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*Scientific paper*

# Climate change and its impacts on the arctic environment

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***Abstract:*** Regional assessments of climate change and its impacts are a high priority in the international programs on global change research. In the Arctic, climate models indicate an amplification of the global greenhouse warming, but the observed high-latitude climate trends over the last few decades are much more regional and patchy than predicted by the models. While considerable uncertainties remain in the long-term prediction of change there is some agreement between model results and observed trends by season on shorter time scales. The warming observed over the landmasses of the Arctic over the last few decades is matched by corresponding observed decreases in snow cover and glacier mass balances, by thawing of the permafrost, and by reductions in sea ice extent and thickness. The available evidence strongly suggests that the observed decrease in Northern Hemisphere sea ice extent is related to anthropogenic global warming. While uncertainties exist about the future, climate change in the Arctic during the past few decades can be shown to have had major impacts already on the arctic environment which will become much more pronounced if present trends continue.

## 1. Introduction

The Arctic plays a crucial role in global climate change. It is a sensitive indicator of change and its snow and ice features are good integrators of change. It also stores long-term climatic records in its glaciers and the Greenland ice sheet. The Arctic also affects the global climate directly through interactions between its atmosphere, ice cover, and oceans, and through a number of important feedback processes. Practically all climate models predict an amplification of the global greenhouse effect in the Arctic (IPCC, 1990, 1996; Everett *et al*., 1998).

Global greenhouse warming affects the arctic environment by melting ice and thawing permafrost. Practically all the snow and ice features of the Arctic will be affected in one way or another. The extent and thickness of the seasonal snow cover, sea ice, permafrost, glaciers and river and lake ice are all expected to decrease as the climate warms. These changes in turn will affect the polar ecosystems with their distinct fauna and flora. Socio-economic consequences to populations, industry, and lifestyles will be inevitable. Not all of these changes are necessarily negative; for example less sea ice may allow the opening of trans-Arctic shipping routes and offshore petroleum exploration (Weller, 1998).

The Arctic, in turn, can affect the global climate through polar feedback processes. The albedo-snow cover-temperature feedback (Kellogg, 1975) is one of the main causes of the amplification of the greenhouse effect in the Arctic. Permafrost-trace gas-temperature feedbacks could also be important. If more $CO_2$ and $CH_4$ is released when permafrost thaws, this will increase the atmospheric temperature and will result in thawing more permafrost. Melting of glaciers and ice sheets raise the global sea level, and the collapse of large ice sheets has been postulated as a possible trigger of the major, rapid climate changes during the last ice age, as seen in the Greenland ice core results (Alley *et al*., 1993).

## 2. Projected future climate impacts

The IPCC report *Climate Change 1995* (1996) includes a chapter (Chapter 7 of Working Group II on the cryosphere – the regions of snow and ice) on climate change and its likely impacts on the polar regions. This assessment states the degree of confidence that the IPCC had in its predictions, which include the following.

- Many components of the cryosphere are sensitive to changes in atmospheric temperature because of their thermal proximity to melting. The extent of glaciers has often been used as an indicator of past global temperatures (High Confidence).
- Projected warming of the climate will reduce the area and volume of the cryosphere. This reduction will have significant impacts on related ecosystems, associated people and their livelihoods (High Confidence).
- There will be striking changes in the landscapes of many high mountain ranges and of lands at northern high latitudes (High Confidence). These changes may be exacerbated where they are accompanied by growing numbers of people and increased economic activities (Medium Confidence).

For a scenario that doubles the atmospheric concentrations of $CO_2$, the following changes and associated impacts on the Arctic are likely, again listing the degree of confidence in these predictions.

- Pronounced reductions in seasonal snow cover, permafrost, glacier and periglacial features with a corresponding shift in landscape processes (High Confidence).
- Increases in the thickness of the active layer of permafrost and the disappearance of most of the ice-rich discontinuous permafrost over a century-long time span (High Confidence).
- Disappearance of up to a quarter of the presently existing mountain glacier mass (Medium Confidence).
- Less ice on rivers and lakes. Freeze-up dates will be delayed, and break-up will begin earlier. The river-ice season could be shortened by up to a month (Medium Confidence).
- A large change in the extent and thickness of sea ice, not only from warming but also from changes in circulation patterns of both atmosphere and oceans. There is likely to be substantially less sea ice in the polar oceans (Medium Confidence).

Many of these impacts are already being experienced in the Arctic, as shown in the next chapter.

## 3. Evidence of climate change

### *3.1. Twentieth century climate trends*

Discussion of the detection of the greenhouse signal in the polar regions usually revolves around two questions: (1) Are we now seeing the greenhouse signal in the high latitudes? (2) If not, how and when will the signal manifest itself? Chapman and Walsh (1993) examined the climate trends in the Arctic for the period 1961-1990, using the climate data set of the Climate Research Unit of the University of East Anglia (Jones *et al.*, 1986). Their analysis, as well as their updated results for 1966-1995, indicates considerable warming over the landmasses of Eurasia and North America, particularly in winter and spring. Over the last three decades, trends of up to 1.5℃ per decade have been towards higher temperatures. On the other hand there are also smaller areas of cooling of similar magnitude within the arctic regions, particularly in the South Greenland and Davis Strait area.

The available data also point to a more vigorous atmospheric circulation associated with a deepening of both the Icelandic and Aleutian Lows (Maxwell, 1995). The primary reason for a warmer climate in the Western Arctic, for example, is that more southerly flow occurs in winter coupled with less northerly flow of cold air from Siberia. Similarly the cooler climate in Southern Greenland is most likely related to a shift in the circumpolar wave pattern with increased northerly flow in that region. Whether this is triggered by the greenhouse effect is not clear at present.

### *3.2. Impacts on snow and ice*

In many different parts of the world, pronounced reductions in seasonal snow, glaciers, permafrost and sea ice have been observed as a consequence of a warmer climate. In the Arctic, where the following observations have been made, these changes are particularly pronounced. Vinnikov *et al.* (1999) state that the probability of the observed trends

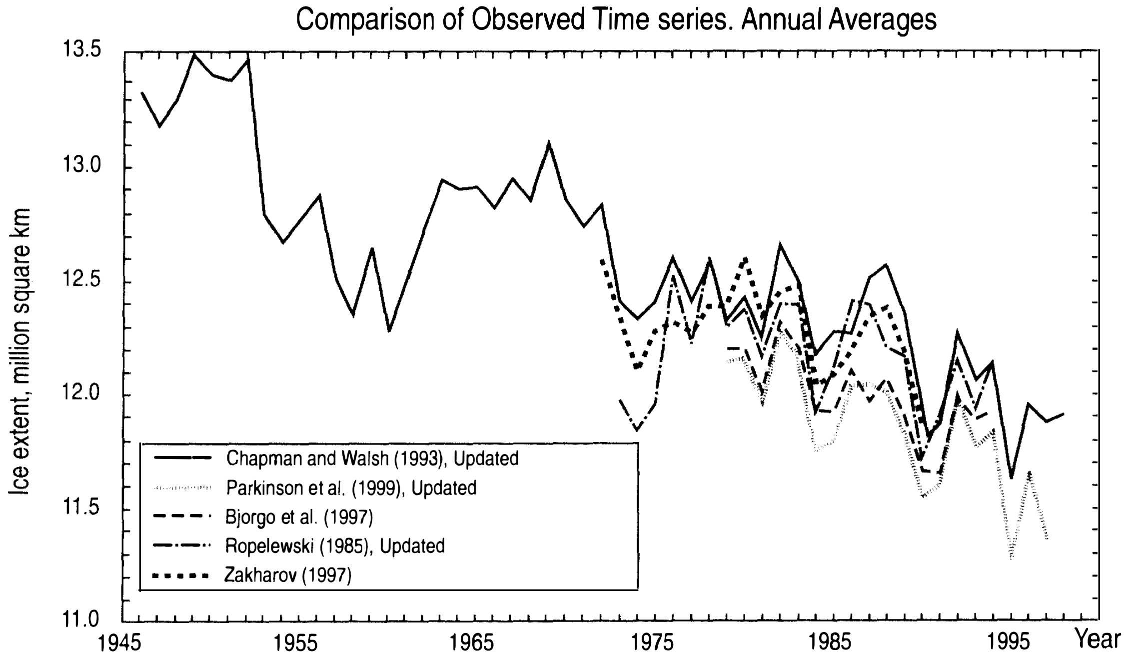


*Fig. 1. Observed decrease of the Northern Hemisphere sea ice extent since 1945 (Vinnikov et al., 1999).*

resulting from natural climate variability is less than 0.1 percent for the observed 1953–98 sea ice trends (Fig. 1). This strongly suggests that the observed decrease in Northern Hemisphere sea ice extent is related to anthropogenic global warming.

3.2.1. Sea ice

There have been substantial reductions in both ice extent and thickness in the Arctic in recent decades:

- The most recent study using passive microwave data from satellites through 1996 has shown Arctic sea ice extent decreasing by 2.9% (±0.2%) per decade (Cavalieri *et al*., 1997).
- New extreme minimums of summer ice extent have been established repeatedly since 1980. The September ice extent in the Beaufort and Chukchi seas was 25% below the prior minimum value over the 45-year record (Maslanik *et al*., 1999).
- Sea-ice extent in the Bering Sea has been reduced by about 5% over the last 40 years, with the steepest decrease occurring in the late 1970s (BESIS, 1997).
- Sea ice thickness, a sensitive indicator of climate change, has decreased by about 1.3 m, from 3.1 m to 1.8 m, in most of the deep water portion of the Arctic Ocean between

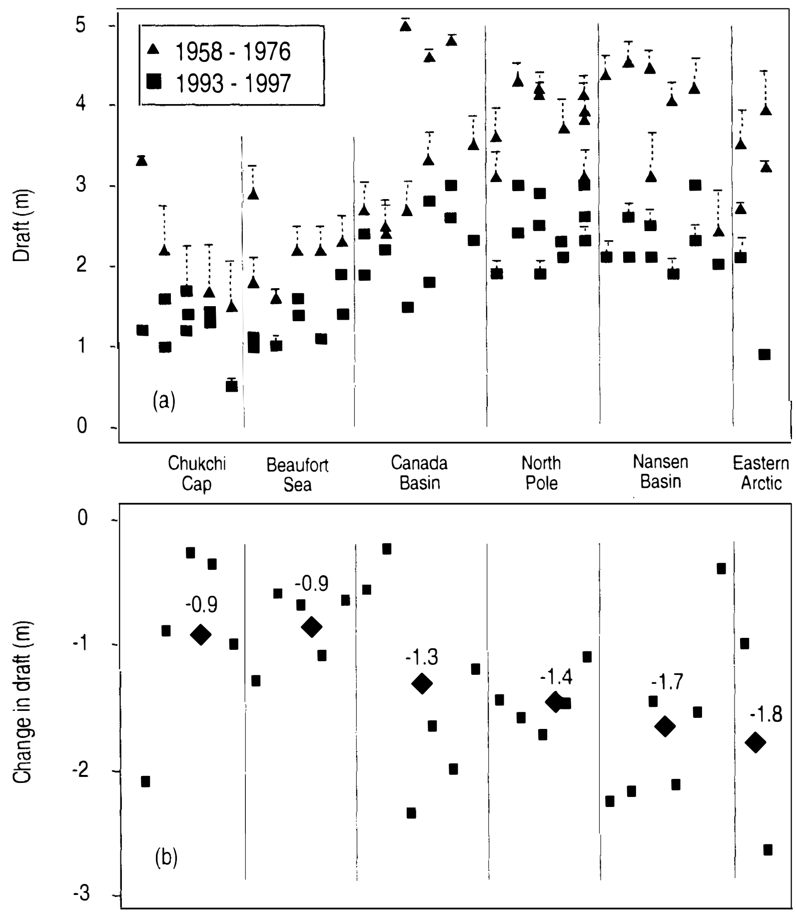


*Fig. 2. Sea ice thickness reductions for various regions of the Arctic from submarine sonar data collected between 1958–1976 and 1993–1997 (Rothrock et al., 1999).*

the 1960/1970s and the 1990s, based on submarine sonar records (Fig. 2 due to Rothrock *et al.*, 1999).

- The sea ice thickness decrease is greatest in the central and eastern Arctic and less in the Beaufort and Chukchi seas (Rothrock *et al.*, 1999).
- Observations at Barrow, Alaska, on the Beaufort Sea coast, showed sea ice to be only 1.4 m thick in 1998, compared with its normal thickness of 1.7–1.8 m; this is thinner than ever observed before (L. Shapiro, 1999, personal communication).

3.2.2. Glaciers and ice sheets

- Glaciers in the Arctic and subarctic regions have generally receded, with typical ice-thickness decreases of 10 m over the last 40 years (Fig. 3), but some glaciers have thickened in their upper regions (BESIS, 1997). A warming of 1°C, if sustained, appears to reduce glacier lengths by about 15%.
- The mass balance of Greenland is still uncertain, but there appears to have been a tendency towards increased melt area between 1979–1991 that ended abruptly in 1992, possibly due to the effects of the Mt. Pinatubo eruption (Abdalati and Steffen, 1997).
- Balances have been positive for European glaciers in Scandinavia and Iceland due to increased winter precipitation (Serreze *et al.*, 2000).
- Over the period 1961–1990, small melting glaciers worldwide have contributed about

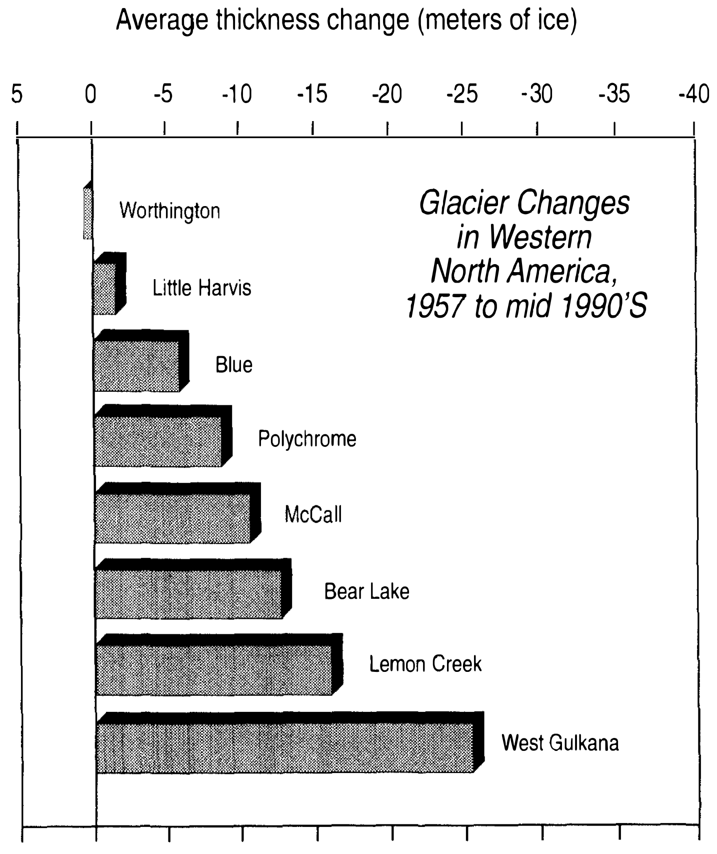


*Fig. 3. Glacier mass balance changes in Western North America from 1957 to the mid-1990s (Sapiano et al., 1998).*

7.36 mm to sea level rise, with the Arctic Islands contributing 1.36 mm, Alaska 0.54 mm, and Asia 3.34 mm (Serreze *et al.*, 2000).

3.2.3. Seasonal snow cover

- Cyclone and anticyclone frequency has increased over the Arctic between 1952–1989 (Everett *et al.*, 1998; Section 3.2).
- Annual snowfall has increased in the same period over northern Canada (North of 55°N) by about 20% and by about 11% over Alaska (Everett *et al.*, 1998; Section 3.2).
- While there is more snow in winter, satellite records indicate that since 1972 Northern Hemisphere annual snow cover on both continents has decreased by about 10%, largely due to spring and summer deficits since the 1980s (Serreze *et al.*, 2000).
- There has also been a decrease in snow depth in Canada since 1964, especially during spring, while winter depths have declined in some areas over European Russia since the turn of the century but have increased in others (Serreze *et al.*, 2000).

3.2.4. Permafrost

- Borehole measurements in continuous permafrost have shown warming of up to 2–4°C

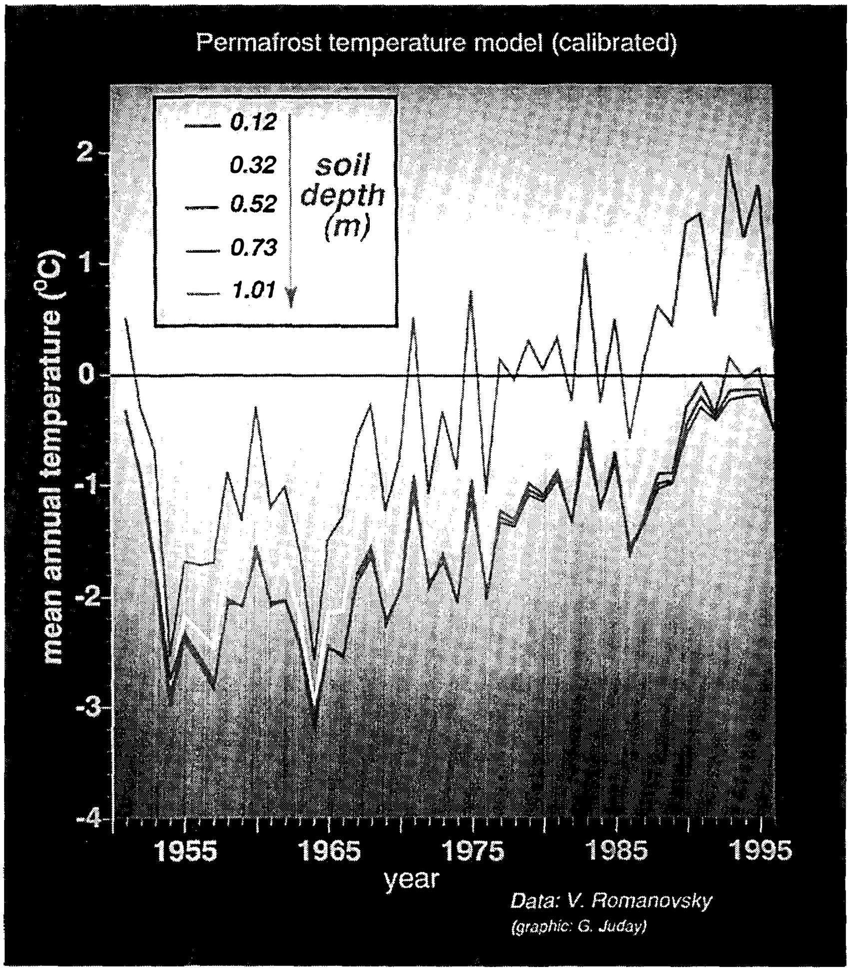


*Fig. 4.* *Change in soil temperatures at various depths in permafrost terrain at Fairbanks, Alaska (V. Romanovsky, personal communication).*

in northern Alaska over the last 80–100 years (Lachenbruch and Marshall, 1986).

- Discontinuous permafrost throughout Alaska has warmed (Fig. 4), and some of it is currently thawing from the top and bottom (Osterkamp, 1994).
- Near-surface permafrost has also become warmer by 0.6–0.7℃ in Siberia during the period 1970–1990; this warming may in part be due to a deeper snow cover in winter (Pavlov, 1994).

3.2.5. River and lake ice

- River and lake ice formation in Alaska occurs later in fall and breakup occurs earlier in spring, leading to shorter ice-covered periods. The annual breakup of the Tanana River ice in interior Alaska has been recorded since the 1920s and shows most breakup dates to occur in April in the 1990s compared with most of them occurring in May in the 1920s (Nenana Ice Classic, 1999).

### *3.3. Fingerprinting climate change*

A view that has been proposed by climate researchers is that the "traditional" emphasis on sea ice extent and Arctic Ocean air temperatures as early indicators of change should be replaced with a broader "fingerprint" of many variables. This "fingerprint" should involve information from ice cores, sea ice concentration and thickness, sea surface temperatures, subsurface polar ocean temperatures, and high latitude precipitation. The set of variables in Table 1 summarizes the evidence of recent changes and provides such a "fingerprint." The observed changes are consistent with those anticipated from greenhouse influences. However, there are still problems since long records exist only for surface temperatures, and even these are not long enough to distinguish unambiguously the natural and man-made influences (Walsh *et al*., 1996).

*Table 1. Summary of changes observed in the Arctic over the last few decades of the 20th century (modified from Walsh et al., 1996).*

| Parameter | Trend | Comments |
|---|---|---|
| Surface temperature | Generally warmer | (on land, in winter/spring, but also some areas of cooling; unclear over Arctic Ocean) |
| Tropospheric temps. | Warmer | (lowest layers) |
| Stratospheric temps. | Colder | (summer only) |
| Precipitation | Increased | (over land, unknown over sea ice) |
| Extreme weather | Not yet assessed | |
| Ocean temps. | Warmer | (Central Arctic) |
| Snow cover extent | Reduced | (Eurasia, in spring; also in Canada and Alaska) |
| Snow cover depth | Reduced | |
| Sea ice extent | Reduced | (throughout the Arctic) |
| Sea ice thickness | Thinner | (throughout the Arctic) |
| Ice sheet elevation | Higher | (S. Greenland, no change in Canada) |
| Ice sheet surface melting | Increased | (S. Greenland) |
| Ice shelf extent | Reduced | (Canada) |
| Permafrost extent | Reduced | (Alaska, Canada, Siberia) |

## 4. Societal and economic impacts of climate change

The societal and economic consequences of climate change in the Arctic are likely to be substantial but are not the subject of this paper. Reference to these impacts can be found in a number of publications (BESIS, 1997, 1998, 1999; Weller and Lange, 1999). Changes in the cryosphere, as a consequence of a warmer climate, that will lead to social and economic impacts have been summarized by the IPCC as follows:

- Widespread loss of discontinuous permafrost will trigger erosion or subsidence of ice-rich landscapes, change hydrologic processes, and release carbon dioxide ($CO_2$) and methane ($CH_4$) to the atmosphere (High Confidence).
- Cryospheric change will reduce slope stability and increase the incidence of natural hazards for people, structures and communication links. Buildings, other structures, pipelines and communication links will be threatened (High Confidence).
- Engineering and agricultural practices will need to adjust to changes in snow, ice and permafrost distributions (High Confidence).
- Thawing of permafrost could lead to disruption of petroleum production and distribution systems in the tundra, unless mitigation techniques are adopted. Reduced sea ice may aid new exploration and production of oil in the Arctic Basin (High Confidence).
- Improved opportunities for water transport, tourism and trade are expected from a reduction in sea, river and lake ice. These will have important implications for the people and economies of the Arctic (Medium Confidence).

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