Chapter 2

Long-term Change in the Arctic

2.1. The distant past, and recorded history

During the last 400 000 years, the Earth has experienced four ice ages which have left records in glacial ice accumulating in Antarctica (Petit *et al.*, 1999) and in Greenland (Dansgaard *et al.*, 1993; Sowers and Bender, 1995). The overall surface air-temperature change between glacial and interglacial periods is thought to have been about 12°C, but perhaps more significant than temperature were the accompanying changes in continental ice masses, sea-ice climate and global ecosystems. In particular, sea-ice cover has proven to be a master variable in the equation of change. During the last glacial maximum, sea ice was locked within the Arctic and seasonal or perennial sea ice extended well south into the North Atlantic Ocean (Darby *et al.*, 1997; de Vernal *et al.*, 1993). The change from glacial to de-glacial to interglacial can be seen widely in Arctic sediments, both in terms of sedimentation rate and in the amounts and sources of organic material derived from marine primary production or land vegetation (see for example, Darby *et al.*, 2001; Nørgaard-Petersen *et al.*, 1998; Phillips and Grantz, 1997; Stein *et al.*, 1994, 2001).

Sea level dropped by about 120 m during the last glacial maximum (Fairbanks, 1989). This exposed much of the Arctic Ocean's enormous continental shelves, forcing rivers to cut channels across them to enter the interior sea directly, and severing the connection between the Arctic and Pacific Oceans. With sea-level rise, about 15 000 years ago the Bering land bridge was flooded (Hopkins, 1979) and then gradually submerged (Dyke *et al.*, 1996b) allowing the Pacific Ocean access to the Arctic Ocean. This sequence of events together with inundation of the continental shelves must have had enormous consequences for the oceanography and regional biogeography of the western Arctic and the Canadian Arctic Archipelago (Dunton, 1992; Dyke *et al.*, 1996a,b; Hequette *et al.*, 1995).

Although the climate has been described as 'exceptionally stable' during the past 10 000 years (Dansgaard *et al.*, 1993), it has actually continued to undergo substantial fluctuations. Indeed, it seems that very small shifts in temperature, perhaps of only a degree or two, account for the so-called Medieval Warm Period (1100-1400 AD) and subsequent Little Ice Age (1450-1850 AD) (for the relevance of these terms see Bradley and Jones, 1993; Crowley and Lowery, 2000). Both of these minor and sporadic deviations in the temperature record had dramatic consequences for humans – especially those living on the margins of northern oceans (Alley *et al.*, 2002; McGhee, 1996; Ogilvie and Junsson, 2000). During the past two centuries, small changes in ice and watermass distribution have continued to have an impact on humans and ecosystems, sometimes leading to migration or abandonment of locations, but certainly requiring adaptation (Miller *et al.*, 2001; Vibe, 1967).

For most of the past 10 000 years (the Holocene), climate change was not accompanied by the added complexity of anthropogenic pollutants. However, over the past two millennia and especially during the past two centuries, Arctic glacial ice has recorded the transient rise in the levels of virtually every contaminant emitted by human activities (Boutron *et al.*, 1995, 1998; Gregor *et al.*, 1995; Hong *et al.*, 1994; Masclet and Hoyau, 1994; Rosman *et al.*, 1997). These include the greenhouse gasses (GHGs) that force atmospheric temperature change (Petit *et al.*, 1999), and it is the dramatic rise in the levels of GHGs during the past several decades that make future projections based on past climates subject to such uncertainty.

2.2. The present and future

The twentieth century has been the warmest in the Arctic for the past 400 years (Overpeck *et al.*, 1997). The Intergovernmental Panel on Climate Change (IPCC) suggests that over the past century the global mean surface temperature has increased by about 0.3 to 0.6°C, mostly attributable to human activities, and will probably further increase by 1.4 to 5.8°C between 1990 and 2100 (Houghton *et al.*, 1995; IPCC, 1995, 2002; Showstack, 2001). According to models, warming will be more pronounced in polar regions (Figure 2·1); perhaps

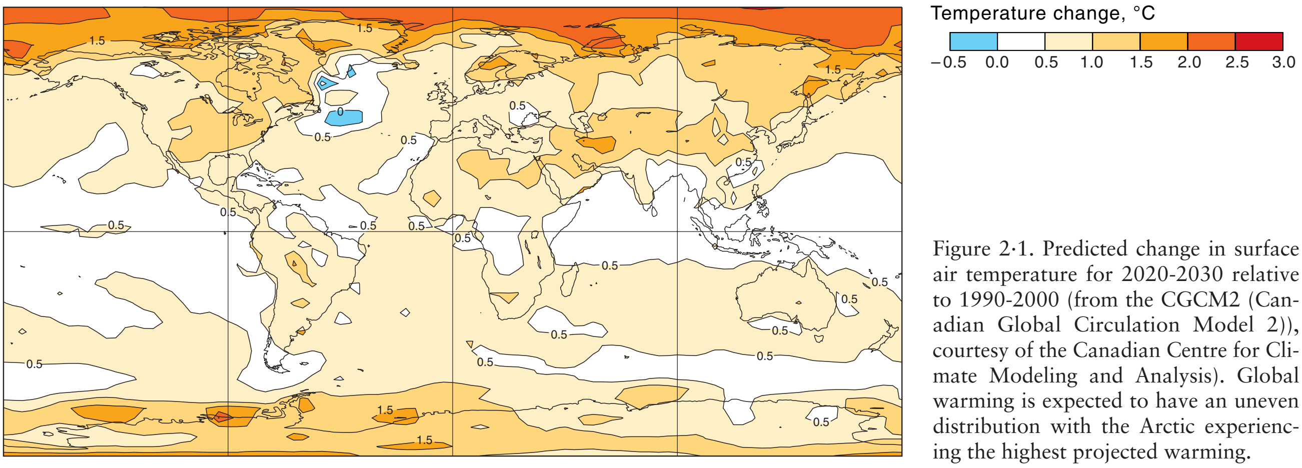

Figure 2·1. Predicted change in surface air temperature for 2020-2030 relative to 1990-2000 (from the CGCM2 (Canadian Global Circulation Model 2)), courtesy of the Canadian Centre for Climate Modeling and Analysis). Global warming is expected to have an uneven distribution with the Arctic experiencing the highest projected warming.

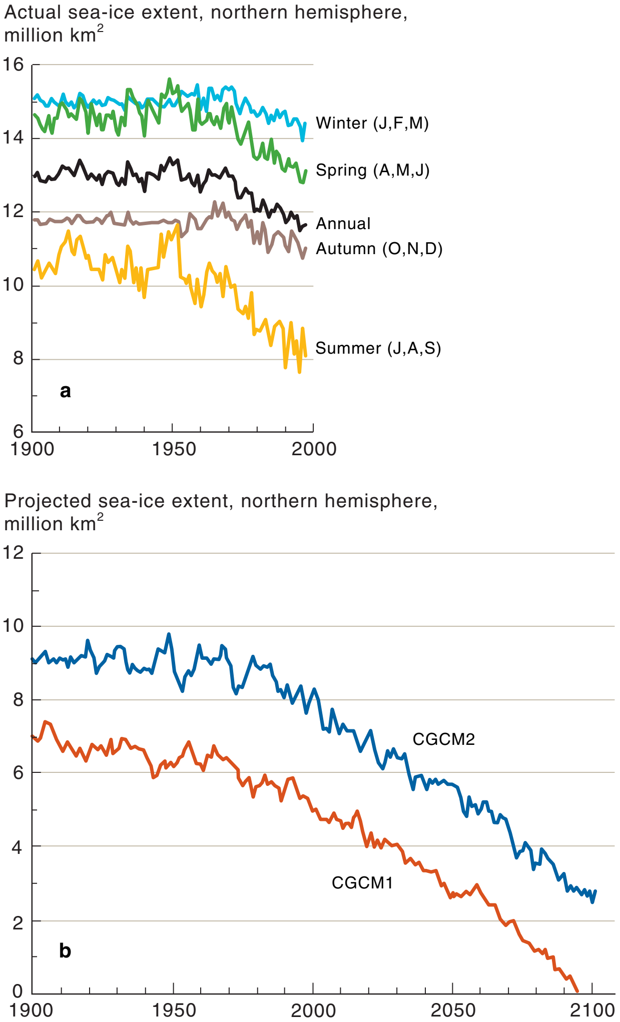

Figure 2·2. Sea-ice extent in the Northern Hemisphere. This figure illustrates a) time series of 'actual' annual and seasonal sea-ice extent between 1990 and 2000 derived from long-term observations and satellite images (adapted from Walsh and Chapman, 2000) and b) simulations of annual mean sea-ice extent from the models CGCM1 and CGCM2 (Canadian Global Circulation Models 1 and 2 of the Canadian Centre for Climate Modeling and Analysis), where the latter differs from the former in mixing parameterization. (After Flato and Boer, 2001.)

5°C or more near the pole and 2 to 3°C around the margins of the Arctic Ocean, with a decreasing temperature contrast between poles and the equator (Manabe *et al.*, 1992; Mitchell *et al.*, 1995; Zwiers, 2002). For gases emitted to the atmosphere, climate warming will increase inter-hemispheric exchange times, mixing times, and mean transit times by perhaps 10% (Holzer and Boer, 2001). Furthermore, the greatest warming will occur in the autumn–winter period due to delay in the onset of sea-ice cover (Manabe *et al.*, 1992; Serreze *et al.*, 2000). Continental interiors will become dryer and sea level will continue to rise, perhaps by a further 50 cm in addition to the estimated rise of 10 to 25 cm during the past century (Proshutinsky *et al.*, 2001; Serreze *et al.*, 2000).

Models predict that after about 80 years of atmospheric CO_2 increase at 1% per year, precipitation will increase within the Arctic and subpolar regions to 0.5 to 1 m/yr, which would more than double the current moisture flux convergence north of 70°N estimated at about 20 cm/yr (Manabe *et al.*, 1992; Walsh, 2000), making the Arctic a considerably 'wetter' place. Over the past four decades sea-ice extent in the Arctic Ocean has decreased in summer by as much as 25%. By the end of the twenty-first century, GHG forcing might produce an Arctic Ocean seasonally clear of ice (Figure 2·2, Flato and Boer, 2001).

Simulations based on GHG forcing predict that mean annual river discharge will increase by about 20% for the Yenisey, Lena and Mackenzie Rivers, but decrease by 12% for the Ob (Arora and Boer, 2001; Miller and Russell, 1992). Furthermore, the projection that high-latitude rivers will undergo marked changes in amplitude and seasonality of flow due to decreased snowfall and earlier spring melt (Arora and Boer, 2001) may already have some support in observations (Lammers *et al.*, 2001).

The coupling of the runoff cycle with northern lake hydrology is probably one of the points most sensitive to climate change (see for example, Vörösmarty *et al.*, 2001) but the understanding of the processes involved is not yet sufficient to make confident projections. If Arctic lakes become more 'temperate' in character, productivity is likely to be enhanced due to less ice cover and more mixing, and there will be greater opportunity for runoff to mix into the lake during freshet, further supporting a more vigorous aquatic food web.

With these primary changes, permafrost melting can be expected to accelerate, disrupting vegetation and enhancing nutrient, organic carbon and sediment loading of rivers and lakes (Vörösmarty *et al.*, 2001). The loss of sea ice in the marginal seas, together with sea-level rise will promote further erosion of poorly bonded, low-gradient coasts, particularly during the period of autumn storms.