

# Arctic climate change: observed and modelled temperature and sea-ice variability

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## ABSTRACT

Changes apparent in the arctic climate system in recent years require evaluation in a century-scale perspective in order to assess the Arctic's response to increasing anthropogenic greenhouse-gas forcing. Here, a new set of century- and multidecadal-scale observational data of surface air temperature (SAT) and sea ice is used in combination with ECHAM4 and HadCM3 coupled atmosphere–ice–ocean global model simulations in order to better determine and understand arctic climate variability. We show that two pronounced twentieth-century warming events, both amplified in the Arctic, were linked to sea-ice variability. SAT observations and model simulations indicate that the nature of the arctic warming in the last two decades is distinct from the early twentieth-century warm period. It is suggested strongly that the earlier warming was natural internal climate-system variability, whereas the recent SAT changes are a response to anthropogenic forcing. The area of arctic sea ice is furthermore observed to have decreased  $\sim 8 \times 10^5$  km<sup>2</sup> (7.4%) in the past quarter century, with record-low summer ice coverage in September 2002. A set of model predictions is used to quantify changes in the ice cover through the twenty-first century, with greater reductions expected in summer than winter. In summer, a predominantly sea-ice-free Arctic is predicted for the end of this century.

## 1. Introduction

A consensus result from different coupled atmosphere–ice–ocean climate models is that greenhouse global warming should be enhanced in the Arctic (Räisänen, 2001). The Intergovernmental Panel on Climate Change (IPCC, 2001) states that the winter warming of northern high-latitude regions by the end of the century will be at least 40% greater than the global mean, based on a number of models and emissions scenarios, while the warming predicted for the central Arctic is  $\sim 3$ – $4^\circ\text{C}$  during the next 50 yr, or more than twice the global mean.

Recent overviews of results from observational studies of atmospheric and climate-sensitive variables (e.g. sea ice, snow cover, river discharge, glaciers and permafrost) have concluded

that, taken together, a reasonably coherent portrait of recent change in the northern high latitudes is apparent (Serreze et al., 2000; Moritz et al., 2002; Peterson et al., 2002). However, it remains open to debate whether the warming in recent decades is an enhanced greenhouse-warming signal or natural decadal and multidecadal variability (Polyakov and Johnson, 2000; Polyakov et al., 2002), e.g. as possibly expressed by the arctic warming observed in the 1920s and 1930s followed by cooling until the 1960s (e.g. Kelly et al., 1982). The uncertainties are exacerbated by a lack of homogeneous, century-scale instrumental data sets (see Moritz et al., 2002, whose fig. 2a includes no temperature data for the central Arctic) needed to resolve the inherent time-scales of variability in the Arctic (Venegas and Mysak, 2000), a region characterized by high variability.

From these concerns, two overarching questions are as follows. (1) To what degree are the gradually changing atmosphere–ice–ocean conditions in the Arctic a consequence of natural

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climate processes and/or external factors such as anthropogenic greenhouse gas (GHG) forcing. (2) To what degree may anthropogenic forcing induce the arctic sea-ice cover to decrease or even disappear in this century? In order to study these questions, we analyse a new set of pertinent multidecadal to century-scale data—surface air temperature (SAT), sea-ice extent, sea-ice area and sea-ice thickness—in combination with global coupled atmosphere–ice–ocean climate model simulations using the ECHAM4 model of the Max Planck Institute for Meteorology (Roeckner et al., 1999) and the HadCM3 model of the UK Meteorological Office (Gordon et al., 2000). ECHAM4 and HadCM3 are state-of-the-art versions of two of the models demonstrated—in an intercomparison of climate-change scenario output from 19 coupled models (Räisänen, 2001)—to be among those most representative of the 19-model mean temperature change.

## 2. Surface air temperature: observed and modelled

Statistical analyses of global SAT data sets have indicated substantial fluctuations in the extratropical Northern Hemisphere on decadal to multidecadal time-scales (e.g. Schlesinger and Ramankutty, 1994; Hansen et al., 1999; Jones et al., 1999). In the high latitudes, differences in spatial–temporal coverage have led to some discrepancies concerning temperature variability trends in the last century (e.g. Jones et al., 1999; Przybylak, 2000; Polyakov et al., 2002). The global gridded SAT data set (Jones et al., 1999) used most extensively for studies of climate variability has major gaps in the northern high latitudes, in particular over the ice-covered Arctic Ocean and some surrounding land areas. Here, we analyse for the first time a unique century-long SAT data set focused on the high latitudes of the Northern Hemisphere. The data set is provided through the Arctic and Antarctic Research Institute (AARI), St Petersburg, Russia, produced through a project within the programme International Association for the Promotion of Cooperation with Scientists from the Former Soviet Union (Alekseev et al., 1999). The input data are daily temperatures from 1486 meteorological stations in the Northern Hemisphere, including land- and drifting-stations from the Arctic. A gridded data set ( $5^\circ$  lat.  $\times$   $10^\circ$  long.) based on these data has been developed from several sources. First, monthly-mean SAT anomaly maps were produced at the USSR's Main Geophysical Observatory for the period 1891–1969 and at the Hydrometeorological Research Center for the period 1970–1976. Secondly, the maps were visually analysed and interpolated into a gridded data set, as described and evaluated previously (Vinnikov, 1977). Thirdly, the data set was extended in the same manner for the period 1977–1986, presented as SAT with reduction to common mean values and taking into the account the moist adiabatic temperature gradient ( $0.6^\circ$  per 100 m) as in Alekseev and Svyaschennikov (1991). Fourthly, the data set was continued at the Hydrometeorological Research Center from 1986–1995, through visual interpolation and reading

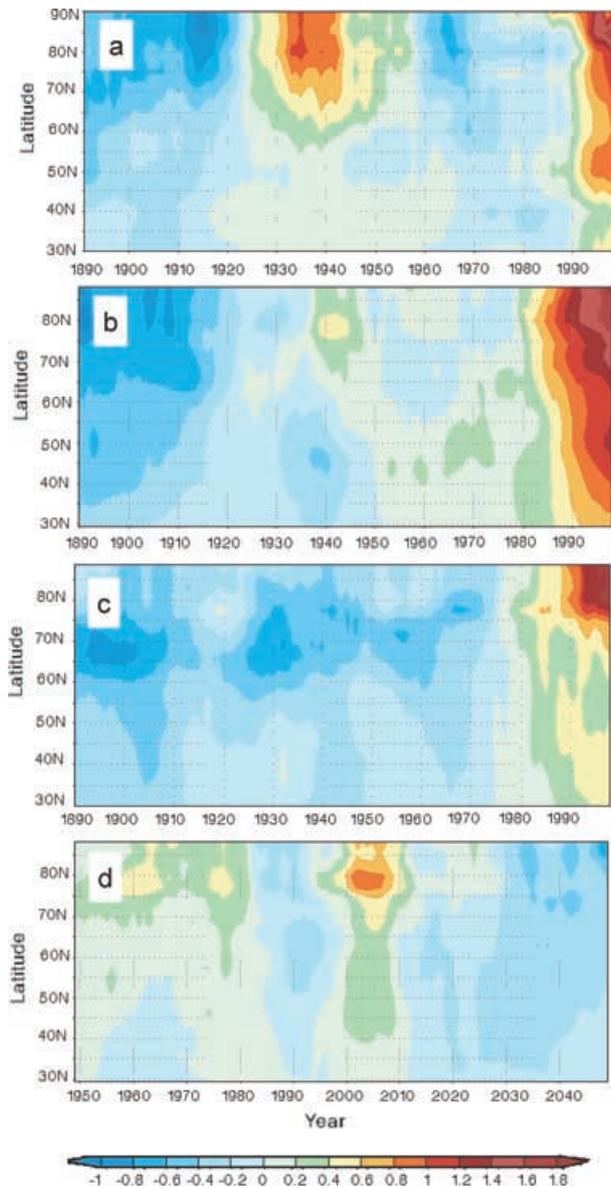
from monthly-mean SAT maps. Since 1995, the monthly-mean SATs have been produced at AARI through monthly averaging of gridded daily SAT from the European Centre for Medium-Range Weather Forecasting (ECMWF).

The reliability of the new SAT data set for climate analyses is evidenced through statistical comparison with the National Center for Atmospheric Research/National Center for Environmental Prediction (NCAR/NCEP) re-analysis data (Kalnay et al., 1996) and the Jones et al. (1999) data set, tested here over common areas and time periods. The quantitative agreement between interannual variations in annual mean SAT north of  $55^\circ\text{N}$  (excluding the Greenland area  $20$ – $70^\circ\text{W}$ ) from NCAR/NCEP and our data set is  $r \sim 0.92$  from 1955–1990. The agreement between the Jones data and our data set from a large arctic–subarctic test area (between  $52.5^\circ\text{N}$ – $67.5^\circ\text{N}$  and  $2.5^\circ\text{W}$ – $62.5^\circ\text{E}$ ) from 1930–1990 is nearly identical, with a correlation coefficient  $r \sim 0.97$  and a mean difference  $\sim 0.15^\circ\text{C}$ . Therefore, the SAT data set put forth here is considered a reliable alternative to the standard data sets and has the advantage of improved coverage in the Arctic and extending over the last century.

Figure 1a shows the time evolution of the zonally averaged anomalies in annual mean SAT from  $30$ – $90^\circ\text{N}$ . Two characteristic warming events stand out, the first from the mid 1920s to about 1940 and the second starting about 1980 and still ongoing. Here, we show that the early twentieth-century warming was largely confined to north of  $60^\circ\text{N}$ , whereas the latter warming encompasses the whole Earth (Jones et al., 1999) but is none the less significantly enhanced in the Arctic (Fig. 1a).

The early twentieth-century warming trend in the Arctic was nearly as large as the warming trend for the last 20 yr, such that some researchers (e.g. Polyakov et al., 2002) regard them to be part and parcel of the same natural low-frequency oscillation. However, our spatial comparison of these periods reveals key differences in their patterns (Fig. 2). The 20-yr SAT trends for the 1920s–1930s warming period (Figs 2a and b) and the subsequent cooling period (Figs 2c and d) have remarkably similar patterns, thus suggesting similar underlying processes. In the winter half-year, the high-latitude warming (Fig. 2a) and cooling (Fig. 2c) patterns are organized symmetrically around the pole, while in the summer half-year, the warming (Fig. 2b) and cooling (Fig. 2d) appear to reflect the positions of the latitudinal quasi-stationary wave structure, predominantly wavenumber three and four. However, the warming trend for the last 20 yr is more widespread and has a markedly different pattern from the earlier periods in both winter (Fig. 2e) and summer (Fig. 2f). Both the 1920–39 and 1980–99 warming are most pronounced during winter for the high Arctic. In addition, in the latter period, there is pronounced warming in the Eurasian midlatitudes, especially in summer.

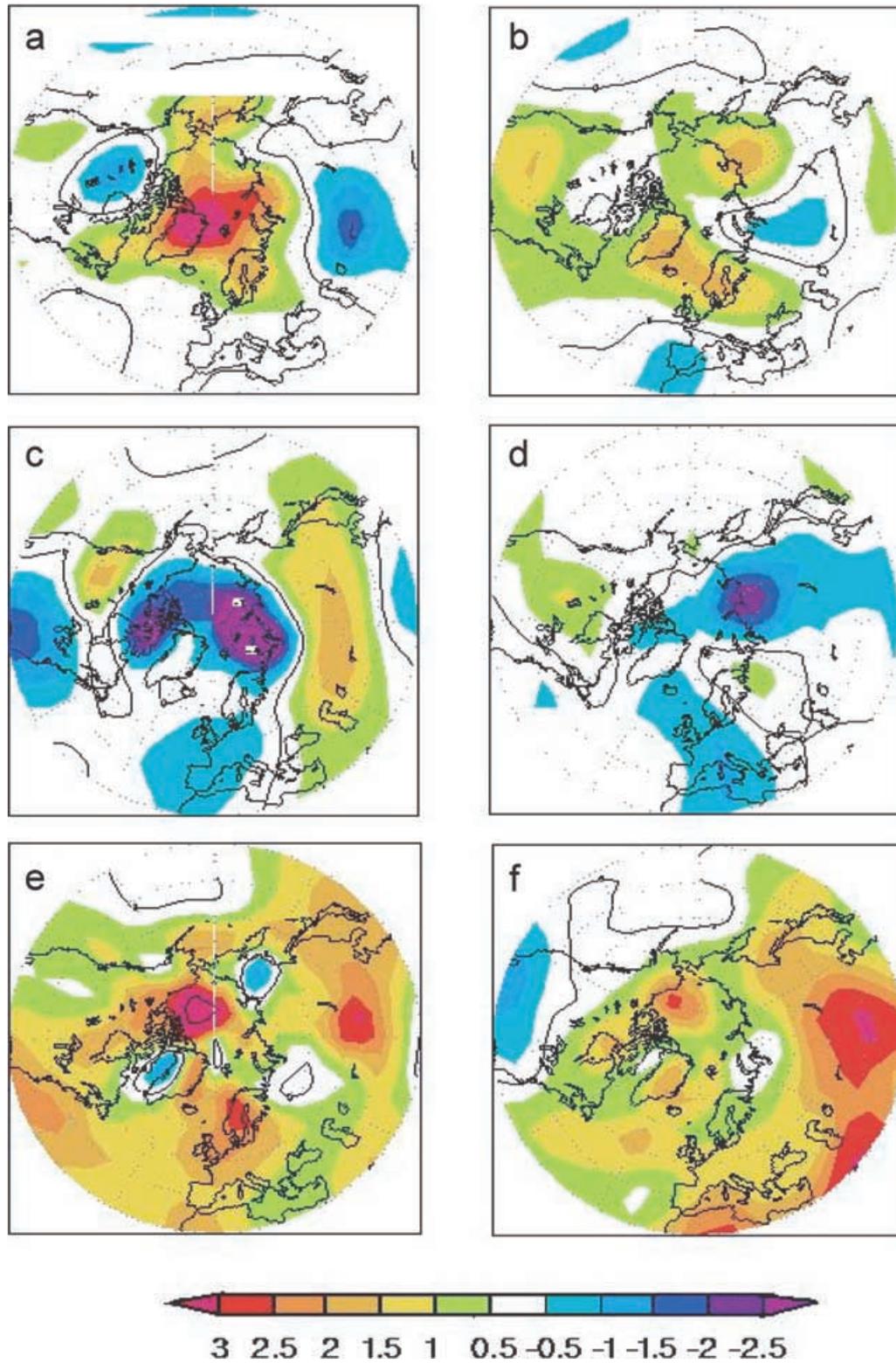
A recent modelling study (Delworth and Knutson, 2000) has suggested that the 1920s–1930s warming anomaly was due to natural processes, insofar as models are capable of simulating such anomalies as due to internal chaotic processes of the



*Fig. 1.* Hovmöller diagram indicating the time–latitude variability of SAT anomalies north of 30°N, 1891–1999: (a) observed; (b) modelled, including changes in GHGs only, 1891–1999; (c) modelled, including changes in GHGs and sulfate aerosols, 1891–1999; (d) modelled, control run, which generates temporal and spatial scales of variability, although the particular years on the *x*-axis are, in effect, arbitrary. The model results (b–d) are from the ECHAM4 coupled atmosphere–ocean–ice model (Roeckner et al., 1999). ECHAM4/OPYC is a state-of-the-art coupled atmosphere–ocean–ice model developed by the Max Planck Institute for Meteorology and the German Climate Computing Centre. It has been used extensively in climate modelling by several research groups worldwide. The atmospheric part is a spectral transform model at T42 resolution and employs 19 vertical levels. The ocean part uses isopycnal coordinates at 11 vertical levels.

climate system. Here, a similar high-latitude anomaly, although less extreme and of a shorter duration, is found in a 300-yr control run (without increasing anthropogenic forcings) with the ECHAM4 model—100 yr are shown in Fig. 1d. This anomaly occurred after 150 yr of integration and lasted for some 15 yr. This simulation without increasing anthropogenic forcing is able to produce an anomaly similar to the observed high-latitude warming in the 1920s–1930s. Therefore, we strongly support the contention of Delworth and Knutson (2000) that this high-latitude warming event represents primarily natural variability within the climate system, rather than being caused primarily by external forcings, whether solar forcing alone (Thejll and Lassen, 2000) or a combination of increasing solar irradiance, increasing anthropogenic trace gases, and decreasing volcanic aerosols, as suggested from an analysis of 400 yr of temperature proxy data from the Arctic (Overpeck et al., 1997). Changes in solar forcing have been suggested (e.g. Lean and Rind, 1998) as the cause of the warming. It has attracted considerable interest because of the apparent similarity between the assumed solar variability and the SAT trend of the Northern Hemisphere extratropics (Friis-Christensen and Lassen, 1991; Hoyt and Schatten, 1993). Reconstructions of solar variability have been used in modelling studies (Cubasch et al., 1997; Cubasch and Voss, 2000; Stott et al., 2001) providing results broadly consistent with long-term estimated or observed temperature trends. This is not surprising because multidecadal and longer trends in solar forcing generate a response in global average modelled temperatures on similar time-scales as the anticipated variation in solar forcing (Cubasch et al., 1997). Rigorous testing of the assumption of solar forcing requires reliable observations; however, these data exist only for the past two decades (Lean and Rind, 1998), such that it remains only a hypothesis. The anthropogenic forcing in the 1920s–1930s was far too weak to generate the observed warming—the change in the GHG forcing in the early decades of the twentieth century was only ~20% of the present (Roeckner et al., 1999). The most plausible explanation in this case is the low-frequency, multi-decadal oscillation related to North Atlantic Ocean circulation (Schlesinger and Ramankutty, 1994; Delworth and Mann, 2000; Polyakov and Johnson, 2000).

In contrast, no comprehensive numerical-model integrations have produced the present global warm anomaly (Fig. 1a) without including observed anthropogenic forcing. Figure 1b shows the ECHAM4 model simulation with anthropogenic GHG forcing. The patterns compare well with the last two decades of observed warming, although the modelled warming occurs slightly earlier and also encompasses lower latitudes than observed (Fig. 1a). The patterns from a simulation including GHGs and sulfate aerosols (GSD) (Fig. 1c) show that, although the recent midlatitude warming is underestimated, the high-latitude enhancement is in agreement with the observations and other modelling results (Räisänen, 2001). Therefore, anthropogenic forcing is the dominant cause of the recent pronounced warming in the Arctic.



*Fig 2.* Observed SAT trends north of 30°N in the winter (NDJFMA) and summer (MJJASO) half-years for 20-yr periods representing warming, cooling and warming in the twentieth century: (a, b) 1920–39, winter and summer, respectively; (c, d) 1945–64, winter and summer, respectively; (e, f) 1980–1999, winter and summer, respectively.

What then are the possible mechanisms by which anthropogenic forcing could bring about high-latitude warming, given that the recent trend in arctic SAT is greater than the direct radiative effect of GHGs? First, as has been demonstrated by Bengtsson (1999) and Hansen et al. (1999), the large-scale spatial pattern of forcing and the pattern of response to forcing are practically uncorrelated, which stresses the key role of advective atmosphere–ocean processes in bringing about regional climate change; see also Schneider et al. (2003). A possible mechanism is suggested by recent findings from observations and modelling experiments (Hoerling et al., 2001; Lin et al., 2002). Hoerling et al. (2001) show that the observed long-term warming trend (up to  $0.2^{\circ}\text{C}$  per decade) in the tropical oceans—anthropogenically forced (Levitus et al., 2000; Reichert et al., 2002)—during the last 50 yr has generated, through enhanced convective activity, an intensification of the midlatitude tropospheric westerlies, and consequently because of geostrophy in the Atlantic sector, an enhanced positive North Atlantic Oscillation/Arctic Oscillation (NAO/AO) pattern (Hoerling et al., 2001). Because the NAO and arctic temperature are linked—the interannual variations in the NAO index (Hurrell, 1995) and SAT from  $60\text{--}90^{\circ}\text{N}$  are found here to be significantly correlated ( $r \sim 0.51$  when using data since the mid twentieth century)—it follows that an NAO enhancement, linked to anthropogenic warming of the tropical oceans, can explain a substantial portion of the warming trend in the Arctic. It is unlikely that this was a mechanism for the early twentieth-century warming phase, because of the small anthropogenic GHG effect at the time and because no positive correlation between arctic SAT and the NAO before 1950 is found; in fact, here we find that the correlation is negative ( $r \sim -0.39$ ).

Secondly, an ice-albedo feedback may enhance the arctic warming, as new ECHAM4 sensitivity experiments have demonstrated a robust relationship between sea ice and air temperature (Bengtsson et al., 2004), in which advective mechanisms—in particular, enhanced wind-driven oceanic heat inflow into the Barents Sea—may have a predominant role.

### 3. Sea ice: observations

#### 3.1. Sea-ice concentration and derived parameters

Sea-ice concentration (percent ice area per unit area) and derived parameters such as ice extent (the area within the ice–ocean margin defined as 15% ice concentration) and ice area (extent minus the open-water area) can be reliably retrieved from satellite passive-microwave sensor measurements, which are available continuously since 1978, thus among the longest satellite-retrieved geophysical records. Satellite data have shown that the winter maximum ice area (Fig. 3a) is typically about  $14 \times 10^6 \text{ km}^2$  while the summer minimum ice area (Fig. 3a) is about  $7 \times 10^6 \text{ km}^2$ . These data, here updated from Johannessen et al. (1995, 1999) and Bjørgo et al. (1997) through March 2003, indicate a decrease of  $\sim 8.1 \times 10^5 \text{ km}^2$  ( $\sim 7.4\%$ ) in the Northern

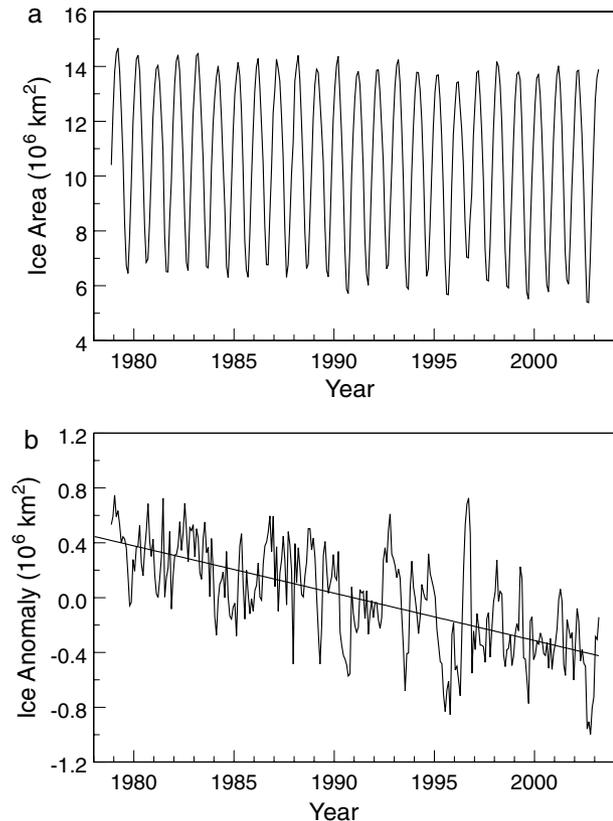
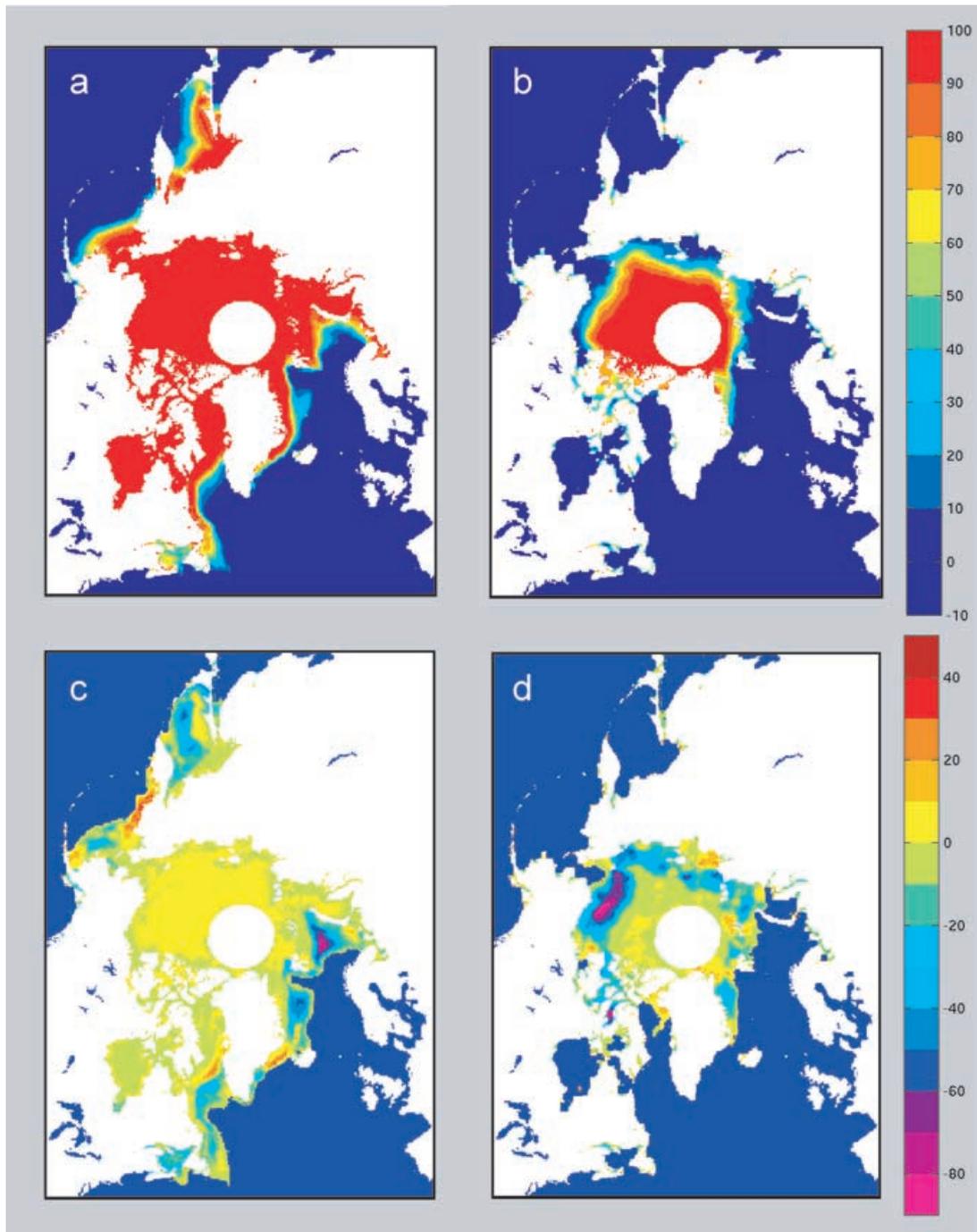


Fig. 3. Total sea-ice area (the area within the ice–ocean margin minus open-water area) for the Northern Hemisphere, 1978–2003, as retrieved from satellite passive-microwave remote-sensing data. (a) Monthly ice area, indicating that the predominant variability is the seasonal cycle. (b) Monthly anomalies or departures from the mean and seasonal cycle. The linear trend was  $-0.34 \times 10^6 \text{ km}^2$  per decade during the period. The largest negative anomaly is found in the most recent data, with record-low ice cover in September 2002.

Hemisphere annual sea-ice area, 1978–2003 (Fig. 3b). During this period, the decreases have been larger in summer (see also Chapman and Walsh, 1993; Parkinson et al., 1999); here, we calculate a  $9.4 \times 10^5 \text{ km}^2$  (14%) decrease in September versus  $6.8 \times 10^5 \text{ km}^2$  (5%) in March (1978–2003). This seasonal difference has resulted in a 7–9% per decade reduction in the area of thicker, multiyear (MY) ice (ice that has survived at least one summer melt) over the last two decades (Johannessen et al., 1999; Comiso, 2002). It is noteworthy that our updated time series through September 2002 indicate that the record minimum summer ice cover recently reported (Serreze et al., 2003) is indeed unprecedented in the nearly quarter-century satellite record (Fig. 3a)—less than  $6 \times 10^6 \text{ km}^2$  in area, which occurred from anomalous warm southerly winds in spring followed by low SLP and high SAT in the Arctic in summer (Serreze et al., 2003). Note also the large positive anomaly in 1996, which occurred in the summer after an extreme temporary reversal in the NAO in the winter 1995/96.



*Fig. 4.* Satellite-retrieved sea-ice concentration (percent ice area per unit area) in winter (March) and summer (September) for the Northern Hemisphere, 1978–2003. Mean concentration for (a) winter and (b) summer, and the linear trends (% change from 1978–2003) for (c) winter and (d) summer.

The spatial patterns of the mean winter (March) and summer (September) sea-ice cover 1978–2002 are shown in Figs 4a and 4b. The winter and summer trends (linear regressions) in sea-ice concentration from 1978–2002 are indicated in Figs 4c and d. During this period, the decreases in winter have been most

pronounced (as large as ~50%) in the Barents and Greenland seas, whereas the summer decreases have been greater than 50% in some areas of the Beaufort and Chukchi seas, and as large as ~30–50% in the Siberian marginal seas. These summer patterns are in agreement with an independent analysis

of ice-cover minima from 1978–1998 (see fig. 2c in Comiso, 2002).

The decreases in recent decades, which are also partially due to circulation-driven ice export through the Fram Strait between Greenland and Svalbard (Vinje, 2001), have coincided with a positive trend in the NAO, with unusually high index values in the late 1980s and 1990s. During this period, the variability of ice motion and ice export through the Fram Strait was correlated strongly with the NAO;  $r \sim 0.86$  for the ice area flux (Kwok and Rothrock, 1999) and  $r \sim 0.7$  for the ice volume flux (Hilmer and Jung, 2000), although the relationship was insignificant ( $r \sim 0.1$ ) before the mid 1970s (Hilmer and Jung, 2000). Deser et al. (2000) analysed a 40-yr gridded data set (1958–97) to determine the association between arctic sea ice, SAT and SLP, concluding that the multidecadal trends in the NAO/AO in the past three decades have been ‘imprinted upon the distribution of Arctic sea ice’, with the first principal component of sea-ice concentration significantly correlated ( $r \sim -0.63$ ) with the NAO index, recently cause-and-effect modelled by Hu et al. (2002). None the less, our calculations and those of Deser et al. (2000) indicate that, even in recent decades, only about one third of the variability in arctic total ice extent and MY ice area (Johannessen et al., 1999) is explained by the NAO index, implying that other factors including enhanced radiative forcing and ice–albedo feedbacks (Björk and Söderkvist, 2002; Bengtsson et al., 2003) must be invoked to explain the variability.

A pronounced reduction in the Northern Hemisphere sea-ice extent, such as seen in the satellite record of the last two decades, is scarcely apparent in the early twentieth-century warm period, at least in the two most widely-used century-long sea-ice data sets (Chapman and Walsh, 1993; Rayner et al., 1996). To ascertain whether this has a physical explanation or is due to acknowledged data deficiencies before the 1950s (Chapman and Walsh, 1993; Vinnikov et al., 1999), we have analysed these data together with a new century-long ‘Zakharov’ data set (Zakharov, 1997; Alekseev et al., 2000), which includes hitherto under-recognized Russian data. The data set comprises sea-ice extent (regardless of ice concentration within the ice–ocean margin) for  $\sim 77\%$  ( $11.3 \times 10^6 \text{ km}^2$ ) of the area of the Arctic Ocean. This region occupies the perennially ice-covered central Arctic Ocean and the Greenland, Barents, Kara, Laptev, East Siberian and western Chukchi marginal seas, leaving out only the eastern Chukchi and Beaufort seas and the Canadian Arctic straits and bays.

In the Atlantic–European sector (Greenland and Barents seas), the sea-ice extents from 1900 to the late 1950s are known only from spring and summer (April to August). It has not previously been possible to gain understanding about the annual ice cover variability in these decades. An attempt has been made to obtain these missing mean annual data. Towards this end, the actual year-round data on the ice extent from 1959–1988 were used to derive an equation to calculate the annual average ice extent in the region ( $Y_1$ ) based on its mean value in April to August ( $X_1$ ):  $Y_1 = 0.89 X_1 + 100$ . The correlation between  $X_1$  and

$Y_1$  is  $r = 0.94 \pm 0.01$ . By means of this equation, the missing annual ice-extent means from 1900–1958 were calculated. The main problem of any reconstruction is errors inevitable in the procedures of data series reconstruction. This problem can be resolved by comparing the actual and calculated annual ice extent averages, in this case for the period from 1959, and by calculating the root-mean-square (rms) error of the reconstruction. The error  $s = \pm 52 \times 10^3 \text{ km}^2$ , and as the rms deviation of the initial actual series  $\sigma = \pm 154 \times 10^3 \text{ km}^2$ , the ratio  $s/\sigma = 0.34$ . Thus, the methodological error of the reconstruction comprises only one third of the rms deviation of the actual series, indicating a sufficiently high reliability of the reconstruction method used.

Data on the ice edge are available for August from the mid 1920s in the Siberian sector (Kara, Laptev, and East Siberian seas). From the 1930s, with the development of shipping along the Northern Sea Route, knowledge of the position of these boundaries was extended to two adjacent months (July and September); however, the accuracy of the ice data from that time cannot be considered high, because observations were not carried out systematically. From the mid 1930s, aviation was used to collect ice information and from the mid 1940s became the main source of sea-ice information in the Siberian Arctic. The observations attain a regular character covering (with some exceptions) the entire navigation season. An attempt has been made to obtain these missing mean annual data, using incomplete data from 1924–1946 to reconstruct the conditions of those years. With this aim, using the 1946–1999 series, the equation:  $Y_2 = 0.528 X_2 + 1065$  was derived, where  $Y_2$  is the mean sea-ice extent in the Siberian seas in June–October, and  $X_2$  is the ice area in the Siberian seas in August. The correlation between  $X_2$  and  $Y_2$  is  $r \sim 0.93$ . The ratio  $s/\sigma = 0.33$  again suggests a sufficiently high reconstruction quality based on the knowledge of ice extent only in August.

Figure 5 shows time series of annual sea-ice extent based on these data and annual sea-ice extent from the standard ‘Walsh’ data set (Chapman and Walsh, 1993), in comparison with the zonal annual mean SAT between 70–90°N since 1900. In contrast to the Walsh data, these new data indicate a substantially reduced ( $\sim 0.6 \times 10^6 \text{ km}^2$ ) ice cover in the 1920s–1930s warming period. Note that the correspondence between the subsequent cooling into the mid 1960s and increasing sea ice is seen from the late 1950s; the ice data from WWII and the early post-war years are inadequate. Note also that the apparent differences in trends in the two sea-ice time series during the last 25 yr are due to relatively large reductions in the Beaufort Sea and Chukchi seas (Fig. 4)—areas not included in the Zakharov data set. The correlations between the SAT and the Zakharov and Walsh sea-ice extents are maximum at 0 lag,  $r \sim 0.6$  and 0.3, respectively. This indicates that the interannual variability in the arctic sea-ice extent in the last century was coupled to the high-latitude SAT variability to a large degree, although the  $r$ -value may partially reflect feedback processes from the ice cover to the atmosphere, e.g. ECHAM4-model sensitivity experiments (see Bengtsson et al.,

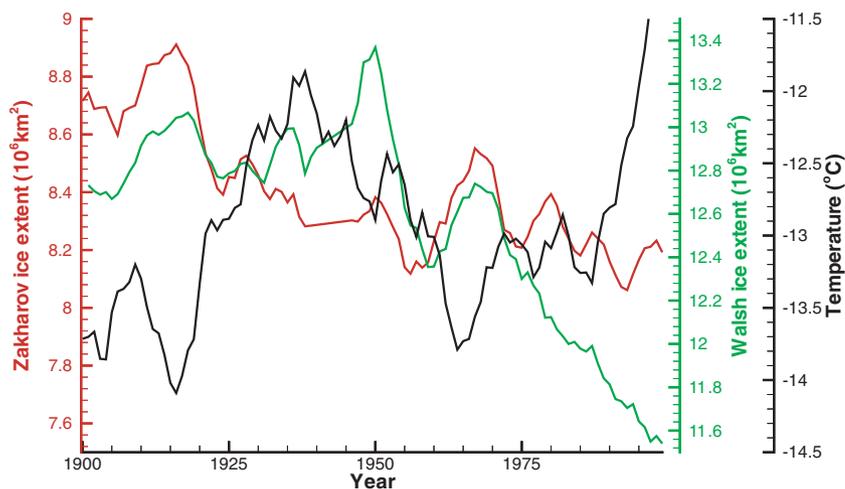


Fig 5. Annual sea-ice extent (area within the ice–ocean margin) derived from a new ‘Zakharov’ sea-ice data set (red), Northern Hemisphere sea-ice extent from the widely used ‘Walsh’ data set (green) and zonal (70–90°N) mean annual SAT (black) since 1900. The time series shown are 5-yr running means.

2004) have demonstrated a strong SAT response—particularly in the Atlantic–European sector—to model-imposed changes in sea ice.

### 3.2. Sea-ice thickness

The variability of ice thickness is relatively poorly known, due primarily to spatial–temporal sampling deficiencies in data from submarines carrying upward-looking sonar (Wadhams, 1997). An analysis (Rothrock et al., 1999) of data from the summers 1958, 1976, 1993, 1996 and 1997 found that between the 1950s/1970s and the 1990s, the mean ice thickness decreased from 3.1 to 1.8 m. The 1.3-m decrease—if representative—corresponds to an ~40% reduction over the three to four decades (Rothrock et al., 1999). However, analyses of sonar data alone from different transects, years and seasons yield a range of estimates, from a comparable decrease (Wadhams and Davis, 2000) to no significant change (Winsor, 2001) to an intermediate estimate (Tucker et al., 2001). An analysis of submarine (Rothrock et al., 1999, 2003) and modelled (Holloway and Sau, 2002) ice thickness over the same common time period has demonstrated that ice motion and high interannual variability could mislead inference of trends from sonar transect data, e.g. 12% (Holloway and Sau, 2002) versus the 40% decrease reported by Rothrock et al. (1999). Thus, the available sonar data alone remain inadequate to produce a reliable, long-term climatology of arctic ice thickness variability.

Here, for the first time, we put forth a unique 20-yr time series of monthly, area-averaged ice thickness derived from field-based measurements of surface elastic-gravity waves from Russian North Polar drifting stations 1970–91, when regular measurements of ice surface vibrations were made in the central Arctic Ocean (Nagurnyi et al., 1994). Long elastic-gravity waves (on the order of 1 km) in the sea-ice cover arise from the interaction with ocean swells. These elastic-gravity waves can propagate for hundreds to thousands of kilometres before dampening out. Based on a linear theory of free vibrations of the sea-

ice cover, the measured wavelength, wave period and direction are then related to thickness through a wave-energy dispersion relation. The ice thicknesses determined from different propagation directions are averaged to provide a basin-wide mean thickness estimate (Nagurnyi et al., 1994, 1999). The values compare well to those observed in the regional ice cover (Romanov, 1995) and their interannual variability correlates well with modelled arctic ice volume (see fig. 1 in Hilmer and Lemke, 2000). The thickness estimates have also been found to correlate strongly (~0.88) to the satellite-derived area of the perennial, MY ice cover in winter (Johannessen et al., 1999), suggesting moreover that the decreases found in MY ice area represent a mass balance change rather than merely a peripheral effect.

Figure 6a shows the 20-yr time series of area-averaged ice thickness, 1970–91, from which trends for winter and summer are derived (Fig. 6b). The mean thickness estimates are ~2.9–3 m in winter and ~2.5–2.6 in summer (i.e. seasonal cycle ~40 cm). The linear trend of anomalies from 1971–90 indicates a decrease of only ~10 cm (less than 4%) over 20 yr. This is comparable with some observational and modelling analyses (e.g. Holloway and Sau, 2002), but is much less than the 1950s/1970s to 1990s sonar data analysis (Rothrock et al., 1999) upon which the IPCC based its statement that the arctic ice thickness has been reduced 40% during summer in recent decades. The large variability inherent in the arctic sea-ice–climate system, coupled with the problem of obtaining ice thickness data, renders the evaluation of ice thickness trends from the available observational data an open question. None the less, it is notable that our ECHAM4 coupled model experiments (not shown) with the IPCC IS92 emission scenarios for greenhouse and related gases indicate that: (1) our 20 yr of ice thickness data are consistent with the modelled results 1970–90, and (2) substantial decreases in modelled ice thickness commence only in the last two decades of the twentieth century. The ice thickness from both observations and models is presently ~2.5–3 m in summer, whereas our model results indicate less than 1 m at the end of this century for the remaining ice cover.

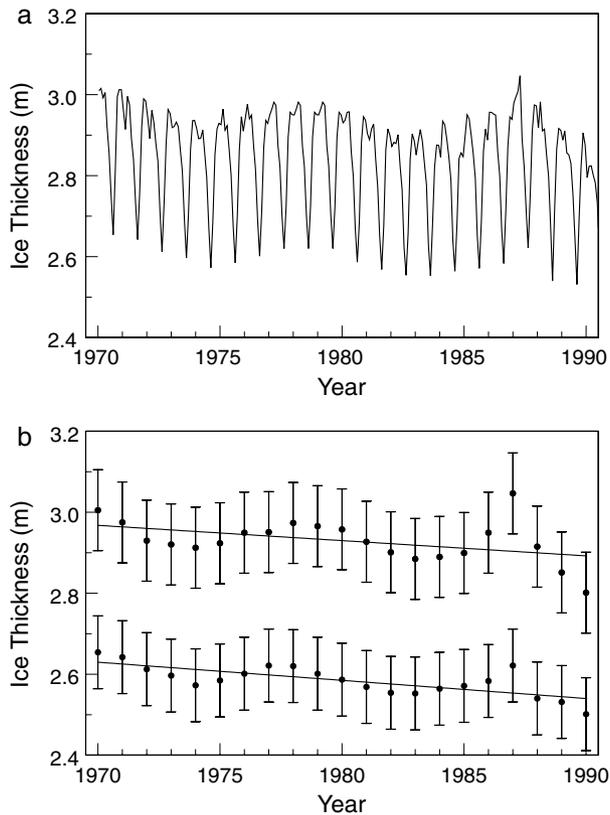


Fig 6. Arctic sea-ice thickness variability from 1970–1990.

(a) Monthly area-averaged thickness estimates as derived from surface-based measurements of ice-surface vibrations made from Russian North Pole drifting stations in the perennial ice pack of the Arctic Ocean (Nagurnyi et al., 1994, 1999). (b) Interannual variability and linear trends for winter (April) and summer (August), with errors bars denoting the 95% confidence interval of the ice thickness estimates.

#### 4. Sea-ice extent: modelled

The variability of annual sea-ice extent has been modelled and compared to observations in previous analyses (Vinnikov et al., 1999; Johannessen et al., 2001), which predicted a reduction of ~15% in the Northern Hemisphere mean ice extent to 2050. However, potentially large and important spatial and seasonal aspects were not considered. Here, for the first time, both the spatial and seasonal variability of the ice cover and its modelled response to anthropogenic forcing are analysed to 2100, using ECHAM-4 and HadCM3 model predictions including different IPCC emissions scenarios.

The observed versus ECHAM4-modelled trends in Northern Hemisphere winter and summer sea-ice extent in the twentieth century are similar (Fig. 7). Our ECHAM4-model run—using an IPCC IS92 emission scenario similar to IPCC Special Report on Emissions Scenarios (SRES) scenario B2—predicts the decreases to continue such that the summer ice cover may be reduced by ~80% at the end of the twenty-first century (Fig. 7,

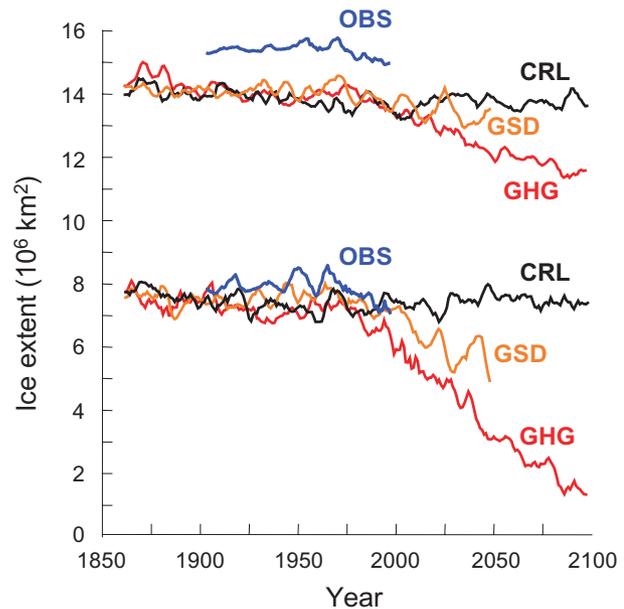


Fig 7. Observed and ECHAM4-modelled Northern Hemisphere sea-ice extent in late winter (March) and late summer (September), 1860–2100, upper and lower, respectively. The observational data (OBS) from 1901–98 are from the ‘Walsh’ data set. The modelled scenarios include a control run (CRL), changes in GHGs and GHGs plus sulfate aerosols (GSD) from the IPCC IS92 emissions scenarios. In winter (upper), the difference between the observed and modelled ice extent is due to seasonal ice in the peripheral seas and bays outside the model domain.

lower). This is much greater than the winter (Fig. 7, upper) or annual means modelled previously (Vinnikov et al., 1999; Johannessen et al., 2001) and is comparable to recent projections for the summer (Gregory et al., 2002).

The spatial distributions of the ECHAM4-modelled sea-ice cover for the present decade (2001–2010) and towards the end of the century (2081–2090) are indicated in Fig. 8. In order to test the robustness of our ECHAM4 estimates, we have used a different coupled atmosphere–ocean model, the HadCM3, which is an improvement upon the HadCM2 model used in a previous sea-ice study (Vinnikov et al., 1999). Furthermore, we use two different SRES scenarios, A2 and B2, which are ‘medium-high’ and ‘medium-low’ scenarios, respectively. Results from the B2 experiments are shown in Fig. 9, which depicts decadal averages of winter (Figs 9a and b) and summer (Figs 9c and d) sea-ice concentrations in 2001–2010 and 2081–2090. The ECHAM4 (Fig. 8) and HadCM3 (Fig. 9) results support each other, both predicting moderate reductions in winter and drastic reduction in the summer ice extent. The spatial distributions of the ECHAM4 and HadCM3 modelled summer ice cover in late century (Figs 8d and 9d) indicate essentially ice-free arctic marginal seas except north of Greenland and the Canadian Arctic Archipelago, although there are some differences in the modelled spatial patterns.

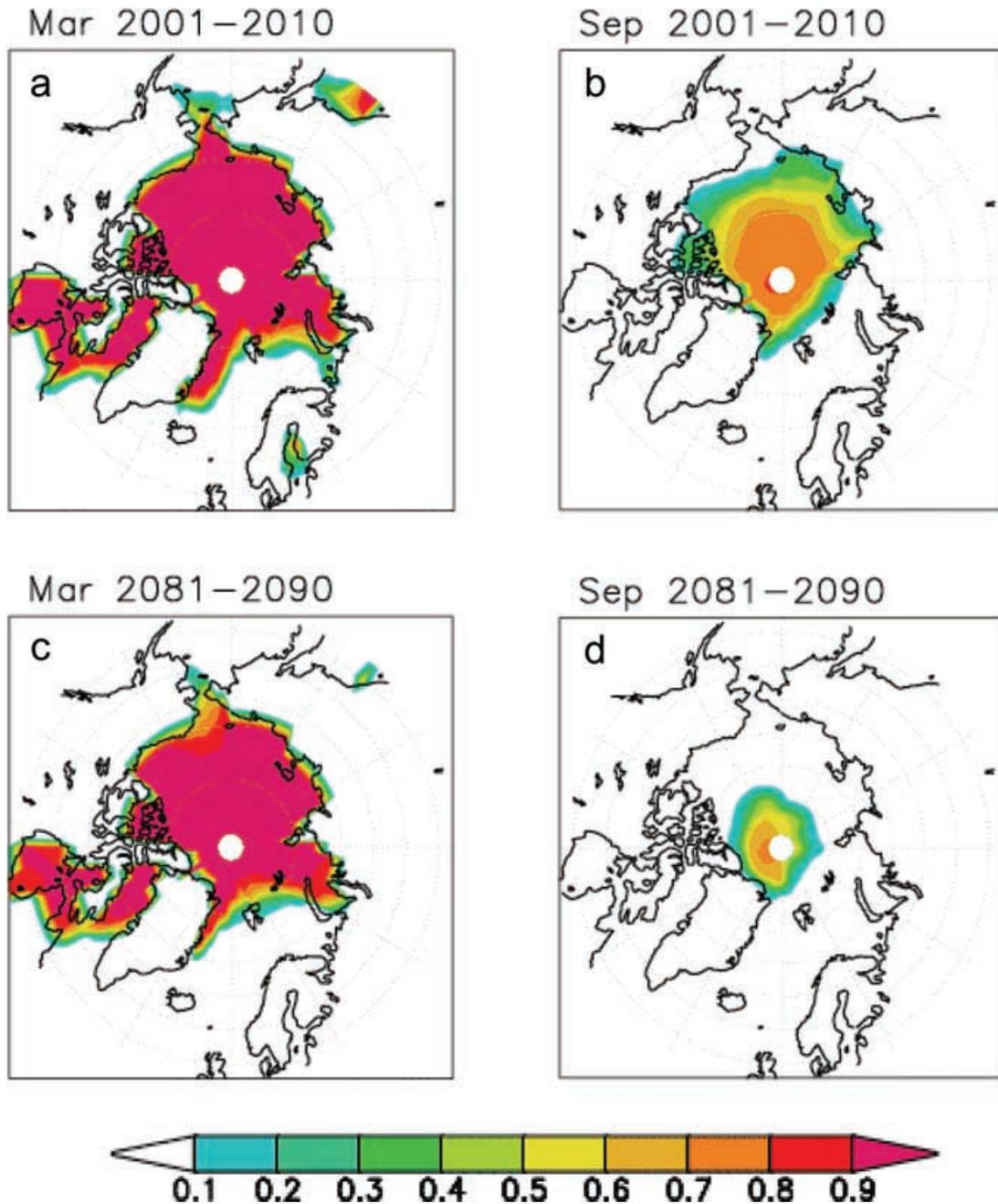
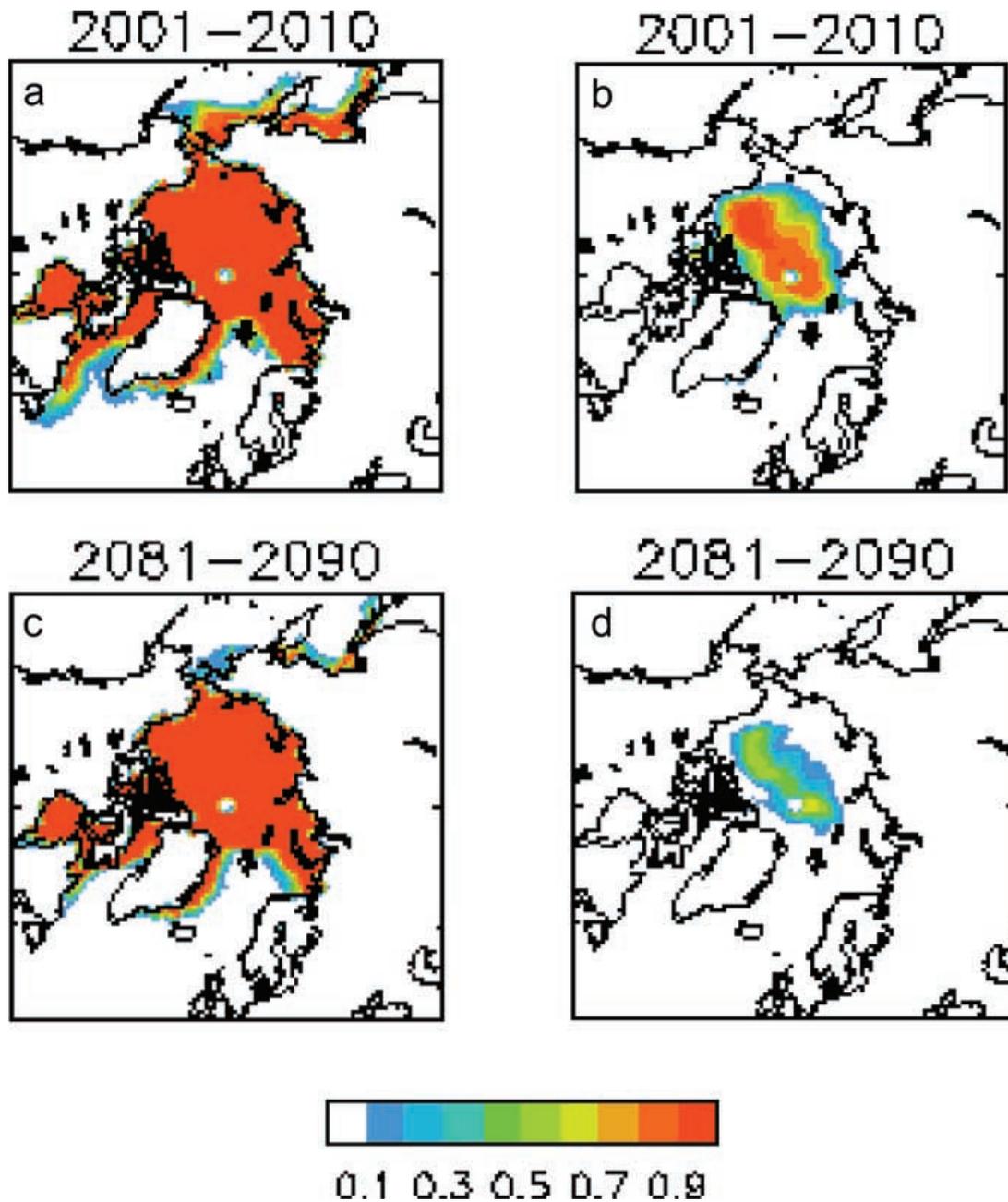


Fig 8. ECHAM4-modelled Northern Hemisphere sea-ice concentration in late winter (March) from (a) 2001–2010 and (b) and 2081–2090, and in late summer (September) from (c) 2001–2010 and (d) 2081–2090. The model has been run using the IPCC IS92 emission scenario comparable to IPCC SRES scenario B2.

## 5. Conclusions and implications

The results of our observational and modelling analysis lead to the following conclusions. First, we theorize that the Arctic warming in the 1920s–1930s and the subsequent cooling until about 1970 are due to natural fluctuations internal to the climate system. Secondly, we believe there are strong in-

dications that neither the warming trend nor the decrease of ice extent and volume over the last two decades can be explained by natural processes alone. Thirdly, the state-of-the-art ECHAM4 and HadCM3 coupled climate models both predict a dramatic decrease of the ice cover, which could result in a nearly ice-free Arctic Ocean during summer at the end of this century.



*Fig 9.* HadCm3-modelled Northern Hemisphere sea-ice concentration in late winter (March) from (a) 2001–2010 and (b) 2081–2090, and in late summer (September) from (c) 2001–2010 and (d) 2081–2090. The model has been run using IPCC SRES emissions scenarios A2 and B2, the latter (shown) being a ‘medium-low’ estimate.

A range of potential consequences of arctic warming and a shrinking ice cover can be hypothesized, as follows.

(i) Reductions in albedo and increased open water would have significant effects on energy balances and atmospheric and oceanic circulation in the high latitudes.

(ii) Exposure of vast areas of the Arctic Ocean with cold open water, which has a high capacity for CO<sub>2</sub> absorption, could

become a new and important sink of atmospheric CO<sub>2</sub> (Anderson and Kaltin, 2001.).

(iii) Broad changes in the marine ecosystem, e.g. changes in plankton in the North Atlantic due to less ice and greater inflow of melt water (Beaugrand et al., 2002), could have a negative impact on arctic and subarctic marine biodiversity. However, there would be a larger area for potential fisheries, as well as increased offshore activities and marine transportation,

including the Northern Sea Route north of Siberia (Ragner, 2000).

(iv) Changes in the pathways and spreading of melt water and in the stratification in the Nordic Seas, and the effects of reduced deep-water formation in the Greenland Sea on the global thermohaline circulation (Rahmsdorf, 1999; Alekseev et al., 2001), could greatly alter the climate of the northern latitudes.

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