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ARCTIC CLIMATE CHANGE – OBSERVED AND MODELED TEMPERATURE AND SEA ICE VARIABILITY

by

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Arctic climate change – observed and modelled

temperature and sea ice variability

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Content

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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 global atmosphere–ice–ocean model simulations in order to better determine and understand arctic climate variability. We show that two pronounced 20th-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 20th-century warm period. It is suggested strongly that whereas the earlier warming was natural internal climate-system variability, the recent SAT changes are a response to anthropogenic forcing. The area of arctic sea ice is furthermore observed to have decreased ~ 8 x 10^5 km^2 (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 21st century, with greater reductions expected in summer than winter. In summer, a predominantly ice-free Arctic Ocean 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 ~3-4°C during the next 50 years, or more than twice the global average.

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 multi-decadal 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 datasets (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 characterised by high variability.

From these concerns, two overarching questions are: (1) To what degree are the gradually changing atmosphere–ice–ocean conditions in the Arctic a consequence of natural climate processes and/or external factors such as anthropogenic greenhouse gas (GHG) forcing, and (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 multi-decadal to century-scale data (surface air temperature (SAT), sea-ice extent and 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 modeled

Statistical analyses of global SAT datasets have indicated substantial fluctuations in the extra-tropical Northern Hemisphere on decadal to multi-decadal time scales (e.g., Schlesinger and Ramankutty, 1994; Hansen *et al.*, 1999; Jones *et al.*, 1999). In the high latitudes, differences in spatio-temporal coverage have led to some discrepancies concerning temperature variability trends in the last century (e.g., Jones *et al.*, 1999; Pryzbylak, 2000; Polyakov *et al.*, 2002). The global gridded SAT dataset (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 dataset focused on the high latitudes of the Northern Hemisphere. The dataset is provided through the Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia, produced through a project within the program International Association for the Promotion of Co-operation with Scientists from the Former Soviet Union (Alexseev *et al.*, 1999). The input data are daily temperature from 1,486 meteorological stations in the Northern Hemisphere, including land- and drifting-stations from the Arctic. A gridded dataset (5° lat. x 10° 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. Second, the maps were visually analysed and interpolated into a gridded dataset, as described and evaluated previously (Vinnikov *et al.*, 1977). Third, the dataset were 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 (0.6º/100m) as in Alekseev and Svyaschennikov (1991). Fourth, the dataset 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 dataset for climate analyses is evidenced through statistical comparison with the National Center for Atmospheric Research (NCAR) / National Center for Environmental Prediction (NCEP) re-analysis data (Kalnay *et al.*, 1996) and the Jones *et al.* (1999) dataset, tested here over common areas and time periods. The quantitative agreement between interannual variations in annual mean SAT north of 55°N (excluding the Greenland area 20-70°W) from NCAR/NCEP and our dataset is r ~ 0.92 from 1955-1990. The agreement between the Jones data and our dataset from a large arctic-subarctic test area (between 52.5°N-67.5°N and 2.5°W-62.5°E) from 1930-1990 is nearly identical, with r ~ 0.97 and a mean difference ~0.15°C. Therefore, the SAT dataset put forth here is considered a reliable alternative to the standard datasets and has the advantage of improved coverage in the Arctic and extending over the last century.

Fig. 1a shows the time evolution of the zonally averaged anomalies in annual mean SAT from 30-90°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 20th-century warming was largely confined to north of 60°N, whereas the latter

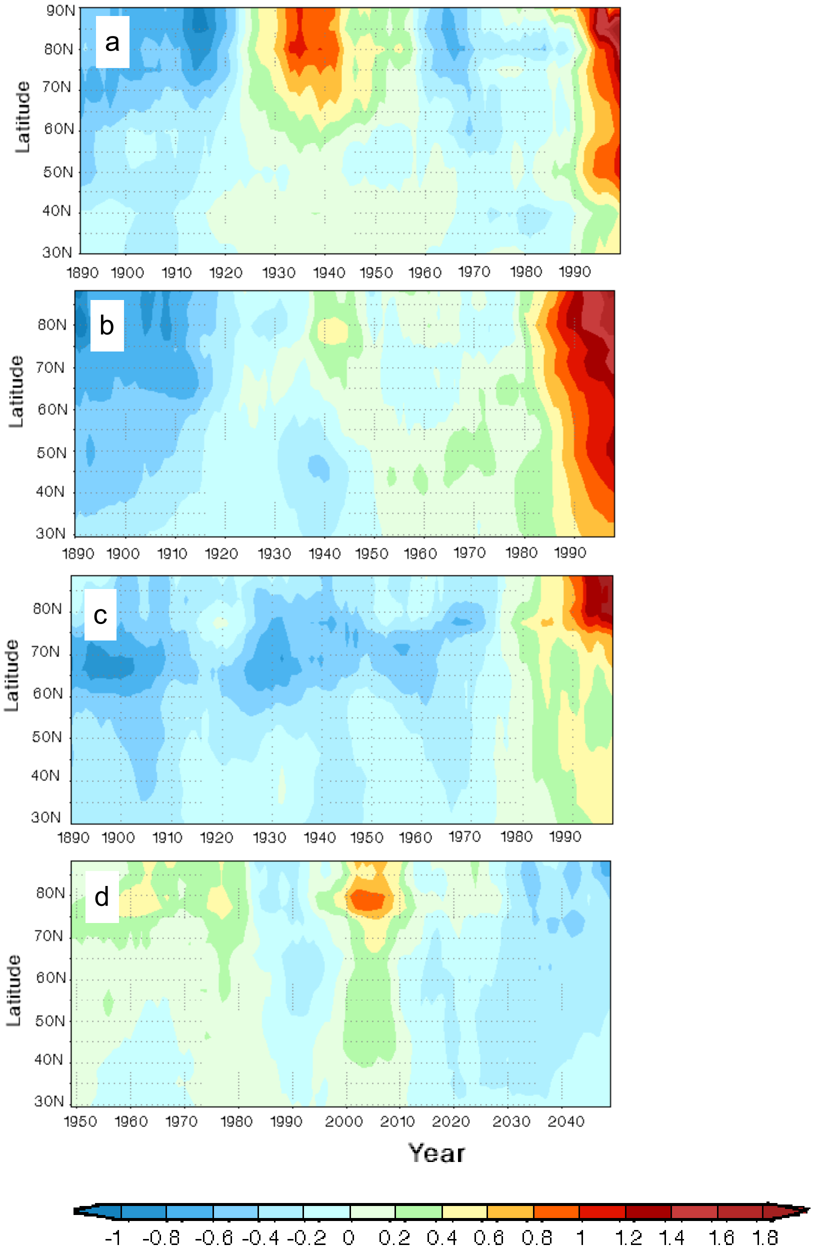

Figure 1. Hovmöller diagram indicating the time–latitude variability of surface air temperature (SAT) anomalies north of 30°N, 1891-1999: (a) Observed, (b) Modelled, including changes in greenhouse gases (GHGs) only, 1891-1999, (c) Modelled, including changes in GHGs and sulfate aerosols, 1891-1999, (d) Modelled, control run, which generates temporal and spatial scales of variability, though 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). The 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.

warming encompasses the whole Earth (Jones *et al.*, 1999) but is nonetheless significantly enhanced in the Arctic (Fig. 1a).

The early 20th-century warming trend in the Arctic was nearly as large as the warming trend for the last 20 years, 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-year SAT trends for the 1920s-1930s warming period (Fig. 2a and 2b) and the subsequent cooling period (Fig. 2c and 2d) 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 organised 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 years 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 is most pronounced during winter for the high Arctic. In addition, in the latter period there is pronounced warming in the Eurasian mid-latitudes, 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 climate system. Here, a similar high-latitude anomaly, but less extreme and of a somewhat shorter duration, is found in a 300-year control run (without anthropogenic forcings) with the ECHAM4 model – 100 years are shown in Fig. 1d.

This anomaly occurred after 150 years of integration and lasted for some 15 years. This simulation without anthropogenic forcing is able to produce an anomaly similar to the observed high-latitude warming in the 1920s-1930s. Therefore, we strongly support Delworth and Knutson's (2000) contention 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 years of temperature proxy data from the Arctic (Overpeck *et al.*, 1997). Testing the assumption of solar forcing requires reliable observations; however these data exist only for the past two decades (Lean and Rind, 1998). 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 20th 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) shows that although the recent mid-latitude 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.

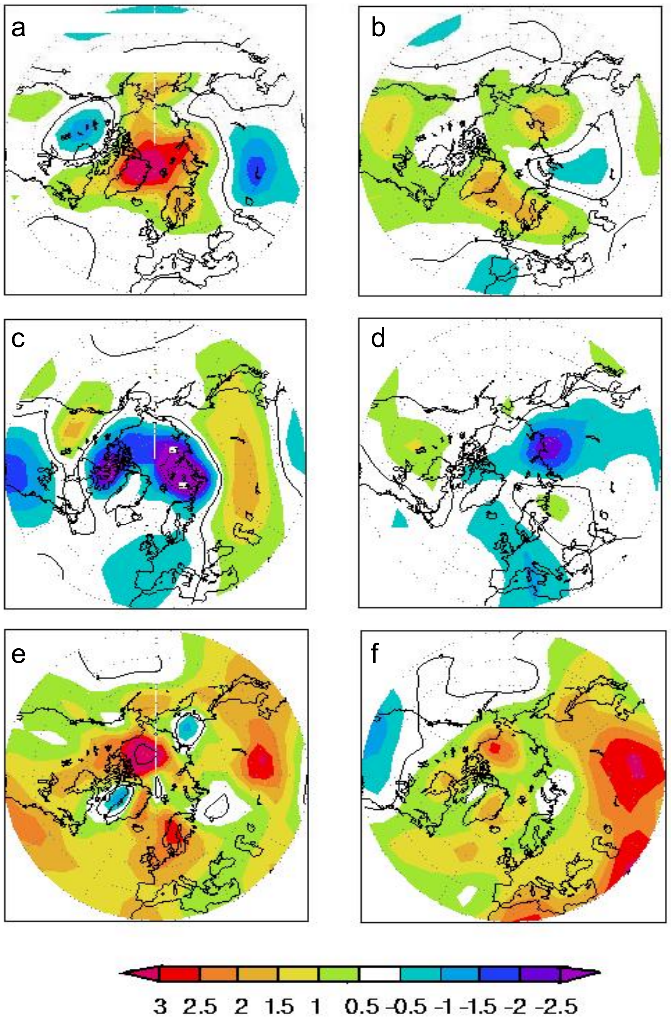

Figure 2. Surface air temperature (SAT) trends north of 30°N in the winter (NDJFMA) and summer (MJJASO) half-years for 20-year periods representing warming, cooling and warming in the 20th century: (a-b) 1920-39, winter and summer, respectively, (c-d) 1945-64, winter and summer, respectively, and (e-f) 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? Firstly, 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 atmospheric–ocean processes in bringing about regional climate change – see also Schneider *et al.* (2002). A possible mechanism is suggested by recent findings from observations and modelling experiments (Hoerling *et al.*, 2001; Lin *et al.*, 2002). Hoerling *et al.* show that the observed long-term warming trend (up to 0.2°C/decade) in the tropical oceans – anthropogenically forced (Levitus *et al.*, 2000; Reichert *et al.*, 2002)) – during the last 50 years has generated, through enhanced convective activity, an intensification of the mid-latitude tropospheric westerlies, and consequently because of geostrophy in the Atlantic sector, an enhanced positive North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) pattern (Hoerling *et al.*, 2001). Since the NAO and arctic temperature are linked – the interannual variations in the NAO index (Hurrell, 1995) and SAT from 60-90°N are found here to be significantly correlated (r ~0.51 when using data since the mid-20th 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 20th-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 ~ -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.*, 2003)[*], 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 image pixel) 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 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 × 10^6 km^2 while the summer minimum ice area (Fig. 3a) is about 7 × 10^6 km^2. These data, here updated from (Johannessen *et al.*, 1995; Bjørgo *et al.*, 1997; Johannessen *et al.*, 1999) through September 2002, indicate an ~ 8.1 × 10^5 km^2 (~7.4%) decrease in the Northern Hemisphere annual sea-ice

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area from 1978-2002 (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 9.4×10^5 km^2 (14%) decrease in September vs. 6.8×10^5 km^2 (5%) in March, 1978-2002. This has resulted in a 7-9% per decade reduction in the area of thicker, multi-year 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)* are indeed unprecedented in the nearly quarter-century satellite record (Fig. 3a), less than 6×10^6 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 the summer after an extreme temporary reversal in the NAO in the winter 1995/96.

The spatial patterns of the mean winter (March) and summer (September) sea-ice cover 1978-2002 are shown in Fig. 4a and 4b. The winter and summer trends (linear regressions) in sea-ice concentration from 1978-2002 are indicated in Fig. 4c and 4d. 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 (caused by the warming tropical oceans, as mentioned before). During this period, the variability of ice motion and ice export through the Fram Strait was correlated strongly with the NAO, r ~0.86 for the ice area flux. (Kwok and Rothrock, 1999) and r ~0.7 for the ice volume flux (Hilmer and Jung, 2000), though the relationship was insignificant (r ~0.1) before the mid-1970s (Hilmer and Jung, 2000). Deser *et al.* (2000) analysed a 40-year gridded dataset (1958-97) to determine the association between arctic sea ice, SAT and SLP, concluding that the multi-decadal 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 ~ 0.63) with the NAO index, recently cause-and-effect modelled by Hu *et al.* (2002). Nonetheless, our calculations and those of Deser *et al.* (2000) indicate that, even in recent decades, only ~1/3 of the variability in arctic total ice extent and multi-year 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.

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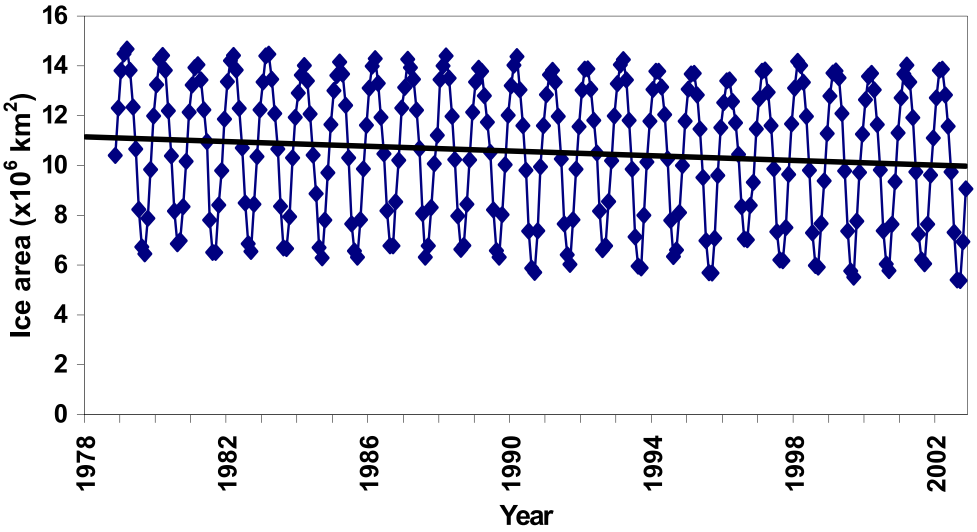
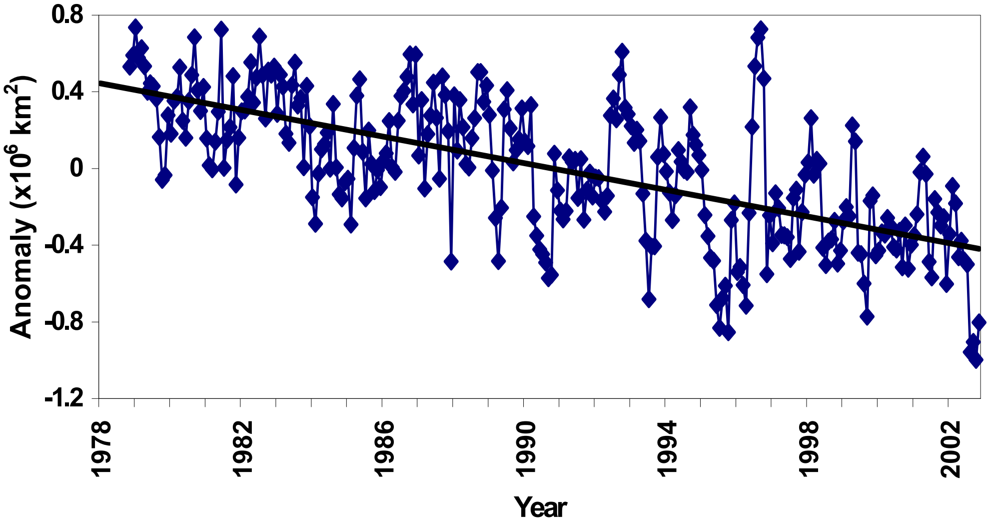


(a)



(b)

Figure 3. Monthly total sea-ice area (the area within the ice-ocean margin minus open water area) for the Northern Hemisphere, 1978-2002, as retrieved from satellite remote-sensing data. (a) Total ice area, indicating that the predominant variability is the seasonal cycle; (b) Anomalies or departures from the mean and seasonal cycle, with the linear trend (~3.4 x 10^4 yr^{-1}) for 1978-2002 superposed. The largest negative anomaly is found in the most recent data, with record-low ice cover in September 2002.

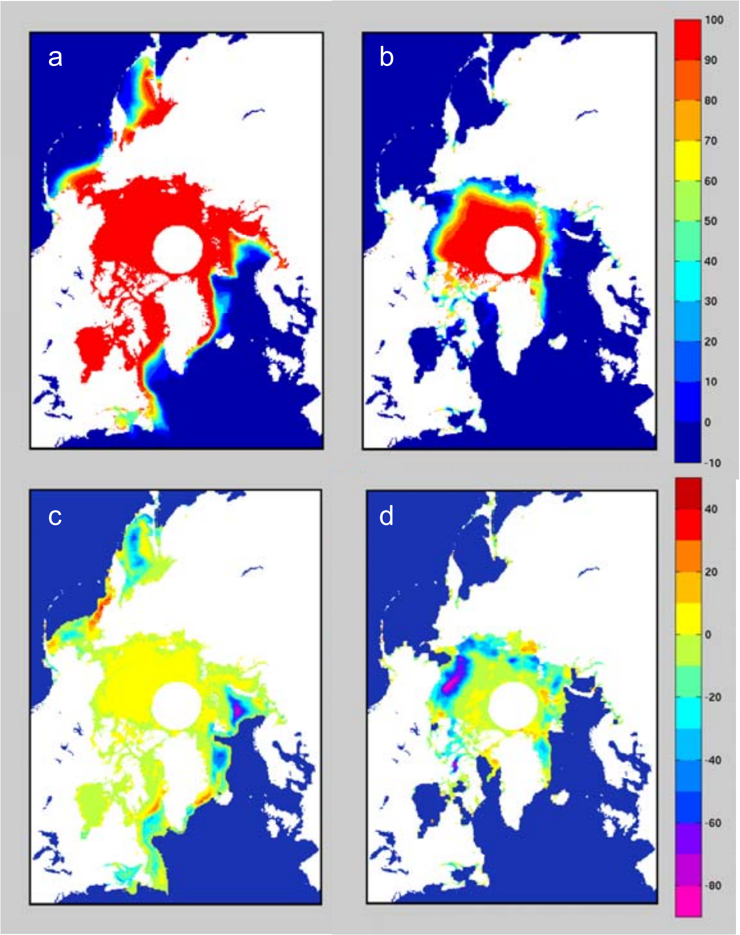


Figure 4. Satellite-retrieved sea-ice concentration (percent ice area per image pixel) in winter (March) and summer (September) for the Northern Hemisphere, 1978-2002: Mean ice concentration for (a) winter and (b) summer, and the linear trends (% change from 1978-2002) for (c) winter and (d) summer.

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 20th century warm period – at least in the two most widely-used century-long sea-ice datasets (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" dataset (Zakharov, 1997; Alekseev *et al.*, 2000), which includes hitherto under-recognised Russian data. The dataset comprises sea-ice extent (regardless of ice concentration within the ice–ocean margin) for ~77% (11.3×10^6 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 areas covered with sea ice 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 ice area average in the region (Y_1) based on its mean value in April-August (X_1): $Y_1 = 0.89X_1 + 100$. 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 RMS error of reconstruction. The error was equal to $s = \pm 52 \times 10^3$ km^2. At the RMS deviation of the initial actual series $\sigma = \pm 154 \times 10^3$ 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.

In the Siberian sector (Kara, Laptev, and East Siberian seas), data on the ice edge are available for August from the mid-1920s. 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 recognized high since 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 exception) 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: $Y_2 = 0.528X_2 + 1065$ was derived, where Y_2 is the mean sea ice extent in the Siberian seas in June-October, X_2 is the ice extent in the Siberian seas in August. The correlation between X_2 and Y_2 is r ~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.

Fig. 5 shows time series of annual sea-ice extent based on these data and annual sea-ice extent from the standard “Walsh” dataset (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 (~ 0.6×10^6 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

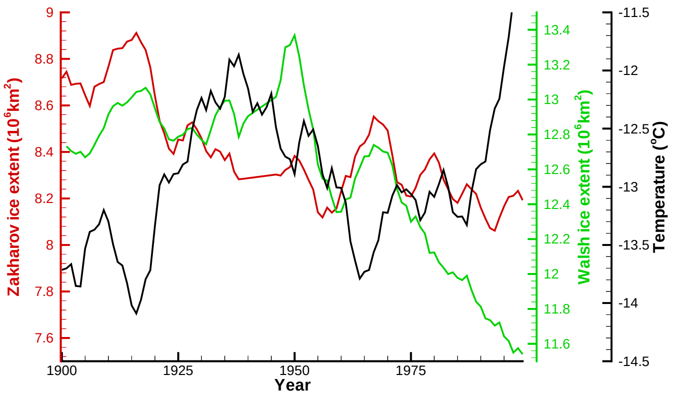


Figure 5. Annual sea-ice extent (area within the ice–ocean margin) derived from a new "Zakharov" sea-ice dataset (red), Northern Hemisphere sea-ice extent from the widely used "Walsh" dataset (green) and zonal (70-90°N) mean annual surface air temperature (SAT) (black) since 1900. The time series shown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

years are due to relatively large reductions in the Beaufort Sea and Chukchi seas (Fig. 4) – areas not included in the Zakharov dataset. The correlations between the SAT and the Zakharov and Walsh sea-ice extents are maximum at 0 lag, r~0.6 and ~0.3, respectively. This indicates (using the Zakharov data set) that the interannual variability in the arctic sea-ice extent in the last century was partially coupled to the high-latitude SAT variability, though the r-value may also reflect feedback processes from the ice cover to the atmosphere, e.g., ECHAM4-model sensitivity experiments (see Bengtsson et al., 2003)[*] 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 spatio-temporal sampling deficiencies in data from submarines carrying upward-looking sonar (Wadhams, 1997). A recent 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 m to 1.8 m. The 1.3-m decrease – if representative – corresponds to an ~40% reduction over the 3-4 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.*, 2000). An analysis of submarine (Rothrock *et al.*, 1999) and modelled (Holloway and Sau, 2002) ice thickness over the same common time period has demonstrated that ice motion and high interannual variability can mislead inference of trends from sonar

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transect data– e.g., 12% (Holloway and Sau, 2002) vs. the 40% decrease reported by Rothrock *et al.* (1999). Thus, the available sonar data remain inadequate to produce a reliable climatology of arctic ice thickness variability.

Here, for the first time, we put forth a unique 20-year time series of monthly, area-averaged ice thickness derived from field-based measurements of surface elastic-gravity waves from Russian North Polar drifting stations 1970-90, when regular measurements of ice surface vibrations were made in the central Arctic Ocean (Nagurnyi *et al.*, 1994). Long elastic-gravity waves (200 to 500 m) 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 and 1999). The values compare well to those observed in the regional ice cover (Romanov, 1993) 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, multi-year 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-year time series of area-averaged ice thickness, 1970-90, from which trends for winter and summer are derived (Fig. 6b). The mean thickness estimates are ~2.9-3m in winter and ~2.5-2.6 in summer (i.e., seasonal cycle ~ 40 cm). The linear trend of anomalies from 1970-90 indicates a decrease of only ~10 cm (less than 4%) over 20 years. 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. Nonetheless, 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 years of ice-thickness data are not inconsistent with the modelled results 1970-90, and (2) substantial decreases in modelled ice thickness commence only in the last two decades of the 20th century. The ice thickness from both observations and models is presently ~2.5-3 m in summer, whereas our model results indicate less than 1m at the end of this century for the remaining ice cover.

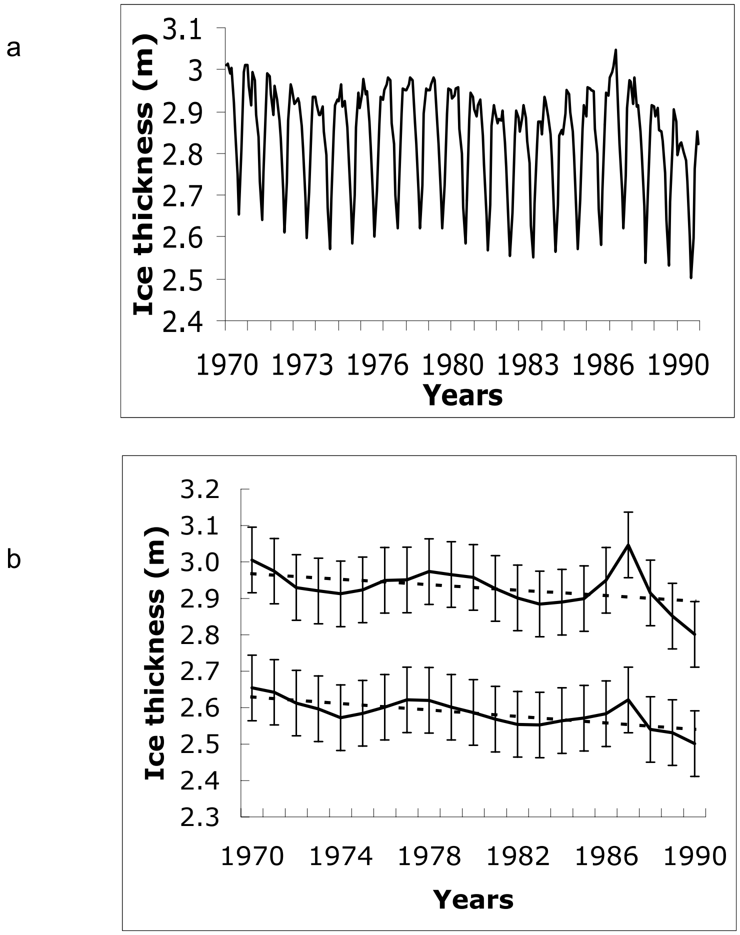

Figure 6. Arctic sea-ice thickness variability from 1970-1990. (a) Monthly area-averaged thickness estimates as derived from surface-based measurements of ice surface vibrations made from Russian North Pole drifting stations in the perennial ice pack of the Arctic Ocean (Nagurnyi *et al.*, 1994 and 1999). (b) Interannual variability and trends for winter (April, upper curve) and summer (August, lower curve), with errors bars denoting the 95% confidence interval. Decadal-scale variability is evident as well as a negative trend (dashed line).

4. Sea Ice Extent – Modeled

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 ECHAM4 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 20th century are similar (Fig 7). Our ECHAM4-model run using IPCC92 IS92 emission scenarios predicts the decreases to continue such that the summer ice cover may be reduced by ~80% at the end of the 21st century (Fig. 7, 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).

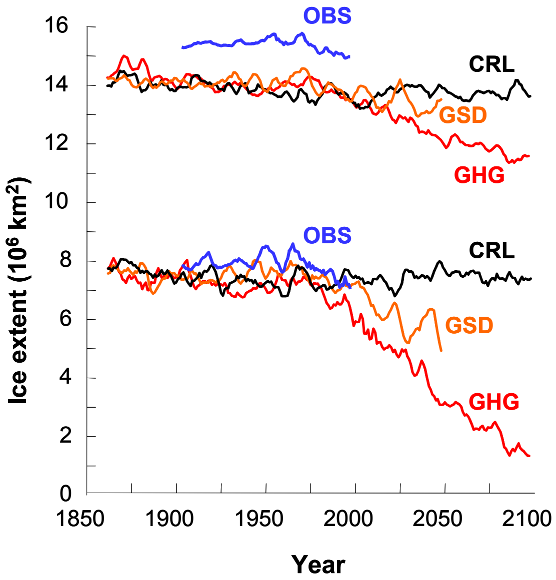

Figure 7. Observed and ECHAM4-modelled Northern Hemisphere sea-ice extent in late winter (March) and late summer (September), 1860-2100 – upper and lower, respectively. The observational data (OBS) from 1901-98 are from the “Walsh” dataset. The modelled scenarios include a control run (CRL), changes in greenhouse gases (GHG) and greenhouse gases 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 freezing in the peripheral seas and bays outside the model domain.

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-ice-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 scenarios from the IPCC Special Report on Emissions Scenarios (SRES) – 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 (Fig. 9a and b) and summer (Fig. 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 distribution of the

HadCM3 and ECHAM4 modelled summer ice cover in late century (Fig. 8d and 9d) indicates essentially ice-free arctic marginal seas except north of Greenland and the Canadian Arctic Archipelago, though there are some differences in the spatial patterns.

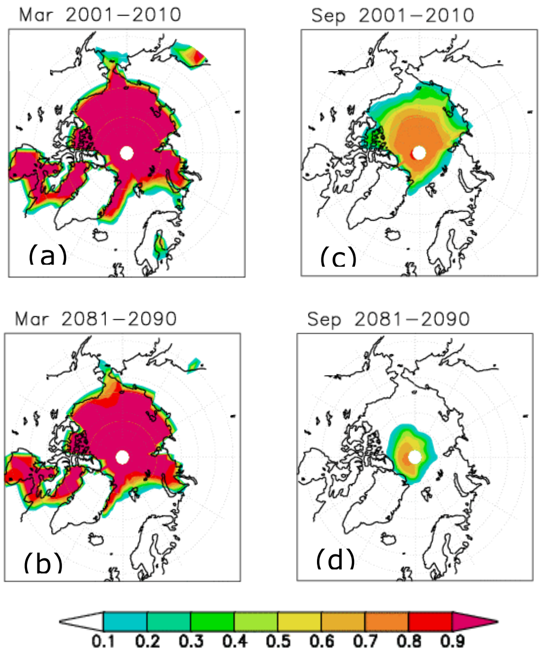

Figure 8. ECHAM4-modelled Northern Hemisphere sea-ice concentration in late winter (March) from (a) 2001-2010 and (b) 2081-2090, and in late summer (September) from (c) 2001-2010 and (d) 2081-2090.

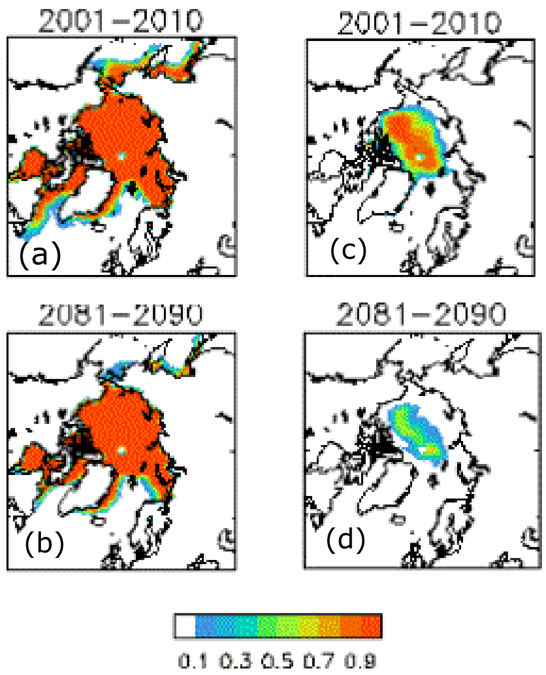

Figure 9. HadCm3-modelled Northern Hemisphere sea-ice concentration in late winter (March) from (a) 2001-2010 and (b) and 2081-2090, and in late summer (September) from (c) 2001-2010 and (d) 2081-2090.

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. Second, we believe there are strong indications that neither the warming trend nor the decrease of the ice extent and volume over the last two decades can be explained by natural processes alone. Third, 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.

A range of potential consequences of arctic warming and a shrinking ice cover can be hypothesised: (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_2 absorption, could become a new and important sink of atmospheric CO_2 (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 deepwater formation in the Greenland Sea on the global thermohaline circulation (Rahmsdorf, 1999; Alekseev *et al.*, 2001), thereby greatly altering the climate of the northern latitudes.

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