts/m^2/decade (Euskirchen *et al*. 2007). The snow cover climate feedback was enhanced by the fact that the snow cover changes were primarily due to earlier melt in the spring, when solar radiation is stronger than during snow return in the fall. Vegetation types with high seasonal contrast in albedo, such as tundra, showed the largest increases in atmospheric heating.

In addition to the changes in albedo due to snow cover changes, the albedo of snow, as well as ice, may have decreased due to anthropogenic soot and thus contributed to atmospheric heating (Hansen and Nazarenko 2004). McConnell *et al*. (2007) estimated an average climate forcing in early summer from soot in Arctic snow of more than 1 W/m^2 between 1850 and 1951, peaking in 1906 to 1910 at more than 3 W/m^2—eight times the natural forcing. The correspondence of this soot peak with early 20th century Arctic warming suggests that anthropogenic soot from biomass and fossil fuel combustion may have contributed to the early century warming trend in the Arctic (Alley, 2007).

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8. River and Lake Ice

Recent trends

As river and lake ice are directly controlled by atmospheric conditions such as air temperature and precipitation, trends in freshwater ice are important indicators of climate variability and change (Prowse et al., 2008). A much-cited study by Magnuson et al. (2000) examined long-term trends (spanning 150 years) in river and lake ice break-up and freeze-up dates from across the Northern Hemisphere. They found an advancement in break-up date by approximately 6 days per hundred years and a delay in freeze-up date by a similar rate. This study gave little insight on regional trends, however, and included few sites from high-latitude areas (ACIA, 2005). Since the publication of ACIA, several studies have used shorter data sets from the latter half of the 20th century to examine trends at a regional or continental scale, mostly in North America. These studies have generally found a reduction in ice-cover duration characterized by earlier spring break-ups, and, to a lesser degree, later autumn freeze-ups.

A study of Canadian lake-ice cover from 1951-2000 found a shortening of the lake-ice season over much of the country with the reduction mainly attributable to earlier break-up dates (Duguay et al., 2006). Lacroix et al. (2005) found that break-up date of ice on Canadian rivers advanced by approximately 1-2 days per decade in the second half of the 20th century, the degree of change increasing towards the end of the century. Changes in freeze-up ranged from 1 day per decade later to 0.1 day per decade earlier. Overall, various analyses of trends in river-ice from the Eurasian and North American circumpolar regions indicate that an approximate 10 to 15 day advance in break-up and a similar delay in freeze-up have occurred over the long-term (Prowse and Bonsal, 2004). There is also an increasing trend in occurrence of mid-winter break-up events of river ice, which is a concern as these events can produce especially severe flooding but are very difficult to model and predict (Prowse et al., 2007b).

There is limited availability of data on other characteristics of freshwater ice such as composition or thickness. ACIA (2005) did not report on any characteristics other than timing, and the IPCC (2007) reported that there is not sufficient published data on thickness to assess trends. One data set for Canada does not reveal any trends over the latter part of the 20th century, although unpublished data from the same period shows small-scale regional trends towards thinner ice over Northern Europe and Asia (Prowse et al., 2007a).

The above studies and others have shown that trends in river and lake ice closely match trends in air temperatures on both spatial and temporal scales (Prowse et al., 2007b). For example, Prowse and Bonsal (2004) found that a 2-3°C increase in spring and autumn produced their estimated 10-15 day change in river ice break-up and freeze-up dates; this 0.2°C/day relationship corresponds well to the findings of Magnuson et al. (2000). The timing of freshwater ice break-up/freeze-up has also been related to 0°C isotherm dates (e.g. Lacroix et al., 2005, Duguay et al., 2006) and large-scale atmospheric and oceanic oscillations (e.g. Bonsal et al., 2006) (Figure 8.1).

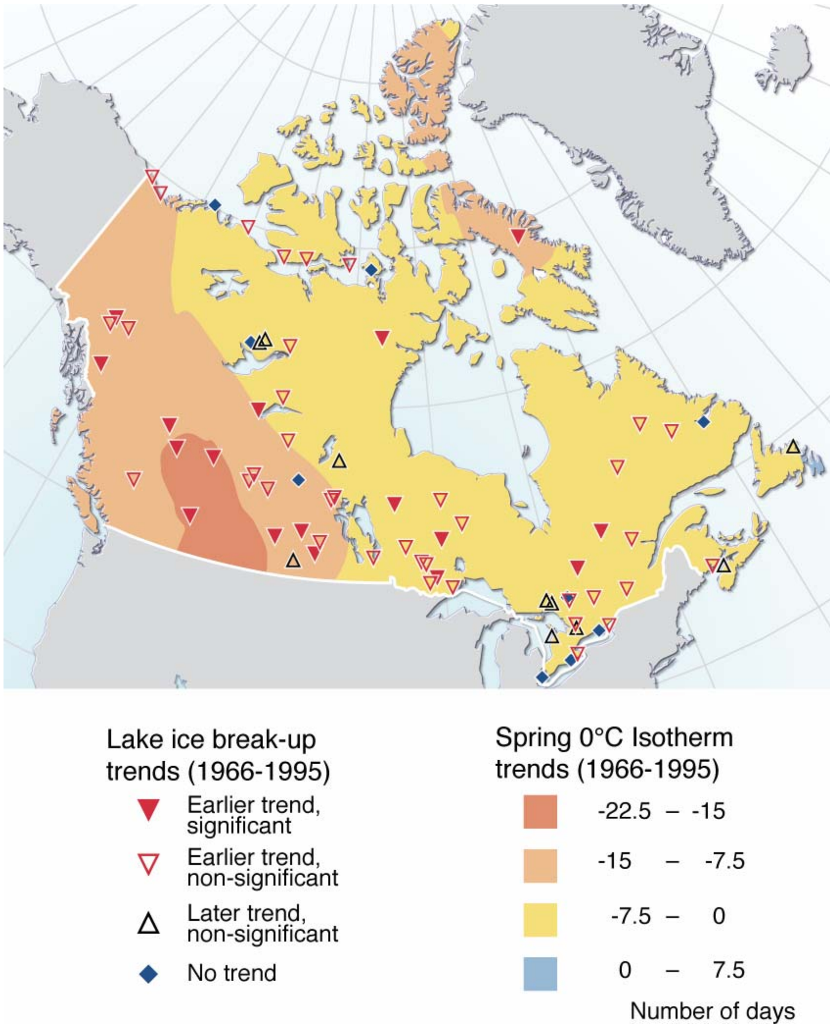

Figure 8.1 Trends in lake ice break-up and spring 0°C isotherms over Canada from 1966-1995. Similar spatial and temporal patterns are found between the two trends, with the most significant trends towards earlier springs and earlier break-up dates over most of western Canada. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) Based on Duguay et al. (2006).

Outlook

Projections of future river and lake ice have largely relied on the temperature- or 0°C isotherm-based relationships described above (Prowse et al., 2008). These projections generally indicate further advancements in break-up dates and delays in freeze-up, with the amount of change depending on the warming that is forecast (Prowse et al., 2007a). For example, based on future changes to spring and autumn 0°C isotherms, by the middle of this century river-ice durations over most of Canada are projected to be approximately 20 days shorter with respect to the 1961–90 baseline period (Prowse et al., 2007b). Although few studies have looked at changes in severity of ice break-up, it is thought that the greater warming projected at higher latitudes could reduce temperature gradients along rivers and thus likely reduce river break-up severity (Prowse et al., 2006).

The problem with making predictions based on temperature- or 0°C isotherm-based relationships is that there is no guarantee that these relationships will hold in the future (ACIA, 2005). The relationship of freshwater ice conditions to large-scale circulation patterns could also be used for prediction. However, the effect of climate change on these patterns remains uncertain, and this would affect the predictions (Prowse et al., 2007b). To predict changes in lake and river ice regimes more effectively, improvement of physical models is required (Prowse et al., 2008). The complicating effect of snow cover is important to consider in predictions: increasing snowfall is predicted to delay ice break-up, while decreasing snowfall will advance break-up (ACIA, 2005, Turner, 2008).

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9. Frozen Ground

Evidence of permafrost warming: temperature and active-layer thickness

The Global Terrestrial Network for Permafrost (GTN-P) identifies permafrost thermal state (i.e. ground temperature) and active-layer thickness as the key permafrost variables to monitor (Burgess et al., 2000). These variables are indicators of permafrost warming. At the time of ACIA, ground temperature measurements showed permafrost warming over the past several decades in Alaska, Canada, Russia, and northern Europe (ACIA, 2005). Since then, further research has generally continued to report permafrost warming over the past several decades, although at a few sites there has been little warming or even cooling.

For example, Smith et al. (2005b) reported warming of the upper 20-30 m of permafrost by about 1°C in the northern Mackenzie Valley of Canada during the 1990s, with smaller warming trends in the central Mackenzie Valley. No significant trend was observed in the southern Mackenzie Valley (Smith et al., 2005b); this is likely due to the fact that this permafrost is ice-rich and requires the absorption of latent heat to melt the ice (Romanovsky et al., 2007b). Warming in northern and interior Alaska from the 1980s-2003 varied by location, but was typically from 0.5 to 2°C at the permafrost surface (Osterkamp, 2005). Isaksen et al. (2007b) reported considerable warming of mountain permafrost in Svalbard and Scandinavia on the order of 0.04°–0.07°C per year, with accelerated warming during the last decade. High air temperature anomalies during 2005-2006 on Svalbard resulted in extreme near-surface permafrost warming, with the 2006 mean ground temperature at the permafrost table 1.8°C higher than the mean for the previous six years (Isaksen et al., 2007a). Across the Russian Arctic and subarctic, mean annual temperatures at the top of the permafrost increased by greater than 1°C from the mid-1950s through 2000 (Zhang et al., 2006). More specifically, Oberman (2007) reported an increase in permafrost temperatures of 0.2 °C to 1.2-1.6 °C (varying from west to east) in northern European Russian over a 20-35 year monitoring period up to 2006. In contrast, in Siberia, permafrost warming trends are currently weak or absent (Melnikov and Pavlov, 2006, Pavlov and Malkova, 2005). Lack of trends in permafrost temperatures at some locations can be explained by the fact that some locations have recently shown no warming trend or even cooling trends in mean annual temperature, as well as slight negative trends in snow depth.

The active layer is the seasonally thawed layer that overlies permafrost. ACIA (2005) did not report on any changes in active layer thickness (ALT). Significant changes in ALT have since been reported, though these findings have been largely inconclusive. Increasing changes in ALT could be expected in response to climate warming (IPCC, 2007); however, ALT depends on many factors such as surface temperature and snow cover thickness (Frauenfeld et al., 2004, Zhang et al., 2005). Thus there can be large inter-annual and spatial variations in ALT at point locations, which presents monitoring challenges (IPCC, 2007). An increase in ALT of more than 20 cm was reported for the last half of the 20th century in the continuous permafrost regions of Arctic Russia, due to an increase in summer air temperatures and in winter snow depth (Frauenfeld et al., 2004, Zhang et al., 2005, Zhang et al., 2006). Earlier reports from central Yakutia in Russia, however, showed no significant changes in ALT (Varlamov et al., 2001, Varlamov, 2003). Nixon et al. (2003) found an increase in ALT in the Mackenzie Valley in Canada; however, after 1998 ALT began decreasing at most of the same sites (Tarnocai et al., 2004). The 2005 active layer around Fairbanks, Alaska was the thickest in 10 years, and the 2006 summer active layer was also one of the thickest on record (Romanovsky et al., 2007a).

Evidence of permafrost degradation

Actual permafrost degradation occurs when permafrost thaws and thus decreases in thickness and/or areal extent (IPCC, 2007). When ice-rich permafrost thaws, the ground surface subsides into the resulting voids, creating what is known as *thermokarst* topography. ACIA (2005) reported some recent incidences of thermokarst formation due to climate warming, and noted that thermokarst processes can pose a serious risk to Arctic biota through over-saturation or drying.

Some prominent findings have since been reported with regards to the impact of permafrost thaw on Arctic lakes and wetlands. A significant decrease in the number and/or size of ponds was found for the last few decades in areas of discontinuous permafrost in south Siberia and Alaska (Yoshikawa and Hinzman, 2003, Smith et al., 2005a, Riordan et al., 2006). This decrease is believed to be due to thawing of the permafrost underneath these thermokarst ponds, which allows subsurface water drainage. In contrast, in areas with cold, continuous permafrost such as northern Siberia and the Beaufort Coastal Plain in northern Alaska, formation of thermokarst due to climate warming has caused an increase in the number and/or size of surface water bodies (Jorgenson et al., 2006, Smith et al., 2005a, Walter et al., 2006). These findings suggest that in areas with thin permafrost, climate warming will cause shrinking of ponds and drier soils, while in colder regions with thicker permafrost, climate warming will act on the large amounts of ground ice close to the surface to create new water bodies (Romanovsky et al., 2007a). Eventually, as the permafrost degrades further, there will be a widespread disappearance of lakes and wetlands even in areas that were formerly continuous permafrost (Smith et al., 2005a, Smith et al., 2007, Walter et al., 2007b).

Outlook

Models project widespread permafrost thaw in the future. By the mid-21st century, near surface permafrost in the Northern Hemisphere may shrink by 15-30%, while the depth of the active layer may increase on average by 15-25% and by 50% or more in the northernmost locations (Anisimov and Reneva, 2006). Stendel et al. (2007) project an increase in mean annual ground temperature by up to 6 K and increase in active layer depth of up to 2 m along the East Siberian transect during the 21st century. Forcing permafrost models with high resolution regional climate models, as opposed to global general circulation models, may result in more realistic models (Stendel et al., 2007).

Impacts of permafrost thaw: feedback processes

ACIA (2005) noted that thawing of permafrost is likely to accelerate biological decomposition of sequestered organic matter and increase the greenhouse gases (carbon dioxide and methane) released into the atmosphere, thus contributing to additional climate warming. Work on carbon fluxes is some of the most prominent recent work on permafrost, as understanding the role of ecosystems and oceans as CO_2 sources and sinks is crucial to predicting the magnitude of future CO_2-induced climate warming. See the Ecosystems section for a review of research on Arctic terrestrial carbon flux, including changes due to permafrost thaw.

Work since ACIA has since provided more information on how much carbon is sequestered in permafrost. The upper 1-25 m of permafrost in boreal and Arctic ecosystems is estimated to contain ~750-950 gigatonnes of organic carbon, excluding carbon contained in hydrates within or under the permafrost (Zimov et al., 2006b, ACIA, 2005, Smith et al., 2004). This indicates that permafrost is a large carbon reservoir, comparable to the atmosphere which currently contains ~730 gigatonnes of carbon (Zimov et al., 2006b). Frozen yedoma, a particularly carbon-rich type of permafrost found mainly in northern and central Siberia, contains roughly half of this ~750-950 gigatonnes of carbon (Zimov et al., 2006a). This represents a significant potential source of carbon emissions, especially as the organic matter in yedoma decomposes particularly quickly when thawed (Zimov et al., 2006a, Walter et al., 2007a, Dutta et al., 2006), and Siberian permafrost is predicted to continue warming and thawing during this century (Sazonova et al., 2004, Lawrence and Slater, 2005).

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10. Ecosystems

Overview

ACIA (2005) extensively documented the ecosystem impacts of climate change in the Arctic, and discussed these impacts in relation to resource use and traditional economies and livelihoods. Since ACIA's publication, research has continued to document changes at the species, community and ecosystem levels in the freshwater, marine and terrestrial systems. Other findings, particularly studies of past ecosystem changes, have provided more insight how ecosystems will likely respond to climate changes in the future. Still other studies have given more background on the structure and function of Arctic ecosystems in order to be better able to understand the effects of climate change.

The ongoing impacts of climate change on ecosystems and their services are in addition to other pressures on Arctic ecosystems such as modern habitat fragmentation, stratospheric ozone depletion, and the spread of contaminants (ACIA 2005, IPCC 2007). There are various ways that climate change will interact with these other pressures. Exposure to known endocrine-disrupting chemicals, for example, may limit that ability of marine birds and mammals to adapt to changes in the environment caused by climate change (Jenssen 2006). It is difficult to predict whether climate change will lead to decreased or increased contaminant levels in Arctic ecosystems in the long-term. Recent work has led to a better understanding of trends of contaminants in Arctic biota, showing increases in some contaminant levels and finding chemicals previously unreported in Arctic biota (Braune *et al.* 2005, Evans *et al.* 2005). It is difficult, however, to assess whether increases are due to increased anthropogenic inputs or to climate change (Braune *et al.* 2005). Contaminant studies need to be broadened to consider climate change effects.

Marine ecosystems

Changes in sea ice, warming and acidification of Arctic and sub-Arctic oceans continue to drive changes in biodiversity, distribution and productivity of marine biota (IPCC 2007). Impacts on marine biota are most evident through sea ice changes. Thinning and reduction in coverage of sea ice are likely to substantially alter ecosystems that are in close association with sea ice, affecting biota from algae and crustaceans to marine birds and mammals (ACIA 2005, IPCC 2007). The IPCC Fourth Assessment Report (AR4) (2007) names the sea ice biome as one of the marine ecosystems most likely to be especially affected by climate change. Polar marine ecosystems are particularly sensitive to climate change because of the effect of small temperature changes on the thickness and extent of sea ice (Smetacek and Nicol 2005).

Recent findings have provided more insight into the importance of the sympagic (ice-associated) ecosystem for marine productivity. Tamelander *et al.* (2006), for example, found that during the seasonal ice melt in a region of the northern Barents Sea, ice algae contribute substantially to the vertical movement of organic matter in the water column and provide food for the invertebrates and fishes living in the depths of the ocean. Hop *et al.* (2006) reported that the biomass of ice fauna transported annually with the ice drift to the Fram Strait and Barents Sea is in the range of a million metric tons. A loss of multi-year pack ice due to climate warming will reduce this large energy input to the seas surrounding the Arctic Ocean (Hop *et al.* 2006).

Declining trends have recently been reported for specific marine species, including some species in the upper trophic levels of the sea ice biome. Ringed seals, a species very closely associated with sea ice, have experienced a long-term decrease in reproductive parameters and survival of pups of ringed seals in western Hudson Bay (Ferguson *et al.* 2005, Stirling 2005). These changes are likely related to earlier spring break-up of sea ice, as well as trends in snow cover. Some populations of polar bears, which prey mainly on ringed seals, have also experienced a decline in body condition and reproductive output in recent years (see polar bear section). Rosing-Asvid (2006) proposes that mild springs allow more polar bear predation on ringed seals, which increases polar bear cub survival during that period but also results in more starving bears later in the season. Thus, mild springs result in a predator-prey dynamic detrimental to both polar bears and ringed seals. The Canadian population of the ivory gull, which lives along the ice edge year-round, has declined by 80 per cent since the early 1980s, with a total count in 2005 of only 210 birds (Gilchrist and Mallory 2005, Stenhouse *et al.* 2006). There are several factors that singly or in some combination could be implicated in this decline, including changes in sea ice in the winter range, hunting during migration through northwest Greenland, disturbance from diamond exploration, and high levels of mercury in their eggs (Braune *et al.* 2006, Gilchrist and Mallory 2005, Stenhouse *et al.* 2006). In Russia, great fluctuations have been documented in ivory gulls but it is believed that these are more or less stable fluctuating populations (Gavrilo 2007, Gavrilo *et al.* 2007).

Alter *et al.* (2007) found that recently observed mortality spikes in gray whales in the north Pacific may be due to shifting climatic conditions in their Arctic feeding grounds rather than a reaching of their long-term carrying capacity, as an analysis of DNA variability shows that the population was historically three to five times larger than at present.

At the ecosystem level, Grebmeier *et al.* (2006) reported significant findings from the northern Bering Sea. In this region, increasing air and water temperatures and reduction in sea ice have coincided with a major shift from an Arctic to a sub-Arctic ecosystem in the last decade. The benthos (bottom fauna) and marine birds and mammals that feed upon them are being replaced by communities dominated by pelagic (water-column) fish. There are a number of possible explanations for this shift, including the fact that less sea ice results in less ice algae which feed the benthos, lengthening growing seasons for zooplankton, and warmer waters which give warm water species a foothold

(Krajick 2007). This effect should be expected to be more widespread in the future, and indeed preliminary evidence suggests that similar effects may have started in the more northerly Barents and Laptev seas off Scandinavia and Siberia (Krajick 2007). Wassmann *et al.* (2006) found that in the Barents Sea, a typical ice-dominated Arctic system, 80% of the harvestable production is channeled through the deep-water communities and benthos. This can be expected to change with climate warming.

Changes in the biochemical properties of the marine environment, which directly affects primary productivity, are also a concern with climate change. Frey *et al.* (2007) showed that climate warming and permafrost thawing are likely to increase the transport of nitrogen and phosphorous from west Siberia to the Kara Sea and Arctic Ocean, with large local impacts on the nearshore environment. In the North Pacific, surface stratification caused by an influx of cold water from the Arctic has led to changes in several key nutrients, with effects on ocean biota (Watanabe *et al.* 2008).

Terrestrial ecosystems

The tundra and boreal forest ecosystems are likely to be especially affected by climate change due to their sensitivity to warming (IPCC 2007). Climate change is predicted to cause major vegetation shifts which will shrink habitats for many animals that depend on tundra and polar desert landscapes. Increases in the biomass of woody shrub species such as willow, for example, may reduce habitat for caribou (Sturm *et al.* 2005b). Arctic fauna will also be displaced by competition from invading animal species from the south. The ability and rate at which ranges of plants and animals can shift will vary among species, resulting in the break-up of current communities and ecosystems and the formation of new ones (ACIA 2005). A recent study showed that Svalbard, a remote Arctic archipelago, has been colonized by plants repeatedly and from several sources, suggesting that Arctic flora seem to able to track their ecological niche and that dispersal is not a large limiting factor in long-term range shifts (Alsos *et al.*, 2007). On the other hand, another recent genetic analysis found that during a northward shift in its habitat at the end of the Pleistocene, the arctic fox became extinct in mid-latitude Europe rather than shifting its range (Dalen *et al.* 2007). This suggests that some Arctic populations may be unable to track decreases in habitat availability, meaning that Arctic species may be even more vulnerable to increases in global temperature than previously thought.

Vegetation

In the last few years, the body of research regarding shifts in Arctic vegetation in response to climate change has grown. As predicted in ACIA (2005), the timeframe for these vegetation changes varies around the Arctic. The weight of evidence for vegetation change is now substantial, but with some surprising aspects.

One expected vegetation shift is an increase in the abundance and extent of shrubs in tundra areas. In northern Alaska, Tape *et al.* (2006) used repeat photography as well as plot and remote sensing studies to show that both larger and smaller shrub species have increased in size, abundance and extent over the last 50 years. Plot and remote sensing studies in Canada, Scandinavia and parts of Russia also show evidence for shrub expansion (Tape *et al.* 2006). A recent updated remote sensing analysis of Arctic tundra vegetation greenness showed positive trends over the period 1982-2005, with a greater rate of change over the North American Arctic (+0.64%/yr) compared to the Eurasian Arctic (+0.44%/yr) (Jia *et al.* 2007). In a set of standardized warming experiments at 11 locations across the tundra biome, Walker *et al.* (2006) found that warming increased the height and cover of deciduous shrubs and graminoids, decreased the cover of mosses and lichens, and decreased species diversity and evenness. These findings provide experimental evidence that recently observed increases in shrub cover in many tundra regions are in response to climate warming. Formation of thermokarst (ground subsidence) due to permafrost thawing, which alters hydrological patterns within a site and thus alters ecosystem structure, is also expected to create more shrub-dominated tundra ecosystems (Schuur *et al.* 2007).

The complex interactions between shrubs, snow and soil warming may act as a positive feedback to shrub expansion (Chapin *et al.* 2005). Pomeroy *et al.* (2006) found that snowmelt rates were enhanced under shrub canopies. Winter processes provide a critical positive feedback effect in increasing shrub abundance: more shrubs leads to deeper snow, which promotes higher winter soil temperatures, greater microbial activity, and more plant-available nitrogen (Sturm *et al.* 2005b, Grogan and Jonasson, 2006). Grogan and Jonasson (2006), however, found that there was a threshold of snow accumulation above which there was little effect on biogeochemical cycling.

The response of the boreal forest to warming does not appear to be as consistent with the expectations of a direct positive relationship between warming and plant growth. Goetz *et al.* (2005) analyzed photosynthetic activity across boreal North America over 22 years (1981 through 2003) and found that the response in growth of high latitude vegetation varies with vegetation type. While tundra areas exhibited increases in photosynthetic intensity and growing season length over this period, such simple trends were not found in forested areas. An updated analysis of photosynthetic activity from 1981 through 2005 confirmed these findings (Bunn *et al.*, 2007). The authors attributed the flat to declining trends in boreal forest greenness to increasing moisture stress due to a combination of factors such as higher evaporative demand due to warmer temperatures and increased soil drainage due to declines in permafrost (Bunn *et al.* 2007). A number of studies from across northwestern North America have shown diverging growth trends at the treeline since the 1950s, with some areas showing growth declines that may be due to temperature-induced drought stress (Driscoll *et al.* 2005, Pisaric *et al.* 2006).

There is evidence of treeline advance in most Arctic regions, although treeline responses are mediated by species-specific traits and environmental conditions at landscape and local scales and are complicated by human factors such as forest management practices.

In North America, Lloyd (2005) found that the timing of recent treeline advance in three separate regions of Alaska varied by more than a century among regions, suggesting large variability in the rate of white spruce forest response to warming due to factors such as limitation of spruce establishment in highly permafrost-affected sites. White spruce trees along the northern Québec–Labrador treeline show different responses according to their position relative to the sea. Along the coast, invading spruce exist several tens of metres above the current tree line, while in the interior recent warming has not been strong enough to change the regressive treeline trajectory (Payette 2007). Treelines in the forest-tundra areas of Québec have risen slightly, either through establishment of seed-origin white spruce or through height growth of stunted spruce already established on the tundra hilltops (Gamache and Payette 2005, Caccianiga and Payette 2006). It is thought, however, that the development of spruce seedlings into forest might be slowed down by the harsh wind-exposure conditions. Danby and Hik (2007) found that during a period of above-average temperatures in the early to mid-20th century in the southwest Yukon, Canada, the treeline advanced rapidly on south-facing slopes whereas on north-facing slopes, the treeline did not advance but there was a 40-65% increase in stand density. This difference was primarily due to the differential presence of permafrost.

Recent investigations confirm that the treeline is now invading higher altitudes in northern Europe due to recent warming trends (Truong *et al.* 2007). Based on a study of treeline changes during the Holocene, Kullman and Kjällgren (2006) predict that the pine treeline in the Swedish Scandes Mountains may shift at least 400 m above its present position. However, Dalen and Hofgaard (2005) concluded that regional differentiation needs to be considered, with the treeline in a stable or possibly expanding state in the southern and northern Scandes Mountains but a recent recession in northernmost Europe. The latter recession is likely due to a shorter growing season due to increasing winter precipitation as well as a higher number of reindeer.

Changes in treeline have also been noted in the Russian Arctic, although data are still rather scarce and inaccessible. Shiyatov *et al.* (2005) noted a marked expansion of forests and increase in density and productivity of existing forests in the Polar Urals due to climate warming and increasing humidity. The Ary-Mas larch forests in northwest Siberia, the world's northernmost forest range, have expanded to the tundra at a rate of 3–10 m per year (Kharuk *et al.* 2006). Again, there is geographical variation in forest changes. While in Russian forests as a whole there has been an increase in the share of green parts (leaves and needles), in the northern taiga of Siberia, where the climate has become warmer but drier, the fraction of the green parts has decreased (Lapenis *et al.* 2005).

Forest fires have increased in North America and Eurasia in the last few decades and are forecast to increase much more under projected climate warming (ACIA 2005). In the boreal forest of the central Yukon Territory in Canada, for example, the average annual fire occurrence and area burned may as much as double by 2069 (McCoy and Burn 2005). It is generally thought that future increases in boreal fire will accelerate climate warming by increasing carbon emissions to the atmosphere (ACIA 2005). Randerson *et al.* (2006), however, found that the long-term effect of forest fires was actually a decrease in radiative forcing, due to post-fire increases in albedo due to increased snow cover. Thus, forest fires may cause regional cooling in northern regions, with a neutral effect on global climate change. Kharuk *et al.* (2008) reported that, because larch seeds require the extreme heat of fires to germinate, the increase in forest fires in larch-dominated forests and “larch-mixed taiga” forests in Russia may help to sustain larch as competitor species migrate north as a result of warmer climates.

One of the clearest and most rapid biological responses to rising temperatures has been shifts in species phenology. Menzel *et al.* (2006) examined an observational series of 542 plant and 19 animal species in 21 European countries from 1971 to 2000, concluding that spring/summer had advanced by 2.5 days per decade and that this advance was closely correlated with temperature increases. A study of spring timing (leaf appearance) over the 20th century in the Eurasian taiga shows that the recent advance is unique in simultaneously affecting most of the Eurasian taiga (Delbart *et al.* 2008). The study of phenological events in the high Arctic has been hampered by the lack of long-term records. Based on records from the high Arctic in Greenland during 1996–2005, Høye *et al.* (2007) reported a rapid advancement in plant flowering, invertebrate emergence, and egg-laying in birds by an average of 14.5 days per decade, with trends closely coupled to the timing of snowmelt. These findings suggest that phenological responses may be particularly dramatic in the high Arctic, with the potential to disrupt trophic interactions among species that are crucial to successful reproduction. Spring began earlier in most Siberian ecosystems from 1982 to 1999, with the start of spring advancing by as much as 12.6 days in urban environments (Balzter *et al.* 2007). The advancement is caused by earlier snowmelt due to increasing temperatures, and may be triggering higher forest fire activity (Balzter *et al.* 2007).

Fauna

ACIA (2005) predicted that shifting vegetation zones as well as freeze-thaw cycles and freezing rain will have significant impacts on caribou/reindeer populations, and reported climate-related declines in some herds. Grayson and Delpech (2005) found that during periods of increasing temperatures at the end of the Pleistocene and during the Eemian interglacial, reindeer were extirpated from southern France, supporting predictions that caribou/reindeer will experience northward displacement due to climate change. In recent years more declines have been found. Populations that have been increasing at a steady rate since the 1970s are either showing signs of peaking or are beginning to decline, following the pattern of the Porcupine caribou herd which was the first herd to decline and was reported on in ACIA (Russell, 2007). In 2005, herd population estimates for the barren-ground caribou of Canada indicated that herds had declined by as much as 86% from the previous decade, and surveys from 2006 indicate that these declines have continued (Nagy and Johnson, 2006). In early 2007, a Caribou Summit was held in the Northwest Territories to bring together co-management boards, agencies, harvesters and groups affected by low caribou numbers to decide upon management actions.

The long-term decline in the Peary caribou of the Arctic Archipelago, which is attributed to the formation of ice layers that limit access to food and thicker-than-usual snow cover, has continued (Figure 10.1). A recent study simulated the effects of climate change on the Peary caribou and found that population die-offs may be lowered in the future if biomass increases due to longer growing seasons and increased primary productivity occur as projected (Tews *et al.* 2007b). This only holds true, however, if the severity of winter disturbance events does not increase. Potential increases in disturbance severity, as opposed to disturbance frequency, pose a particular threat to Peary caribou (Tews *et al.* 2007a). Gunn *et al.* (2006) reported a 98% decline in the number of caribou on the south-central Canadian Arctic islands (Prince of Wales, Somerset, and Russell islands) between 1980 and 1995. Seasonal migration to nearby Boothia Peninsula, which experienced heavy annual harvests, played a large role in the decline (Miller *et al.*, 2007). The delay in detecting the decline and its severity are likely to handicap the recovery of the populations.

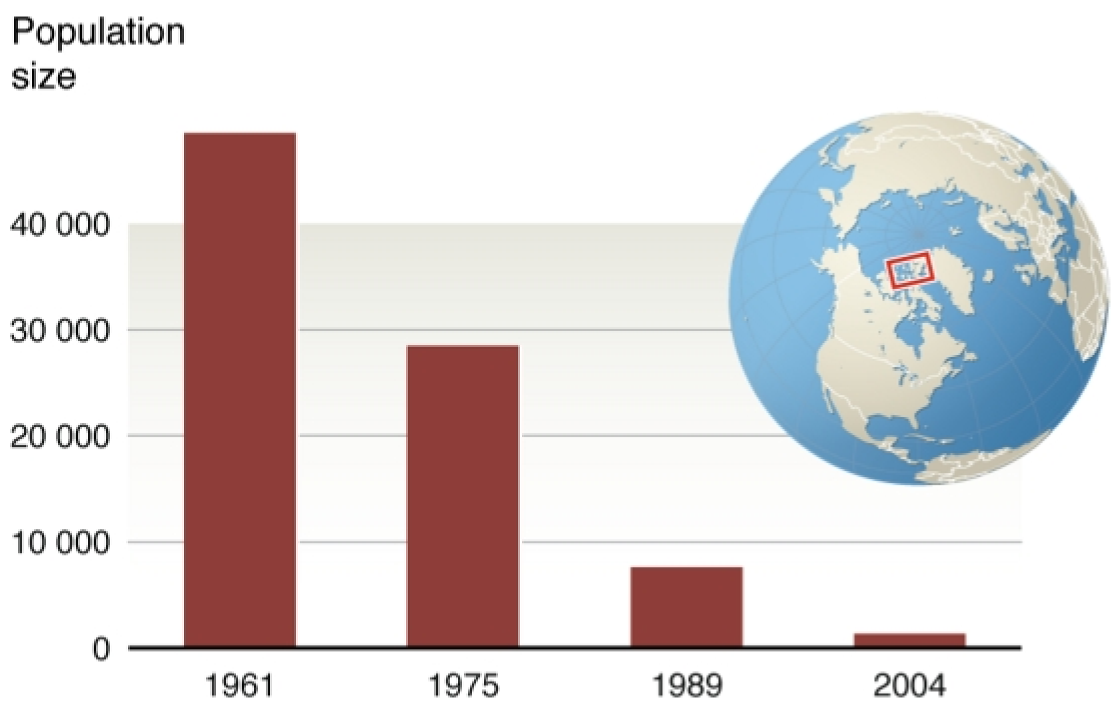

Figure 10.1 Population size of Peary caribou in the Canadian Arctic islands, 1961-2004. Source: UNEP/GRID-Arendal, 2007 (UNEP/GRID-Arendal Maps and Graphics Library.) Data source Don Russell, Environment Canada, Whitehorse, YK, Canada, 2007

In addition to climate change, caribou/reindeer are threatened by increased industrial expansion in the north and the increased sophistication and mobility of harvesters, highlighting the need for careful monitoring and analysis of populations (Russell, 2007). The CircumArctic Rangifer Monitoring and Assessment Network (CARMA) was formed to coordinate monitoring efforts across the north and will take advantage of the International Polar Year to increase its activities over the next few years.

Some infectious diseases of Arctic fauna have already increased due to climate change and there are a variety of mechanisms by which climate change is expected to influence disease patterns (Bradley *et al.* 2005). Warmer temperatures, for example, could benefit survival, development, and transmission of bacteria and parasites and their insect hosts, and host species may become more vulnerable due to changing environmental conditions or increased environmental pollutants. Kutz *et al.* (2005) found that increasing temperatures may have already altered the transmission dynamics of a parasitic nematode of muskoxen in the Canadian Arctic, and that this trend is expected to continue. Similarly, the length of parasite 'growing season' and amount of warming available for parasite development has increased over the last 50 years for two nematode parasites of Dall's sheep in the subarctic, and climate warming may soon allow northward range expansion and extension of the seasonal window for transmission (Jenkins *et al.* 2006).

ACIA (2005) reported that vegetation changes (for example, decline in mosses and lichens), ice crust formation due to freeze-thaw events, and collapse of under-snow spaces can have detrimental impacts on other terrestrial Arctic fauna as well. A recent review of Arctic population cycles, which are centered on lemmings and are very influential to the functioning of Arctic ecosystems, concluded that changes have taken place in the dynamics of some key herbivores and predators involved in these cycles (Ims and Fuglei 2005). Mild weather can lead to collapse of the under-snow spaces that are so important to lemmings and voles, while ice crust formation reduces the insulating properties of the snowpack (ACIA 2005).

Effects of Arctic climate change on migratory species will be felt in communities and ecosystems well beyond the polar regions (IPCC 2007). Migratory bird species are likely to be affected by changes in habitat such as drying of ponds and wetlands, as well as changes in timing of their main food sources. Breeding dates of many bird species have advanced to track changes in the underlying food chain but this advancement is limited by the timing of arrival in breeding areas. Both *et al.* (2005) found that time of arrival depends on temperatures along the migratory flyway that do not necessarily change at the same rate as those in breeding areas. A recent review of the effects of weather and climate on the breeding of Arctic shorebirds concluded that the decision of whether or not to breed, the timing of egg-laying, and the chick-growth period were all strongly affected by weather, with the clutch initiation date highly correlated to snowmelt date (Meltofte *et al.* 2007). Climate changes may increase survival and productivity of Arctic shorebirds in the short term, while in the long term, habitat changes in the Arctic and in non-breeding grounds further south will put them under considerable pressure (Meltofte *et al.* 2007).

Populations of Arctic breeding geese have gone through a geometric increase in size since the 1970s, with the global goose population nearly doubling in the last decade to the current total of 21.4 million (Wetlands-International, 2006). This population increase has been attributed to the establishment of more refuges, reduced mortality from hunting, and, most importantly, increased feeding on agricultural food sources (Gauthier *et al.* 2005). Increased foraging by geese has led to localized loss of vegetation and exposure and erosion of sediment in some Arctic staging or breeding areas (Abraham *et al.* 2005, Jefferies *et al.* 2006).

The most recent review considers 23% of Arctic goose populations to be declining, a slightly higher proportion than ten years ago (Wetlands-International 2006, Loonen *et al.* 2007). Geese are particularly vulnerable to the impacts of climate change due to a close match in their migratory timing and the spring flush of plant growth (Drent *et al.* 2007). Jensen *et al.* (2008), however, predict that at least some Arctic breeding goose populations will increase as a result of warming trends, with projections of large expansions in potential breeding range. An increase in average temperatures throughout the geographic range of geese since the 1960s may have already contributed to the observed northward shift in wintering range and earlier spring migration (Gauthier *et al.* 2005).

Freshwater ecosystems

ACIA (2005) predicted that increasing water temperatures, permafrost thawing, ice cover changes, and increasing levels of contaminants all have the potential to cause major shifts in freshwater species. Climate change is expected to cause changes in freshwater chemistry, with thawing permafrost causing nutrient and carbon enrichment and altering the status of freshwater ecosystems as carbon sources or sinks (Wrona *et al.* 2006b). Changes will also be felt in food web structure, altering the biodiversity and productivity of freshwater ecosystems. Aquatic mammals and waterfowl will also be impacted, including possible alterations in migration routes and timing and increased incidence of disease and parasites (Wrona *et al.* 2006b). Ranges of aquatic species are predicted to change, particularly for fish (Reist *et al.* 2006). Sharma *et al.* (2007), for example, predict that by 2100, lakes in the Arctic will have temperatures suitable for warm-water fish species such as smallmouth bass.

Like other Arctic ecosystems, freshwater ecosystems are subject to stresses from human activities other than climate change. These include the depletion of stratospheric ozone, elevated concentrations of persistent organic pollutants, and rapid development activities (Schindler and Smol 2006). Projected warming and changes in precipitation will result in higher contaminant loads and biomagnifications, while changes in ice cover are predicted to increase UV radiation levels, producing cumulative and/or synergistic effects on aquatic ecosystem structure and function (Wrona *et al.* 2006a).

Recent studies, particularly through the use of paleolimnological methods, have looked at the changes that have already occurred in Arctic ponds and lakes. Studies generally indicate major changes in freshwater characteristics over the past one to two centuries due to the warming trend (Prowse *et al.* 2006). Smol *et al.* (2005) conducted an analysis of algae in sediment cores from 55 lakes across the Arctic, revealing widespread species changes and ecological reorganizations in lakes over the past 150 years. Lakes have become more productive, and there are more species of algae in the shallow lakes. The changes are more marked at higher latitudes, following the pattern of polar amplification of climate warming. The timing of the changes also corresponds well to timing of climate warming inferred through records such as sediment cores and tree rings. Twentieth century increases in primary productivity and changes in biochemistry have also been found in lakes in other areas of the Arctic such as Baffin Island and Svalbard (Michelutti *et al.* 2005, Wolfe *et al.* 2006, Guilizzoni *et al.* 2006). Lake sediment cores such as the recently extracted sediment core from Lake El'gygytgyn in Siberia, which is believed to be the longest and most continuous terrestrial record of past climate change in the entire Arctic, will continue to offer a means not only to reconstruct the past climate but also to assess the impact of climate change on lake systems (Brigham-Grette *et al.* 2007).

Similar ecological changes, such as shifts in algal populations and increases in diversity of aquatic insects, have been documented in high Arctic pond ecosystems over the last 200 years due to climate warming and reduced ice-cover (Quinlan *et al.* 2005). Keatley *et al.* (2007) found that specific conductivity and concentration of nutrients and related variables were significantly higher in lakes and ponds in an atypically warm high Arctic oasis compared to lakes and ponds in a more typical cooler high Arctic environment. These findings are consistent with expectations of changing limnological characteristics in a warming climate. Most lakes and ponds in the Arctic oasis site also have higher pH than they did 40 years earlier, again consistent with expectations.

A more recent study indicated that the final ecological threshold may have been crossed for some aquatic ecosystems in the Arctic. Monitoring of high Arctic pond ecosystems, the most common aquatic habitat in many polar regions, on Ellesmere Island from 1983-2006 showed that many of these ecosystems have desiccated as a result of climate warming (Smol and Douglas 2007). The desiccation is likely due to increased evaporation due to warmer temperatures and extended ice-free conditions. Surrounding wetland ecosystems have also been severely affected by the warming and drying. The desiccation has profound implications for pond biota as well as other plants and animals which make use of the ponds, e.g. as waterfowl habitat and breeding grounds or drinking water for animals. Unlike the temporary thermokarst ponds in subarctic regions, water level in these "permanent" high Arctic ponds is not influenced by permafrost drainage as they are generally underlain by bedrock. In areas of the Arctic with permafrost, initial permafrost thaw will form new wetlands and ponds, allowing for the dispersal of aquatic communities (Wrona *et al.* 2006b). As permafrost drainage continues, however, surface waters will drain, resulting in loss of freshwater habitat. Smith *et al.* (2007) project a 46% reduction in the number of lakes in a permafrost-free Arctic.

Freshwater river delta ecosystems in the Arctic are highly susceptible to the effects of climate change. Lakes and ponds that surround such deltas depend on floodwaters from spring river-ice jams to supply water and nutrients, as demonstrated by, for example, Peters *et al.* (2006b) for the Peace-Athabasca Delta in northern Canada. In the Peace-Athabasca Delta, a lack of ice-jam flooding has already resulted in reduction in lake and pond area in recent decades. Beltaos *et al.* (2006) projected a severe reduction in ice-jam flooding in the Peace-Athabasca Delta based on future climate conditions, due to thinner river ice and reduced spring runoff from a smaller spring snowpack. Evaporation, the most important factor in water drawdown in these ecosystems, will also increase due to warmer temperatures (Peters *et al.* 2006a). These factors combined will cause declines in delta-pond water levels and loss of aquatic habitat.

Global feedback processes as a result of arctic ecosystem change

Albedo

Changes in Arctic ecosystems influence regional as well as global climate through changes in albedo and carbon flux. It is well established that transitions from tundra to shrub or forest ecosystems lowers albedo and produces a net increase in summer heating. Chapin *et al.* (2005), for example. estimate that shrub and tree expansion could amplify atmospheric heating by two to seven times. Shrub landscapes have lower albedo compared to tundra landscapes during the winter as well, producing an estimated 69 to 75% increase in absorbed solar radiation during the snow-cover period (Sturm *et al.* 2005a).

Arctic terrestrial carbon flux

Field-based measurements of net carbon exchange in the Arctic (e.g. Corradi *et al.* 2005), show great spatial variability in the magnitude of the Arctic as a carbon sink or source (Sitch *et al.* 2007, IPCC 2007). Models, however, show that the Arctic is currently a small sink for carbon (Sitch *et al.* 2007, IPCC 2007). There are numerous uncertainties in both measurements and models. Model projections generally indicate that Arctic terrestrial ecosystems will be a small sink for carbon in the next century as higher temperatures, longer growing seasons and projected northward movement of productive vegetation enhance carbon capture (Sitch *et al.* 2007, IPCC 2007). In addition, expansion of shrubs may constitute a negative feedback to global warming due to differences in leaf litter decomposition rates (Cornelissen *et al.* 2007). At the same time, however, soil warming and an increase in the availability of organic material due to permafrost thaw will enhance greenhouse gas emission to the atmosphere, contributing to climate warming (Sitch *et al.* 2007, Anisimov 2007, Davidson and Janssens 2006). Grogan and Jonasson (2006) showed that enhanced snow accumulation due to taller vegetation results in greater insulation from air temperatures, thus increasing the production of CO_2. The wetting and drying of tundra which occurs along with warming and thawing of permafrost will also affect the magnitude of carbon fluxes and determine the balance of gases involved (IPCC 2007).

Recent work has quantified the large amount of methane that can be released when lakes form as a result of permafrost thaw. The thawing of ice-rich permafrost, whether or not it is dependent on climate change, forms thermokarst topography. As meltwater cannot drain away due to underlying permafrost, depressions in thermokarst topography usually form into thermokarst lakes (Romanovsky *et al.* 2007). Thermokarst lakes emit methane as opposed to carbon dioxide because permafrost beneath these lakes thaws, releasing organic matter into the lake bottom which is then decomposed anaerobically (Zimov *et al.* 1997, Walter *et al.* 2006). By quantifying bubbling, which is how 95% of the methane is released from the lakes, Walter *et al.* (2006) found that methane release from thermokarst lakes in their study area of Siberia may be five times higher than previously estimated. By extrapolation, this increases previous estimates of methane emissions from northern wetlands by 10-63% (Figure 10.2). Thermokarst lakes on the Siberian yedoma alone would emit as much as ~49 000 teragrams of methane if the yedoma was to thaw completely (Walter *et al.* 2007), an amount that is ten times the 4850 teragrams of methane currently contained in the atmosphere (IPCC 2001). Methane emissions from Arctic lakes will change in conjunction with the changes in lake area as permafrost thaws (Walter *et al.* 2007).

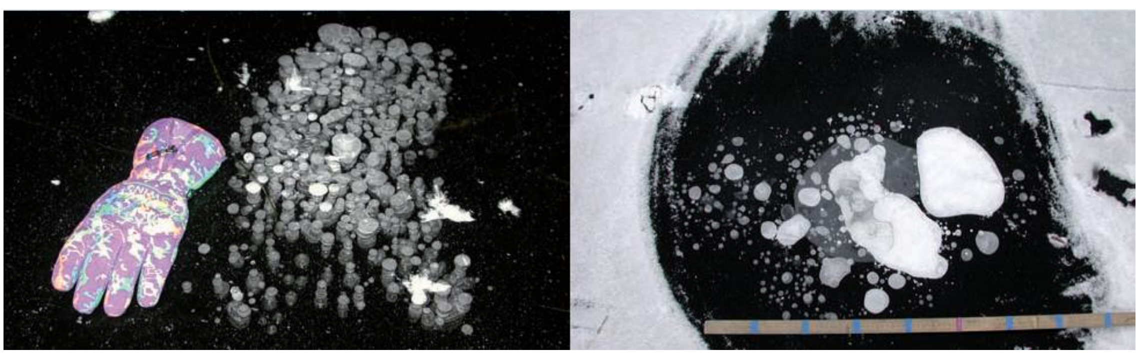

Figure 10.2 Methane bubbles trapped in lake ice form distinct patterns as a result of differing rates of methane bubbling. In Walter et al. (2006), methane emissions from the entire lake were estimated by surveying the distribution of bubble patterns in lake ice in early winter. Source: UNEP/GRID-Arendal. 2007. Global Outlook for Ice and Snow

Other recent studies have quantified other changes in carbon flux as a result of permafrost thaw. Thawing permafrost and subsequent vegetation changes from hummock vegetation to wet-growing plant communities from 1970-2000 increased the growing season atmospheric carbon dioxide sink function by about 16% while at the same time increasing methane emissions by 22% in a subarctic mire (Johansson *et al.* 2006, Malmer *et al.* 2005). Turetsky *et al.* (2007) showed that the loss of surface permafrost in peatlands increases the net carbon storage as peat. They estimate, however, that increases in methane emissions will offset this increased storage for about 70 years following permafrost thaw.

Arctic freshwater and marine carbon flux

The status of aquatic ecosystems as carbon sources or sinks is very likely to change as a result of climate change. Desiccation of wetlands as shown by Smol and Douglas (2007) could switch them from a carbon sink to a source. Changes in food webs and nutrients can alter CO_2 flux from lakes by changing sedimentation (Flanagan *et al.* 2006). Thawing of permafrost is likely to result in carbon enrichment of aquatic ecosystems (Wrona *et al.* 2006b). Frey and Smith (2005) predicted that permafrost thaw will result in up to ~700% increases in stream dissolved organic carbon (DOC) concentrations and increases in DOC flux to the Arctic Ocean in the next century. The surface layer of shelf water on the East Siberian Arctic shelf was supersaturated up to 2500% relative to the present average atmospheric methane content, indicating that rivers coming from watersheds underlain with permafrost are a strong source of dissolved methane (Shakhova and Semiletov 2007). The marine methane cycle may also be affected by environmental changes. Significant changes in the thermal regime of bottom sediments have already been noted on the East Siberian Arctic shelf (Shakhova and Semiletov 2007).

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11. Polar Bears

Polar bears have been deemed unlikely to survive as a species if there is an almost complete loss of summer sea ice, with significant consequences for the ecosystems that they occupy (ACIA 2005, Derocher et al. 2004). Since the mid-1980s, significant declines in body condition and specific demographic parameters such as the number of cubs born have been observed in the West Hudson Bay population of polar bears, one of the most southerly populations (Stirling et al. 1999, ACIA 2005). These changes have been related to earlier break-up of sea ice on western Hudson Bay due to rising spring air temperatures (Stirling et al. 1999). Since the time of ACIA, there have been several new findings which further confirm the impacts of climate warming on polar bear populations, as well as acceleration in Arctic sea ice loss with new projections of enormous loss in sea ice during this century. These findings have occurred in parallel with a controversial proposal by the U.S. Fish and Wildlife Service (USFWS) in January 2007 to list the polar bear as a threatened species under the U.S. Endangered Species Act, which led to renewed analysis and debate regarding the polar bear's status.

Overview

A recent assessment of published and unpublished findings by the IUCN Polar Bear Specialist Group (PBSG) showed that of the 19 polar bear populations across the Arctic (Figure 11.1), six populations have insufficient data to assess status (PBSG 2006). Of the populations for which data are available, two populations are increasing, both of which are recovering from severe past reductions through conservative harvest limits. The two populations that have long time series of data, Western Hudson Bay and Southern Beaufort Sea, are both declining, although for the Southern Beaufort Sea population, large confidence intervals in the earlier estimate of abundance mean that a statistically significant measure of trend is not possible (PBSG 2006). The declines in these two populations have been related to climate change and are discussed in more detail below. Several other populations, such as the Baffin Bay population, are also declining, although it is likely that much of these declines are attributable to over-harvesting rather than climate change (PBSG 2006). Although there have not been findings related to climate change in populations other than Western Hudson Bay and Southern Beaufort Sea, recent work has been done in other populations to establish the population baselines which will be important for future research. In the Barents Sea population, for example, a line transect analysis was conducted in August 2004, finding the population to be 3000 bears, and there are plans to undertake a re-assessment of the Barents Sea population every 5 years (Aars et al. 2006).

Figure 11.1 Distribution of polar bear populations throughout the circumpolar basin. (Source: UNEP/GRID-Arendal. Distribution of polar bear populations in the Arctic. UNEP/GRID-Arendal Maps and Graphics Library.)

West Hudson Bay population

Recent analysis of the Western Hudson Bay polar bear population found a decline from 1,194 bears in 1987 to 935 bears in 2004, a reduction of about 22% (Regehr et al. 2007b). This decline appears to have been initiated by the earlier observed declines in body condition and demographic parameters, caused by the earlier spring break-up of sea ice (Regehr et al. 2007b). Sea ice break-up in western Hudson Bay occurred more than 0.8 days per year earlier from 1971-2003, meaning that by 2003, break-up was occurring approximately 26 ± 7 days earlier than in 1971 (Gagnon and Gough 2005). After the population decline began, it was probably aggravated by continuation of an existing harvest which was no longer sustainable (PBSG 2006). In 2004, the Government of Nunavut actually increased the quota of polar bears that could be harvested from the Western Hudson Bay population from 55 to 64, based on the perception of communities which, due to the increased sightings of polar bears around human settlements, believed that the size of the population was increasing (Stirling and Parkinson 2006). An alternate explanation for the increased bear sightings is that polar bears, nutritionally stressed due to earlier sea ice break-up, are encroaching on human habitations in search of supplemental food (Stirling and Parkinson 2006, Regehr et al. 2007b). The PBSG (2006) advocate a precautionary approach when setting harvest levels in a warming Arctic, and they recommend that appropriate management action be taken in response to the decline in the Western Hudson Bay population.

The findings in the Western Hudson Bay population are consistent with the expectation that the earliest impacts of warming will be seen in the southern limits of the species' range (ACIA 2005, Derocher *et al.* 2004). In the most southerly polar bear population, the Southern Hudson Bay population, Obbard *et al.* (2006) reported a significant decline since the mid-1980s in body condition for all age and reproductive classes of polar bears. This trend could be expected to impact reproductive output and survival, thus leading to a decline in the population in the future. However, a recent assessment of the status of the Southern Hudson Bay population revealed no change in the size of the population since the mid-1980s (Obbard *et al.* 2007). That the Southern Hudson Bay population does not yet appear to be in decline may be explained by the fact that changes in sea ice patterns have to date been greater in western Hudson Bay than in the eastern or southern portions of Hudson Bay (Gagnon and Gough 2005, Obbard *et al.* 2007).

Southern Beaufort Sea population

In the Southern Beaufort Sea population of polar bears there have been various indications that the population is being affected by changes in sea ice, including changes in population size and demographic parameters, distribution of bears, and observations of change in behaviors. Regehr *et al.* (2006) estimated the population size to be 1,526 bears in 2006, a reduction from the previous estimate of 1,800, although due to low precision of earlier estimates the two population sizes were not statistically different. Studies also show that between 1982 and 2006 there has been a decline in mass and body conditions of sub-adult males, declines in growth of males and females, and declines in cub recruitment, altogether suggesting that polar bears of the Southern Beaufort Sea have experienced a declining trend in nutritional status (Regehr *et al.* 2006, Rode *et al.* 2007). Several of these measurements show a significant relationship with sea ice cover (Rode *et al.* 2007). The declines in body size and cub recruitment are similar to the conditions preceding the significant decline in the Western Hudson Bay population, suggesting that the Southern Beaufort Sea population should be closely monitored in the near future (Regehr *et al.* 2006). Results from the Southern Beaufort Sea region are relevant to over one-third of the world's polar bears, which inhabit regions of the polar basin with similar sea ice dynamics and have in some cases experienced more severe declines in the extent and duration of sea ice than the Southern Beaufort Sea (Regehr *et al.* 2007a).

Other studies, though they did not focus on a specific population, have shown changes in the distribution and behaviour of polar bears in Alaska associated with changes in sea ice. Schliebe et al. (2006) reported an increasing trend in use of coastal areas in the southern Beaufort Sea by polar bears during the fall open water period, starting in the 1990s. There was a significant relationship between the mean distance to the ice edge and the numbers of bears observed on the coast—as distance to the ice increased, the number of bears near shore increased. Gleason et al. (2006) confirm these findings, reporting a change in September bear distribution in the Alaskan Beaufort Sea from being primarily associated with offshore ice from 1979-1986 to being primarily observed on land during 1997-2006. These findings are consistent with the lack of pack ice caused by a retraction of ice in the study area during the latter period. In northern Alaska, the proportion of maternal dens on pack ice as opposed to in coastal areas declined from 62% in 1985–1994 to 37% in 1998–2004 due to changes in sea ice that have likely reduced the availability and quality of pack ice denning habitat (Fischbach et al. 2007). Observations of polar bear mortalities associated with extended open-water swimming during 2004 in the Beaufort Sea suggest that drowning-related deaths are one direct hazard posed by changes in sea ice (Monnett and Gleason 2006). Observation of three incidences of intra-specific killing and cannibalism among polar bears in the Beaufort Sea during a three-month period in 2004 supports the notion that polar bears in this area are already nutritionally stressed due to longer ice-free seasons (Amstrup *et al.* 2006).

Outlook

Several projections of polar bear habitat and population have been made as part of the analyses to inform the USFWS decision regarding listing the polar bear on the U.S. Endangered Species Act. Using 10 general circulation models (GCMs) that best approximate observed trends in sea-ice loss, Durner *et al.* (2007) projected a 42% loss in optimal polar bear habitat during summer in the polar basin by mid-century. As the projected rates of habitat loss tend to be less than the rates observed during the past two decades, these estimates are considered by the authors to be conservative (Durner *et al.* 2007). Amstrup *et al.* (2007) predicted that realization of the changes in sea ice projected by the same 10 GCMs would mean the loss of approximately two-thirds of the current polar bear population by mid-century. A recent paper argued that extrapolation of polar bear disappearance is premature as climate models cannot accurately project sea ice changes (Dyck *et al.* 2007). The USFWS has postponed its decision on the listing, which was due in January 2008.

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12. Human Dimensions of Climate Change in the Arctic

Introduction

Human Dimensions (HD) of environmental change research in the Arctic, as elsewhere, examines the interrelationships between humans and their environment, particularly with respect to changes in ecosystems. This review of literature examines new findings on HDs of climate change that have emerged since the publishing of the Arctic Climate Impact Assessment (ACIA 2005). The purpose of this review is three-fold: (1) to summarize the state of scholarship as it now stands given the increasing rate and awareness of climate change in the region; (2) to synthesize new results such that we can further evaluate the conclusions and recommendations of the original ACIA; and (3) to assist in identifying research needs, both as explicitly identified by the HD research community and as evidenced by gaps and shortcomings in research that emerged during this review process.

Directional climate change and its impacts has emerged as the largest area of HD research in Arctic regions, and most research initiatives seem to reflect the notion that climate change cannot be studied in a void. The impacts of climate change on communities and ecosystems are understood to interact with ongoing human activities at a variety of scales, as well as with other contemporary divers of change, e.g. land development and globalization, to produce varied and localized impacts (Huntington *et al.* 2006a; Schroter *et al.* 2005). Profound uncertainties remain, however, in respect to these interactions and how they translate to community-scale vulnerabilities. Community members themselves are in a better position than anyone else to understand these unique interactions--thus research has been directed to studying vulnerability and interactions in local contexts (Huntington *et al.* 2007; Lynch and Brunner 2007; Schroter *et al.* 2005). It is increasingly clear that local context matters in science, policy, and in the creation of decision-making structures for adaptation to climate change and other influences on environmental variability (Huntington *et al.* 2006b; Lynch and Brunner 2007).

One significant observation common to a large set of new HD research is that human activities in the Arctic have the potential to either amplify or mitigate the effects of climatic variability and change on Arctic societies (Huntington *et al.* 2006a; Lynch and Brunner 2007; Patz *et al.* 2005; Schroter *et al.* 2005). The corollary that follows from this observation is that if human activities can so significantly contribute to localized expressions of climate change, they must also be as capable of mitigating or reconfiguring these impacts through adaptation and innovation. Of course, adaptation is not the same as preventing the change, but the capability of humans, through innovation, to positively affect the impacts of environmental change should not be underestimated (Huntington *et al.* 2007; Irvine and Kaplan 2001).

This review of HD research published recently (and in some cases still in press) highlights research findings that were not available for inclusion in the ACIA synthesis. In the year or so following the release of the ACIA, much of the case work that was included in the document was then published in a variety of peer-reviewed journals. These have been omitted, except where these cases have been used to further refine theory or develop understanding beyond what is covered in the ACIA. This new literature has been synthesized in respect to the goals and recommendations of the ACIA in order to capture the extent to which new research is following the trajectory put forth by the report. It is not intended to be read as comprehensive, but several research techniques were employed to ensure that the most influential reports have been included. In some cases, for example, with respect to the impact of climate change on human health, significant ground has been broken in the last three years, whereas in other areas of interest, e.g. the effects of global climate change on infrastructure and economy, the pace appears to have been slower. The emphasis and distribution of recent work is a significant finding in and of itself, with clear ramifications for collaborative research approaches, which we discuss in the final section of this document.

Finally, this review examines how recent work has influenced and adjusted existing theoretical frameworks and research methodologies. Significant attention has been paid in the last few years to vulnerability, adaptability and resilience theories, and many of the regional case studies found in the ACIA have since been leveraged as primary source material in support further developing these frameworks, theories and models. The emphasis in this work has been on achieving fine-scale resolution while maintaining large-scale comparability and relevance. If there is one recognizable working hypothesis that permeates all of this literature, it is that this cross-scale approach is needed to deliver results that will support policy changes, leading to local-scale action in response to, and (ideally) in advance of, climate change impacts. Though there is a great deal of duplication of effort in this respect, the sum of the scholarship provides us with new insights.

Climate Change and Human Health

Understanding and addressing climate change-related health impacts has become more urgent with the realization that impacts are already occurring, with one study estimating that global anthropogenic climate changes already claims at least 150,000 lives annually (Patz *et al.* 2005). Assessments of the potential health impacts of climate variability and change are therefore needed to inform the development of adaptation options in healthcare and other public health sectors, and to provide information on the impacts and the adaptation requirements to international policy processes (Ebi *et al.* 2006a). In general, the health impacts of climate change have been broken down into the following three categories: (1) impacts that are directly related to weather and climate, (2) impacts that result from environmental changes that occur in response to climatic change, and (3) indirect impacts resulting from consequences of climate-induced environmental decline, economic dislocation and conflict (McMichael *et al.* 2001). It is essential, however, when considering climate change as a driver of these impacts, that climate change be considered together with concurrent trajectories of change in other sectors, e.g. economic and political change, as the synergistic, end-results of climate and these other drivers of change are often inexorably intertwined.

Physical health

Direct Impacts: Interactions between climate and contaminants

Various interactions between climate change and the bioaccumulation, biomagnification, and transfer of contaminant compounds, e.g. persistent organic compounds (POPs), methylmercury and organochlorides, are anticipated, though remain relatively poorly understood (Gantner *et al.* 2007; Schiedek *et al.* 2007). Though climate warming has now been shown to support the faster break-down of persistent organic pollutants (POP), (an apparent benefit, whereby pollutant concentrations are reduced for many localities), this otherwise positive effect is most likely coupled with an enhanced mobility of these chemicals, and hence enhanced potential for long range atmospheric transport (Dalla Valle *et al.* 2007). Atmospheric transport of contaminants to the Arctic is expected to undergo considerable change over the next few decades as a result of climate change, with higher Arctic temperatures and reduced sea ice cover possibly increasing rates of deposition to marine polar ecosystems (Macdonald *et al.* 2005; Meyer and Wania 2007). It is expected, therefore, that there will be greater contaminant transfer to Arctic regions moving forward, where degradation and removal of POPs from the environment is more difficult, with the long-term net effect being greater bioaccumulation and biomagnification of these compounds (Dalla Valle *et al.* 2007; Meyer and Wania 2007).

Increased temperatures associated with climate change are expected to affect aquatic ecosystems and living resources, with implications for coastal communities and fisheries management. Many aquatic ecosystems are also affected by human releases of contaminants, for example, from land based sources or the atmosphere, which also may cause severe effects. So far these two important stresses on ecosystems (climate and contaminants) have mainly been studied and discussed independently. Both forms of stress are likely to interact in terms of the end-result impacts on aquatic ecosystems and biota (Schiedek *et al.* 2007). A general conclusion in this field is that more research is required to understand and predict how on-going and future climate change may alter risks from chemical pollution.

The most recent research into the possible health-impacts of these new trends in contamination suggests that the extent and distribution of contaminant concentrations will vary in new and unpredictable ways across the food and water resources of a region (Burger *et al.* 2007; Jewett and Duffy 2007; Moiseenko *et al.* 2006; O'Hara *et al.* 2005). Some examples are methlymercury levels in Aleut subsistence foods which range from

0.001 ppm in kelp (*Fucus distichus*) to nearly 1 ppm in pacific halibut (*Hippoglossus stenolepis*) (Burger *et al.* 2007). Also organochlorine concentrations in country foods from northern Alaska have been found to range from very high in beluga whale blubber (*Delphinapterus leucas*) to quite low in pink salmon (*Oncorhynchus gorbuscha*) (O'Hara *et al.* 2005). Research examining mercury levels in the hair of sled dogs fed country foods as a proxy for local exposure in communities along the Yukon River also supports the possibility that methylmercury concentrations will vary significantly and unpredictably across the landscape (Dunlap *et al.* 2007). These datasets suggest that mitigation and response strategies will need to be tailored considerably to local scenarios which address differently impacted communities and subgroups within that community (Burger *et al.* 2007).

Indirect effect: Country foods and nutritional security

There are significant physical health-related concerns associated with improper nutrition and contaminant exposure that must be considered when evaluating the impact of climate change on community food systems. The country foods that come from the land, lakes, rivers and sea remain central to the way of life, cultural identity and health of northern indigenous peoples (Bersamin *et al.* 2007; Gerlach *et al.* in press; Graves 2005; Van Oostdam *et al.* 2005). Decreased access to country food resources as a result of climate change has been identified as potential indirect impact of climate change, though only in terms of the resultant levels of food security (e.g. Furgal *et al.* 2002; Nuttall *et al.* 2004), and in respect to the stresses on psychological and cultural well-being that result from the discontinuation of traditional ways (see below). However, diets across the Arctic are in transition, with store bought foods replacing country foods to some extent (see Brustad *et al.* 2007 (Saami); Kuhnlein *et al.* 2004 (Inuit); Loring 2007a (Athabascan); Samson and Pretty 2006 (Innu)). Tremendously important, therefore, is research that shows that country foods almost universally exhibit superior nutritional aspects to market foods, especially in respect to meeting the dietary needs of locally adapted populations (Bersamin *et al.* 2007; Ebbesson *et al.* 2005; Hassel 2006; Kuhnlein *et al.* 2002; Kuhnlein *et al.* 2004; Mohatt *et al.* 2007). Alaskan Yup'ik peoples of the Yukon-Kuskokwin delta, for example, were found in a study by the Center for Alaska Native Health Research (CANHR) to be metabolically healthy as a result of a country food diet and lifestyle that provides a delicate combination of protective factors (Mohatt *et al.* 2007). As the overall proportion and diversity of country foods that contribute to diet in indigenous communities continues to follow a downward trend, the prevalence of eating from the store increases.

Indirect Effect: Conflict and Violence

Climate change is increasingly being seen as a security problem globally, with conflict and violence identified as not just possible but likely outcomes, based on significant historical and contemporary precedent (Barnett and Adger 2007; Smith and Vivikananda 2007). The down-scale impacts of climate change, whether direct (e.g. extreme weather events, drought) or indirect (increased cost of food) are all anticipated to impact populations variably, with the most severe impacts predicted to be experienced by those least prepared or able to cope with or adapt to change. Poverty, discrimination, access to economic opportunities, and the extent of social cohesion within vulnerable groups are just some examples of social factors that will determine livelihood outcomes in these scenarios. Climate change has the potential to aggravate poverty through changes in natural resource availability and to decrease the state's ability to provide infrastructure services (and increase the costs of those services). Thus, these changes can be expected to elevate hostility between differently-impacted groups and communities, as a result of feelings of inequity, debates over the use (and abuse) of resources, the level of equity present in aid services and disaster response, and as a result of the migration of environmental refugees from impacted areas.

The Arctic has not been specifically targeted as a primary region for concern regarding conflict (e.g. Ink 2007). However, all of the circumstances that are expected to lead to conflict elsewhere in the world are also of significant concern in Arctic regions, e.g. changes in hydrology and the likelihood of drought, competition for land and resources, and inconsistent governance regimes that differentially handle issues of equity and sovereignty (Smith and Vivikananda 2007). These analyses of potential conflict 'hot-spots' around the world assumed Arctic regions to be on the lower end of climate change impacts in the short term. Considering that the Arctic is in fact experiencing climate change sooner and more strongly than other regions, the projections regarding potential for conflict and violence likely need to be reconsidered.

Psychological and cultural health

Indirect Effects: environmental and cultural change, social and psychological stress

Rural communities of the Arctic are all experiencing a restructuring process, including economic, social, demographic and political changes. The rate of this trend has increased in recent years, in part because of global climate change (Dalla Valle *et al.* 2007; Ebi *et al.* 2006b; Fuller-Thomson 2005; Gerlach *et al.* in press; Huskey *et al.* 2004). This restructuring process poses significant implications for the health of people and their communities, through the impacts of community decentralization and out-migration, declines in natural resources (e.g. country foods), environmental degradation and pollution, loss or lack of healthcare services, downturn in global economies and climate change.

Place, culture and mental health

Culture in indigenous communities is a localized experience, where people achieve security through social cohesion and support, linked through the economies of their livelihoods to each other and to particular socio-geographic spaces (Basso 1996; Rolfe 2006). The importance to people of the places in which they live has been shown to contribute significantly to their mental well-being, especially in circumstances of economic uncertainty (Fone and Dunstan 2006). Continued depopulation of rural areas in the Arctic as a result of the impacts of environmental change are expected to continue at least in the short-term (Moiseenko *et al.* 2006).

This decline of rural areas, in tandem with the restriction of people from their traditional harvest areas as a result of wildlife management policy, landscape change or development should, therefore, be expected to affect individuals, households and community relationships in a multiplicity of ways, often with profound impacts on the mental, physical and social health of individuals and communities (e.g. Degal and Saylor 2007; Fraser *et al.* 2005a; Graves 2005; Wolsko *et al.* 2007). As an example, Graves (2005) explored how a decline in the emphasis on Alaska Native men's responsibilities for hunting, fishing and gathering has proven to destabilize gender roles as well the men's perceptions of their overall position within their families and community. Similarly, Wolsko *et al.* (2007) researched correlations in Alaskan Yupik communities between happiness, psychosocial stress and substance abuse in relation to self-perceptions of one's degree of enculturation or acculturation (Wolsko *et al.* 2007). These findings also point toward the untapped mitigative power of culturally-based participatory therapies, which succeed via focusing on traditional activities, pedagogical relationships, religion and support groups (Graves 2005; Samson and Pretty 2006; Saylor *et al.* 2006; Wolsko *et al.* 2007).

Differently-impacted sub-groups: Elders

Grandparents and elders are just one example of an Arctic community subgroup that is currently understood to be experiencing the down-scale impacts of climate change and societal change differently than others in their communities (Fuller-Thomson 2005; Gerlach *et al.* in press; Poppel *et al.* 2007). As elders grow older, they bear a greater vulnerability to health risks and are faced with challenges associated with remaining in their rural communities (e.g., lack of social support system, inadequate health care services). Ongoing climatic and socioeconomic changes are all expected to compound these challenges through new threats to physical, cultural and psychological health. It has become increasingly necessary for elders to relocate to urban communities (Huskey *et al.* 2004; Poppel *et al.* 2007). This not only has implications for the grandparents themselves, but also for their communities and culture, as grandparents can be sources of resilience to aid their communities through these challenges, as keepers and transmitters of history, culture, and values, and as role models and mentors to youth (Fienup-Riordan 2005; Fuller-Thomson 2005; Greve and Staudinger 2006). Also, as elders die or are forced to leave their communities, that community's ability to engage in issues of climate change and adaptation is undermined as elders are consistently considered to be the keepers of essential knowledge about the land and landscape.

Community Update: The case of Shishmaref, AK

Shishmaref, Alaska is one of many examples across the Arctic where climate change impacts are following these direct and indirect pathways to affect human health. Shishmaref is located on Sarichef Island, off the north-west coast of Alaska's Seward Peninsula. New and extreme weather patterns, sea-ice retreat, permafrost thaw and sea level rise are already undermining the integrity of the community's basic public infrastructure and posing significant threats, both immediate and long-term, to the health of its residents. The impacts on the community's infrastructure (buildings, sanitation systems, etc.) are so severe that the community faces certain relocation to the Alaskan mainland (NOAA 2006). In cases like this, where the outlook for the community is so dire that relocation has become the only plausible option, health impacts must be assessed on the adaptations side (e.g., relocation and its impacts) as well as on the impacts side of the equation (e.g., the many hazards of remaining at the current location).

Concurrent to the compilation of the ACIA, researchers were performing a cultural impact assessment of the relocation options available to the community. Relocations like these have the potential to be the most abrupt kind of environmental change imaginable for Arctic indigenous communities, whose lifestyles have been linked to specific places for centuries, if not millennia. Released in December of 2005, the US Army Corps of Engineers' "Collocation Cultural Impact Assessment" compiled local perceptions of the potential sociocultural impacts to the Shishmaref community of collocation to either Nome or Kotzebue (Schweitzer and Marino 2005). Interviews were also undertaken with members of the two potential host communities. The assessment group perceived potential impacts into four categories: culture, subsistence practices and lifestyle, health, and social structure. The document also offered an anthropological taxonomy of community relocation types that is particularly useful, drawing on historical case-studies from across the Arctic. While the document was comprehensive in its inclusion of local input, it did not provide a framework for linking the perceived and potential impacts into measurable health outcomes.

Moving forward

Research challenges

As exhibited by the case of Shishmaref described above, more research attention is needed on the pathways by which the direct and indirect impacts of environmental change can result in measurable health outcomes, especially with respect to the most vulnerable subgroups. Also needed is research leading to, a more practical grasp of the adaptive capacities necessary for those subgroups to respond, and the lack of this understanding has implications for public health policy and practice (Ebi *et al.* 2006a; Schwartz *et al.* 2006). There is a continued lack of reliable local and regional climate change projections, which limits researchers' ability to quantify the burden of diseases attributable to climate change (Ebi *et al.* 2006b). Until reliable quantitative estimates of both impacts and adaptive capacity are developed, the net impacts of climate change on human health will inevitably be described as uncertain.

Short term responses: raising awareness and changing behaviour from the bottom up

In general, institutional responses to the climate crisis, through mechanisms such as policy and regulation, are expected to happen too slowly to keep up with the short-term outcomes of climate change. Despite the increasing understanding by the scientific community of the immediate threats climate change poses to human health worldwide, the general public continues to focus on worries closer to home, ranking climate change behind many other environmental issues such as pollution of rivers, lakes, and reservoirs and toxic waste (Schwartz *et al.* 2006). Healthcare practitioners can play a significant role in changing current behaviour until these slower, institutionalized responses take effect. In particular, the authors call upon clinicians to counsel their patients using tools that measure ecological footprints; for health care and environmental-health professionals to collaborate in the development of such tools; and on the development of a global environmental health index for use in year-to-year monitoring that combines "planetary health" with human health (Schwartz *et al.* 2006).

Box 1. Six primary principles for stakeholder-driven health and environmental impacts research (Ebi *et al.* 2006).

- Identify current associations and recent trends in the variance between populations for climate-sensitive health determinants and outcomes
- Note existing strategies, policies and measures designed to reduce the burden of climate-sensitive health determinants and outcomes, as well as ones that might restrict adaptive options
- Forecast health implications of the potential impacts of climate variability and change in other sectors, e.g. water resources, agriculture, flood hazard management and the built environment
- Hypothesize future potential health impacts, in terms of the synergistic effects of future changes in climate, socioeconomic and other factors
- Suggest adaptation policies and measures which bear the potential for reducing potential negative health impacts
- The impacts of implemented, as well as planned, adaptation options in response to actual or projected climate change need to be evaluated in terms of potential adverse health effects.

Long-term planning: assessing vulnerability and adaptability to health-related stressors

There is a need to develop a stakeholder-driven framework which evaluates the impacts of climate variability and change on individuals and communities, one which can identify vulnerable populations and support the necessary analysis, understanding and enhancement of capabilities of local areas to respond and adapt to the health impacts at the local level (Box 1) (Ebi *et al.* 2006a; Furgal and Seguin 2006). One such framework for assessment is the Health Impact Assessment (HIA), which, though limited in use to date, has recently been successful in conjunction with an Environmental Impact Statement to evaluate health outcomes of proposed oil development on Alaska's North Slope for Inupiat communities (Werhham 2007). HIAs provide a systematic process and methodology to anticipate and proactively address the potential health consequences of an environmental change or disturbance, in order to minimize adverse outcomes (Quigley *et al.* 2006). HIAs take a comprehensive and inclusive approach to evaluating potential health effects, basing analysis on the conceptual frameworks of the social and environmental determinants of health (WHO 2007). HIAs can be scoped broadly (i.e. via a holistic, qualitative, participatory approach rooted in anthropology or sociology) or tightly (i.e. quantitative and epidemiologically focused with a limited scope) (Cole and Fielding 2007). The HIA, as an alternative assessment approach that uses an integrated health model for understanding health outcomes, would have provided more insight in the case of Shishmaref described above, and should be considered in the future as researchers tackle the challenge of quantifying the complex regional health outcomes of climate change.

Economy and Infrastructure

The ACIA summarized a variety of ways that climate change can - and indeed already does - impact the infrastructure, and thus economies, of northern communities. A warming climate poses threats to infrastructures in the Arctic because they are designed for the cold climate. Warming can result in damage in places where permafrost thaws, flooding increases, and coastal erosion gets worse. The efficacy and relevance, however, of economic estimations of these impacts, as well as of the methods and assumptions used, whether at large or at discrete scales, is a subject of debate (Bosello *et al.* 2007; Nordhaus 2007; Stern 2007; Weitzman 2007).

Nevertheless, assessments are being performed at a variety of scales. The Stern Review (Stern 2007) took an international perspective. It explored how economic theory can help analyse how business-as-usual approaches versus decisive-action approaches to adaptation and mitigation strategies will play out in the long run in terms of neoclassical growth and development paradigms. Stern challenged both approaches and discussed the economics of stabilizing directional climate change trajectories, including the costs of mitigation, and examined how economic models can lead to the development of economically viable climate change policies.

Stern's report has already faced significant controversy, in particular with respect to assumptions regarding discounting and models for determining what discount/interest rates are valid within the climate change realm (Nordhaus 2007; Weitzman 2007).

At a far smaller scale, the University of Alaska Anchorage's Institute for Social and Economic Research (ISER) recently completed a sweeping economic assessment of the costs that climate change poses to the public sector, specifically in terms of infrastructure (Larsen *et al.* 2007). The public infrastructure assessed includes all of Alaska's publicly maintained roads, bridges, airports, harbors, schools, military bases, post offices, fire stations, sanitation systems, the power grid, and more. Damages from climate change were estimated to add $3.6 to $6.1 billion (10%-20% of existing infrastructure maintenance costs) from now to the year 2030. The extra costs will likely diminish over time as government agencies increasingly adapt and/or replace infrastructure in order to suit changing conditions. Figure 2 represents these estimates for the state, along with some other details about the infrastructure included in the modeling. The framework and modeling tools used here might provide a prototype that other Arctic countries can use to make similar assessments.

Vulnerability, Adaptation and Resilience

- Tailoring theory and assessment to understand how we experience global environmental change.

A recurring conclusion of the research reviewed here is the need for locally- and regionally-scaled projects capable of picking up interactions between climate and other drivers of change, of identifying differently-impacted sub-groups (household, community, demographic sub-group, etc.), and of identifying the specific pathways by which change translates into localized impacts. Though general statements may be made about the impacts of climate change throughout the Arctic, the manifestations of these general trends at the local level vary considerably and unpredictably from place to place (Gearheard *et al.* 2006). Vulnerability, adaptation and resilience frameworks are widely considered to be complementary approaches that are suited to this kind of fine-resolution research without sacrificing the broader applicability of findings (Adger 2006; Chapin III *et al.* 2006b; Ebi *et al.* 2006a; Ford *et al.* 2007; Patwardhan 2006; Schroter *et al.* 2005; Smit and Wandel 2006). The novelty of such approaches is that they allow for the integration of techniques across a wide variety of intellectual domains. The ACIA did not benefit, however, from many recent advances in these three areas of theory. Together, vulnerability, adaptation and resilience are easily the most frequently discussed analytical frameworks in HD climate change literature since 2004, with many articles revisiting older case studies from these new theoretical perspectives. These include Chapin III et al (2006) for the boreal forest, Ford et al. (2007) and Furgal and Seguin (2006) for Nunavut and Canada's First Nations, Berkes et al (2005) also for the Canadian North, Patwardhan (2006) for coastal zones, Tyler et al (2007) for Saami reindeer pastoralism, and Fraser et al (2005b) for food systems.

Reconciling theory

The concepts of vulnerability, adaptation and resilience are hardly new; indeed each is rooted in a variety of academic traditions. However, despite even the most recent attempts to consolidate and/or reconcile definitions and frameworks (e.g. Adger 2006; Patwardhan 2006; Schroter *et al.* 2005; Smit and Wandel 2006), they continue to be used without standardization or cross-referencing across the literature (Newton *et al.* 2005). They do, however, share many relatively stable fundamentals.

In general, *vulnerability* of a system, be that system a household, community, or a municipal transportation infrastructure, is considered the matter of two factors: its exposure and sensitivity to an outside force, e.g. climate-change-related impacts (Adger 2006; Adger *et al.* 2005; Schroter *et al.* 2005; Smit and Wandel 2006). Exposure is influenced by the character, magnitude and rate of predicted variation in climate and weather variables, especially where the system would otherwise hold those variables constant as state factors. In other words, a system's exposures to the effects of climate change include its susceptibility to the effects of extreme weather events as well as long-term trajectories of change. Sensitivity to changes in those variables is the extent to which that system's normal function can be disrupted by such changes in climate and weather.

Adaptation captures the strategies, policies and measures undertaken, both at present and in the future, with the intent of reducing exposure and/or the burden of sensitivity to change. In the same vein, *adaptive capacity* is the ability of the system to implement these measures. In the context of human dimensions of climate change, adaptation usually refers to a process, action or outcome in a system, undertaken to better cope with, manage or adjust to some changing condition, stress, hazard, risk or opportunity. Though contemporary literature only captures adaptation as a response function, it is important to note that adaptation does not only happen in the context of vulnerability or change (Bennett 1996). Adaptations can be anticipatory (actions taken in advance to reduce exposure), responsive (to mitigate sensitivity), or innovative (without clear precedent) and can encompass both spontaneous responses to climate variability and change by affected individuals and also planned responses by governments or other institutions (Adger *et al.* 2005; Smit and Wandel 2006). Adaptations usually happen as the result of cascading decisions across a sociopolitical landscape of agents, from individuals, firms and civil society, to public bodies and governments at local, regional and national scales, and international agencies. Agents at all of these scales have varying abilities to adapt their behavior both in response to past or current events, but also in respect to some assessment of conditions in the future. Thus, one common purpose of assessing adaptive capacity is to understand the political, social and economic institutions that limit or support decision-making, particularly when deciding between mitigative, preventative or innovative responses (Adger *et al.* 2005; Loring *et al.* in press).

Resilience is most commonly defined as the extent to which a system can experience change while retaining its ability to return to its original state. Resilience itself is an emergent property that is most often the result of strong negative (i.e. stabilizing) feedbacks that buffer the system against change. Biodiversity on a landscape, for example, is generally considered a contributor of resilience, as a food web with high connectedness is less likely to undergo a dramatic cascade event when faced with a disturbance or introduced species (Chapin III *et al.* 2006b). Thus, institutions that foster biological, cultural, institutional and economic diversity are all examples that can increase the likelihood that important functional components of a social–ecological system will be resilient to surprise. Resilience is not an inherently good or bad quality of an ecosystem; many undesirable states, from polluted and degraded landscapes to socio-political dictatorships, can be quite resilient. However, the system properties that give rise to resilience are clearly of particular interest when managing systems with the goal of maintaining certain state conditions.

How resilience fits into frameworks of vulnerability and adaptation is significantly inconsistent across treatments. In some frameworks, resilience is handled independently from vulnerability and adaptation (e.g., Chapin III *et al.* 2006b), and in others, resilience is not referenced at all (Adger *et al.* 2005; Schroter *et al.* 2005; Smit and Wandel 2006). Sometimes vulnerability and resilience are presented together as opposites, alternative system states, or as partners in a problem-solution relationship (e.g. Adger 2006; Forbes *et al.* 2004), and at other times, resilience is used interchangeably with adaptive capacity. The ACIA glossary, for example, defines the term as “synonymous with adaptive ability.” At best, it is clear that the concept is important but its role in vulnerability frameworks cloudy.

Learning from the confusion

Vulnerability and resilience frameworks share common elements of interest – the shocks and stressors of change, systematic responses to those shocks and stressors, and the capacity for adaptive response (Adger 2006). Several subtle differences, however, are clear: adaptive capacity, for one, suggests the possibility of change, whereas resilience is the amount of change a system can undergo without changing state (Walker *et al.* 2004). Thus, a key difference not captured by resilience is that adaptive capacity can involve a potential for changing into a state that is less vulnerable than before (Schroter *et al.* 2005). Similarly, vulnerability is not just a matter of sensitivity to change (which might be effectively expressed as a lack of resilience), but also as a matter of exposure to change, which though having nothing to do with resilience is potentially influenced by adaptive capacity (Chapin III *et al.* 2006b).

Transformability

A fourth concept, transformability, is sometimes handled on its own but in others is captured by adaptation. The fine nuance between the two is that transformability directly reflects the capacity to create a fundamentally new system with different characteristics, when the current state of a system is undesirable (Carpenter and Folke 2006; Walker *et al.* 2004). In cases where frameworks distinguish transformability from adaptation, it is because the latter is understood to imply that the overall system state, or identity, has remained the same, whereas the former implies fundamental change (Chapin III *et al.* 2006b). As such, a conservative approach would be to represent transformation as an extreme form of adaptation, allowing definitions of identity to remain endogenous. Figure 3 shows some ways we might conceive of the relationships between these four phenomena. In this diagram the system (e.g. household, community, nation, etc.) responds to a suite of interacting drivers (stresses, events, shocks) to produce one of three potential outcomes: persistence of the existing system through resilience; transformation to a new, potentially more beneficial state through transformability; or deterioration to a more degraded state due to vulnerability and the failure to adapt or transform.

Recognizing stability or change in identity for social-ecological systems is very much a matter of perspective, with especially problematic ramifications when exogenous definitions of identity become reified within policy and/or law (Gerlach *et al.* in press; Loring 2007b). Put another way, whether localized responses to some exogenous impact or trend are considered ‘adaptive,’ ‘maladaptive’ or ‘transformative’ is linked to how that system is defined. Perhaps the best way, then, to conceive of vulnerability, resilience and adaptive capacity, is not as analogues, opposites or alternative states but as three interrelated phenomena, each resultant from their own set of relevant system properties and desired outcomes that must be defined and identified by the stakeholders of that system (Figure 4).

Policy and Mitigation

Policy structures, in general, tend to deal reactively with environmental change and surprise, operating from the perspective of mitigating outcomes rather than proactive capacity building (Brock and Carpenter 2007; Chapin III *et al.* 2006b; Ebi *et al.* 2006a). Indeed, research shows that individuals and communities in the Arctic (and elsewhere) rarely have the liberty to adapt freely. The relocation options available to the community of Shishmaref, for instance, only include two potential sites for collocation. Options are often constrained by institutional processes such as regulatory structures, property rights and social norms associated with rules in use (Adger *et al.* 2005; Ford *et al.* 2007; Gerlach *et al.* in press). Policies and strategies intended to reduce vulnerability and promote resilience and adaptability are often in conflict with the status quo of agencies and institutions, and can amplify existing conflicts over objectives between private and public agents (Adger 2006). Also, when there *is* institutional involvement in adaptation initiatives, implementation rarely occurs according to a prioritization that emphasizes local needs or physical/social/cultural risk; rather, decisions regarding management and implementation are often couched within the economics trade-offs between the benefits of action and the costs of inaction (Stern 2007).

Ultimately, the choice of how environmental problems are handled within a jurisdiction is on one level a reflection of the strength of the interests and power of the actors who define the problem, and on another, the result of design features in institutional arrangement (Dagget 2005; Newton *et al.* 2005). Institutional wildlife management regimes regularly espouse different conservation and political agendas, represent different core groups of interest and are informed by different perspectives on wildlife management and management science than are local communities (Gerlach *et al.* in press; Huntington *et al.* 2006b). In Alaska, for instance, formal state and federal institutions that manage natural resources address a single category of fast ecological variable (e.g. abundances of fish and game, or timber yield) rather than the slower supporting and regulating subsystems that are most fundamentally affected by warming. Fish and wildlife managers focus almost exclusively on the population consequences of variations in predators and human harvest and give little time, authority or funding to address the consequences of warming (Chapin III *et al.* 2006b). Thus, many communities are restricted in their ability to make anything more than the most superficial adaptations to hunting and fishing strategies. In circumstances where institutional constraints are particularly binding, adaptations and the evaluation of their efficacy will, therefore, need to focus on efforts to changing those broad economic–social–political structures themselves (Smit and Wandel 2006).

Making room in policy for adaptation

By targeting policy, not only do you affect abilities to adapt in the short term but you strengthen community resilience to longer-term climate change as well. Nevertheless, there has been limited progress across the North in moving from policies that favour mitigation to ones that foster local adaptation initiatives (see Figure 5) (Ford *et al.* 2007; Newton *et al.* 2005). A new direction in research is necessary to identify what sorts of policy measures are required to moderate or reduce the negative effects of climate change, as well as how best to develop, fund and integrate these policies into existing regulatory and decision-making structures (Patwardhan 2006). One approach to facilitating climate-change adaptation is known as “mainstreaming” (Ford *et al.* 2007; Smit and Wandel 2006). Mainstreaming climate-change means incorporating it within policy areas normally seen as outside the scope of climate change, such as poverty alleviation, education, healthcare and sustainable development (Ford *et al.* 2007; Schwartz *et al.* 2006). Actively involving communities in the research process is another important way in linking research to adaptation-friendly policy outcomes (Berkes 2005; Chapin III *et al.* 2006b; Newton *et al.* 2005). Interventions to reduce vulnerability will be more successful if they are identified and developed in co-operation with local actors as the community will be more likely to trust them and find them consistent with local goals and norms (Irvine and Kaplan 2001).

Research in Nunavut into the linkages between adaptation options and policy obstacles or shortfalls has identified three specific entry points for policy reform that can address factors contributing to community vulnerability to climate change: cultural preservation, wildlife management and harvester support (Ford *et al.* 2007). Quota systems within the Nunavut wildlife management policy regime, for instance, while intended to maintain long-term sustainability of marine mammals as a subsistence resource, ultimately limit the temporal and spatial flexibility of hunters’ procurement strategies and, therefore, limit their ability to respond to changes in weather and seasonality that are resulting from climate change. In addition, quota allocation, whether impacted by climate change or other sociopolitical factors, has become a source of social conflict, both within communities and between communities and federal regulators. Implementation of new co-management policies that instead place more oversight in the hands of local resource users, and have the flexibility to allow for adjustment of quotas geographically as well as throughout the season or year, provide an example of policy changes that would significantly increase the adaptive capacities of these communities. Although these are regionally specific examples, they carry significant lessons for other northern regions in respect to both research and action.

Vulnerability indicators

Indicators are generally seen as ideal information tools for policymaking so many researchers have begun searching for a portable set of vulnerability indices which can provide relative vulnerability scores that are comparable across geographic, temporal and political scales (Adger 2006; Eriksen and Kelly 2007; Winograd 2007). Vulnerability indicators help policy-making and implementation processes by identifying adaptation strategies that address the most pressing impacts of change first. However, one of the main challenges in selecting representative vulnerability indicators at regional and national levels, and in conceptualizing vulnerability at these scales, derives from the fact that the effects of climate-induced pressures are unevenly distributed in time and space, and they are mediated by society (Eriksen and Kelly 2007). Thus, when selecting robust vulnerability indicators, capturing patterns of local variability and temporal variability is essential (Adger 2006). Also, indicators must capture the factors and processes that operate on scales higher than the household or community level, which determine the existence of opportunities to adapt when faced with a climatic event.

How much attention policy-makers should give to indicators of short-term versus long-term vulnerabilities to climate change, and how best to integrate them, depends very much on local circumstances (Newton *et al.* 2005). Any policy initiative that is undertaken must possess the integration among immediate benefit and longer-term regional, national and global implications. Where these policies expand individual and community freedom to adapt and innovate, citizens will thus be able to assume responsibility, empowered to act in their own best interests as a more cohesive group. The results of people's capability to mould themselves to changing conditions and environments are evidenced by the tenaciousness of human survival throughout the Arctic. Only where policy-makers embrace the inevitability of climate change impacts in the short term, and draw on local people's strength and knowledge, will new policy solutions foster the kind of dramatic adaptation that is required to meet short-term needs, as well as to influence new climate change trajectories in the long term.

Vulnerability, adaptation and resilience theory in practice

Studies of historical adaptations to vulnerability and change have provided many insights to researchers hoping to anticipate the possible impacts of climate change. To date, however, these studies have only yielded moderate practical effect in helping planners, policy makers and community members themselves to reduce the future risks associated with climate change (Smit and Wandel 2006). An important research goal for the practical study of social and cultural adaptation to climate change should be the diagnosis of the processes of climate, weather and system's sociopolitical dynamics, that together result in problematic, risky or hazardous outcomes (Box 2) (Ostrom 2007; Smit and Wandel 2006).

A framework for evaluating the efficacy of past or planned adaptations would need to make those evaluations at the scale of the discrete adaptation actions, as well as in terms of resultant sociopolitical vulnerability and sustainability at larger and smaller scales (Adger *et al.* 2005). Adaptations are usually undertaken with locally-relevant objectives in mind. Defining success or failure simply in terms of the effectiveness of meeting these objectives, therefore, will not capture circumstances where adaptations at one scale are maladaptive at another (Patwardhan 2006). A normative evaluative criterion for judging the success of adaptations across scales, therefore, would need to incorporate elements of effectiveness, efficiency, equity and legitimacy as important for judging overall adaptation success (Patwardhan 2006). Any such framework must assume, however, that there is already in place a process through which adaptations are actively selected and implemented by a community, as opposed to adaptation happening as the culmination of agent-driven, bottom-up change or by legislated, top-down change, and also that a structured evaluation analysis could be fit in to this process (Smit and Wandel 2006).

From vulnerability to policy: Saami reindeer pastoralism

The design of vulnerability studies must reflect the nuances of the case under investigation (Schroter *et al.* 2005). An excellent example of such a study is found in the Tyler et al. (2007) study of reindeer pastoralism in Norway. The economy of this sector of human activity is endemically weak, and has been identified as an area of society in Norway particularly vulnerable to the impacts of climate change. The region is characterized by extreme climate variability, but the social and economic arrangements and strategies of reindeer herders have historically provided both efficient and sufficient adaptive capacity for them to manage these environmental challenges. Predictions for new warming-induced weather trends in the region in terms of the effects on reindeer browse and winter precipitation, however, are severe (Chan 2006). As in other parts of the world, new variation is expected to be different, more erratic or more severe than has been experienced in the past.

Weather patterns influence reindeer herds indirectly, affecting the quality and quantity of available browse in the short term, through conditions that influence growth and abundance of the flora in the summer, and the snow-pack cover that can limit access to the browse in the winter. In addition, these systems are influenced not just by climate but by a mixture of interacting factors such as access to land, competition, predation, and the market for reindeer products (Figure 7). Herders regularly inform their strategies with cues from the behaviour of their animals and observations of weather. In the past, this has been sufficient for informing strategic mitigating of the impacts of undesirable environmental conditions and erratic weather. Movement across the diverse landscapes, for instance, was invariably the best way to ameliorate heterogeneous distribution of browse resources. Phenotypic diversity was a prized characteristic for herds, e.g. diversity in reindeer age, sex, size, and colour; indeed the belief was that a beautiful herd was a diverse one. This diversity brought great resilience to the herd itself. Larger males, for instance, considered in the past by agronomists to be largely unproductive, were capable of breaking up the heaviest of snowpack in the winter, freeing food for the smaller or lighter females and youth. This understanding of past strategies suggests that the contemporary, increasing trend of comprising herds with only the highest-market-value females, will have serious ramifications for herd vulnerability now and in the future.

Loss of habitat to environmental change, land development, and restriction by institutions and governance, all have the potential to reduce herders' ability to cope through movement strategies. In general, herders in the region have identified four areas of government policy and institutional arrangement that are amplifying rather than mitigating the effects of new climate variability: (1) loss of habitat both when it is physically destroyed as the result of land development and when it is legally made unavailable by redistribution of grazing rights; (2) predation, where current conservation regimes restrict the hunting of predators, has not been addressed by policy; (3) outside influence on the reindeer economy through price fixing and rules that favour industrial players which, in turn, destroys the profitability of reindeer pastoralism for small-holders; and (4) legislation governing the sector which is antiquated, complex, and written by lawmakers with no endemic understanding of the system. Policy, at all of these scales, and not weather, is therefore the most significant source of vulnerability for this herding system, and so also the most important area of opportunity moving forward.

New, Adaptive Policy and Management Approaches

Since the ACIA, there has also been a significant prioritization by the research community to explore how existing policy structures and resource management regimes will interact with the down-scale impacts of climate change, and how the findings of HD research can inform new innovations in policy-making to affect more sustainable response strategies.

Ecology-based management

Given the extent to which human activity influences the fundamental structure and function of ecosystems worldwide, we have no choice but to manage ecosystems (Chapin III *et al.* 2006a; Chapin III *et al.* 2006b). But given that the relationship between ecosystems and society is in constant flux and varies significantly throughout the world, it is difficult to predict the impacts of management actions at any scale, not just in terms of impacts on ecosystems but also in respect to different stakeholder groups.

Management approaches, therefore, can either take a precautionary or an exploratory approach (Lee 1999). Adaptive management is of the latter sort, premised on the idea that decisions should be part of an iterative process; they should be continually evaluated, and strategies altered to meet changing parameters (Irvine and Kaplan 2001; Kofinas *et al.* 2007; Lee 1999). This type of learning-based system is dependent on continuously updated information to make evaluations. Such information could come from traditional science but also from local knowledge systems that provide insights into functioning of local ecosystems and their linkages with the social system. Though capable of incorporating local knowledge, adaptive management's ability to contribute to local expertise is a pressing shortcoming of the approach. Local participants to management regimes are usually identified one-by-one, as local specialists. Even in cases of strong local participation, involvement often wanes past the goal-setting stages. Thus, the ‘learning’ that happens in the adaptive management process is happening to managers and scientists; the results of experimentation are fed back into the system, not shared outwardly.

Recent interest in “adaptive co-management” represents a movement from former research problems associated with co-management and adaptive management to a synthesis of these two management approaches (Armitage *et al.* 2007). Because of the key role of governance in ecosystem management, the concept of adaptive governance has to broaden the focus from “policy” to processes of policy management and governance in which groups interact across vertical and horizontal scales to observe, understand and respond to environmental change (Carpenter and Folke 2006; Folke *et al.* 2005). Governance in this sense differs from government in that adaptive responses to climate change are undertaken by the collaborative efforts among local communities, non-government organizations and research institutes, as well as with government agencies. An understanding of ecological processes is essential for effective adaptive governance. For instance, with an increasing recognition that local community responses may in some cases be slower than those undertaken at a national scale, a focus on cross-scale linkages in understanding climate change becomes necessary (Carpenter and Folke 2006; Young *et al.* 2006). In addition, since climate change is likely to present society with a set of novel problems, lessons from how ecosystems respond to novelty, including the internal dynamics which facilitate spontaneous innovation (Box 3), are critical (Carpenter and Folke 2006).

Numerous case studies of adaptive co-management processes illustrate these and other aspects (see, for example, the cases in Armitage *et al.* 2007; Berkes *et al.* 2005).

The speed, however, with which learning-through-management approaches can help us learn about and thereby adapt to change is questionable when compared with the rates of global climatic change. Recently (Schweik *et al.* 2005) identified inefficiencies with the traditional methods of scientific learning and make a compelling case for open collaboration in social-ecological research. As mentioned above, adaptive management is somewhat selfish with the fruits of its labour, feeding new data back into its own system. Schweik et al. suggest that open-sharing of such data could result in a knowledge production process that mirrors the speed and efficiency of the open source/open collaboration model responsible for the creation of software like Linux. Identifying a framework for this sort of scientific collaboration could represent a critical step for establishing adaptive management as a valid methodology for mitigating global change.

Box 3. Kofinas et al (2007) identified conditions that facilitate innovation in adaptive co-management, including:

1. Interdependence of actors' needs and interests and sufficient levels of social ca (i.e. trust) provide the basis for creative engagement in an adaptive co-manage process.
2. Appropriate levels of social heterogeneity and productive conflict provide for the comparison of perspectives and stimulation of novel solutions.
3. A culture of openness to new ideas and the taking of risk promote an environm which innovation can be cultivated.
4. Policy leaders and policy entrepreneurs promote and guide innovative problem solving and gain the acceptance of innovative solutions by the greater public.
5. Reflection and innovation don't just happen, but require the allocation of time a careful facilitation of process.
6. Decision-support tools, such as the use of scenario analysis with simulation mc can help in anticipating possible futures and stimulating creative thinking.
7. Prior experience with successful innovation builds confidence to experiment an in the future.

The Millennium Ecosystem Assessment Framework

The Millenium Ecosystem Assessment (MA, www.maweb.org) establishes an ecology-based approach for understanding and thus managing human interactions with the environment (MEA 2005). It was designed to capture how groups of people interact with and rely on ecosystems, and how changes to those ecosystems, either as the result of natural process or of human actions, influence individual and community well-being (MA 2005). The MA identifies services that ecosystems provide as belonging to one of four categories: provisioning services (e.g. food, fiber, freshwater), regulating services (e.g. water and air purification, climate regulation), cultural services (e.g. educational, social, psychological, recreational and spiritual benefits), and supporting services (e.g. primary production, nutrient cycling). These types are not static; the same aspects of an ecosystem are likely to be experienced by people in more than one of these ways simultaneously. Ecosystem services are therefore inevitably interrelated: they can overlap and be nested hierarchically (Costanza *et al.* 1997; De Groot *et al.* 2002; Ostrom 2007).

Thus, the strength of the MA is that its language is not specific to natural resources, but instead to the different modes by which ecosystems support human well-being, i.e. through regulating, supporting, provisioning and cultural services. This functional abstraction from ecological resources to 'ecosystem services' allows the MA to focus on the linkages between ecosystems and society; support multi-scale and multi-stakeholder comparisons; and organize and cross-reference assessments conducted at many different geographic and temporal scales, ranging from local communities to the entire planet, and from months or years to decades or centuries (MA 2005).

The interaction of our reliance on these services in our daily lives can be understood as functioning together to create outcomes that influence individual and community well-being (Figure 8). Common to an ecosystem's ability to provide any and all of these services are past, present and future measures of species, ecosystem and landscape biodiversity (Carpenter and Folke 2006). Thus, ecosystem services provide a baseline for assessing the impacts of ecosystem management decisions and diagnosing outcomes in a context of change (Loring *et al.* in review).

Conclusion

Impacts and mitigation versus innovation and sustainability

People, especially those in urban areas, are increasingly alienated from their dependence on ecosystems, except when faced with crisis. As such, many societies face challenges to realizing long-term sustainability of resource use. Climate change has emerged as one platform for bringing the sustainability conversation to the table, but this review of recent research suggests that the overall approach to HD research in the Arctic has favored the study of vulnerability to impacts and of the limits to mitigation and adaptation, with little attention to framing the debate over current behavior and climate-related risk in terms of long-term socio-ecological sustainability.

Recent papers suggest that changing the tone and focus of the conversation may be necessary (Carpenter and Folke 2006; Chapin III *et al.* 2006a; Chapin III *et al.* 2006b; Fischer *et al.* 2007). Scenarios with positive vision are quite different and often far more effective than projections of environmental disaster (Carpenter and Folke 2006; Costanza 1999). Though current trajectories are no longer a matter of debate, we appear to have allowed these projections of disaster to capitalize our attention. Ecological and resilience thinking, however, bear the great potential to create visions for the future that involve new approaches to human agency as members and managers of ecosystems (Carpenter and Folke 2006; Fischer *et al.* 2007).

Fischer *et al.* (2007) suggest that the lack of relative progress to influence trends like the accumulation of greenhouse gases and the continued global decline of biodiversity reflect a fundamental problem with our present approach to defining and pursuing sustainability. Specifically, we continue to define sustainability in a relativistic way, as if it were possible for societies to exist independent of ecosystems or for economies to exist independent of societies. In order to capture these realities, they recommend a shift from what they call the "triple bottom line" conception of sustainability that has become so popular, to a hierarchical one which reflects these undeniable dependencies within social-natural systems. Figure 9 compares the popular sustainability vision to this new hierarchical approach.

In order to address the "sustainability gap" between current global trajectories of and limits to growth, Fischer *et al.* (2007) recommend that the hierarchy of their new model can be taken as a prioritization for action. Many agree that only through this sort of paradigm shift, from an attitude of eco-domination through science and technology to one of interconnectedness and humility, will it be possible to address these issues in time, as it is the spirit of exemption that has led to this crisis in the first place (Berry 2000; Fischer *et al.* 2007; Leopold 1966; Quinn 1991; Snyder 1969). Future efforts must first and foremost address critical, foundational issues (slow variables) which underlie the present crisis, e.g. the degradation of vital ecosystem services without which societies could not function, not in terms of impacts, but in terms of causes (Chapin III *et al.* 2006a). Fischer *et al.* (2007) claim that to do so calls for researchers to achieve more than just technical dissections of change; instead they mandate a critical self-assessment of the implications in this crisis for our societies and institutions. By coming to terms with our culpability, a new vision is possible, of what economies are for and how we can measure concepts like success and progress using the health and well-being of the natural world as a yardstick (Berry 2000; Costanza 2006). Fischer *et al.* (2007) conclude that, armed with this new perspective, we are capable of making great strides towards reversing current trends like global warming and global resource depletion, if we are willing to set for ourselves ambitious targets and approach them with resolve and imagination.

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13. Appendix

Appendix 1: List of reviewers (of the literature review sections)

Dr. Roger Barry, National Snow & Ice Data Center, Boulder, Colorado, USA

Dr. Bogi Hansen, Faroese Fisheries Laboratory, Torshavn, Faroe Islands

Dr. Janet E. Hohn, U.S. Fish and Wildlife Service, Anchorage, Alaska, USA

Dr. Henry Huntington, Huntington Consulting, Eagle River, Alaska, USA

Dr. Gary Kofinas, University of Alaska Fairbanks, Fairbanks, Alaska

Dr. Hans Meltofte, National Environmental Research Institute, Copenhagen, Denmark

Dr. Olav Orheim, Research Council of Norway, Oslo, Norway

Dr. David Robinson, Rutgers University, Piscataway, New Jersey, USA

Dr. Vladimir Ryabinin, WMO, World Climate Research Programme, Geneva, Switzerland

Dr. Mark Serreze, Snow & Ice Data Center, Boulder, Colorado, USA

Dr. Chris Southcott, Lakehead University, Thunder Bay, Ontario, Canada

Dr. Robert Thomas, NASA Wallops Flight Facility, Wallops Island, Virginia, USA

Dr. Katey Walter, University of Alaska Fairbanks, Fairbanks, Alaska, USA

Dr. Muyin Wang, National Oceanic and Atmospheric Administration, Seattle, Washington, USA

Dr. Christoph Zockler, UNEP-World Conservation Monitoring Centre, Cambridge, UK

Appendix 2: About the report

The overview of findings from arctic climate change research listed in the sections of this report is based primarily on findings published after those included in the Arctic Climate Impact Assessment (ACIA 2005).

In the physical sciences sections the IPCC AR 4 (IPCC 2007) and UNEP's Global Outlook for Ice and Snow (UNEP 2007) were relied on for overviews of recent findings and their significance. This material was supplemented with literature searches and inclusion of more recent results. Other sections, most notably the human dimensions and ecosystem sections, draw primarily from reviews of recent literature.

The authors and editors would like to thank the reviewers, who provided important comments, perspectives and contributions to this work.

In the Summary section, the selection of highlights reflects major recent research published since the Arctic Climate Impact Assessment (ACIA 2005). The selection was foremost guided by the literature itself and by the reviewers, who were asked to identify findings that they felt were of particular significance in their fields. However, it should be noted that the highlights are also partly reflecting a prioritisation by the authors and editors. The reader should refer to the relevant sections of the reviewed literature review for details, discussion and references.

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