Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM

J. M. Gregory, P. A. Stott, D. J. Cresswell, N. A. Rayner, C. Gordon, and D. M. H. Sexton
Hadley Centre for Climate Prediction and Research, Met Office, Bracknell, UK

Received 16 December 2001; accepted 18 March 2002; published 21 December 2002.

[1] The HadCM3 AOGCM has been used to undertake an ensemble of four integrations from 1860 to 1999 with forcings due to all major anthropogenic and natural climate factors. The simulated decreasing trend in average Arctic sea ice extent for 1970–1999 (−2.5% per decade) is very similar to observations. HadCM3 indicates that internal variability and natural forcings (solar and volcanic) of the climate system are very unlikely by themselves to have caused a trend of this size. The simulated decreasing trend in Arctic sea ice volume (−3.4% per decade for 1961–1998) is less than some recent observationally based estimates. Extending the integrations into the 21st century, Arctic sea ice area and volume continue to decline. Area decreases linearly as global-average temperature rises (by 13% per K), and volume diminishes more rapidly than area. By the end of the century, in some scenarios, the Arctic is ice-free in late summer. *INDEX TERMS:* 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 1635 Global Change: Oceans (4203); 4255 Oceanography: General: Numerical modeling. **Citation:** Gregory, J. M., P. A. Stott, D. J. Cresswell, N. A. Rayner, C. Gordon, and D. M. H. Sexton, Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM, *Geophys. Res. Lett.*, *29*(24), 2175, doi:10.1029/2001GL014575, 2002.

1. Introduction

[2] Reduction of Arctic sea ice area and thickness is predicted by climate models in response to the warming associated with increasing atmospheric concentrations of greenhouse gases. The reduction leads to an enhanced climate warming at high latitudes during the winter, since sea ice insulates the ocean from heat loss. Because sea ice has a higher albedo than the sea surface, reduction of sea ice area gives a positive feedback on global and regional climate change.

[3] In this letter we compare the Arctic sea ice changes simulated by the HadCM3 atmosphere–ocean general circulation model (AOGCM) [*Gordon et al.*, 2000] with observations for the 20th century and with other model results, and we examine its projections for the 21st century. We have undertaken an ensemble of four integrations with HadCM3 including all major anthropogenic and natural climate forcings from 1860 to 1999. These simulations reproduce the large-scale features of 20th-century temperature change [*Stott et al.*, 2000]. We have continued the simulations to 2100 [*Johns et al.*, 2001] following four illustrative scenarios from the IPCC Special Report on Emission Scenarios (SRES) [*Nakićenović et al.*, 2000].

[4] To assess the statistical significance of changes we use the HadCM3 control run, a simulation with a constant atmospheric composition corresponding to the late 19th century. There are no significant trends in sea ice in the HadCM3 control run [*Gordon et al.*, 2000]. We also refer to an ensemble of four integrations with natural forcings only (solar and volcanic) for 1860–1999, omitting anthropogenic changes.

2. Recent Changes in Extent

[5] Until the 1960s, Arctic sea ice extent was relatively stable, but in recent decades there has been a marked decline. We compare the HadCM3 simulations with HadISST1 [*Rayner et al.*, in preparation], a new integrated dataset of sea ice and sea surface temperature, which amalgamates several hemispheric and global-scale chart and passive-microwave derived sea ice datasets. Monthly Arctic sea ice data are available throughout the century except during 1940–1952. Monthly Antarctic sea ice data are available from 1973. A climatology is used when monthly data are unavailable.

[6] The sea ice extent is defined as the area within which the concentration of sea ice is greater than 15%. From observations, the extent can be more reliably evaluated than the total area, since it does not depend on accurately knowing the ice concentration throughout the area of pack-ice. We calculate sea ice extent from the seasonal-mean concentration fields of HadISST1 and HadCM3, and then average them to obtain annual means.

[7] For 1970–1999 HadISST1 shows a reduction in Arctic sea ice extent of 2.5% per decade (Figure 1a, Table 1). This trend is not consistent with internal variability, as simulated by HadCM3, since it is more negative than the lower 5-percentile of the distribution of 30-year trends estimated from the control run. *Vinnikov et al.* [1999] drew similar conclusions from the GFDL and HadCM2 climate models. For practical reasons *Vinnikov et al.* [1999] derived ice extent from ice thickness, rather than from ice concentration. We note that the size of discrepancy shown in their results between HadCM2 and observations is somewhat sensitive to the choice of thickness threshold.

[8] The evolution of Arctic sea ice extent over the last 100 years simulated by HadCM3 agrees closely with that observed by HadISST1 (Figure 1a, Table 1). Differences between model and observations are very small, and consistent with internal variability estimated by the control simulation. The HadCM3 natural-forcings ensemble does not show a significant decline in Arctic sea ice over the last

Published in 2002 by the American Geophysical Union.

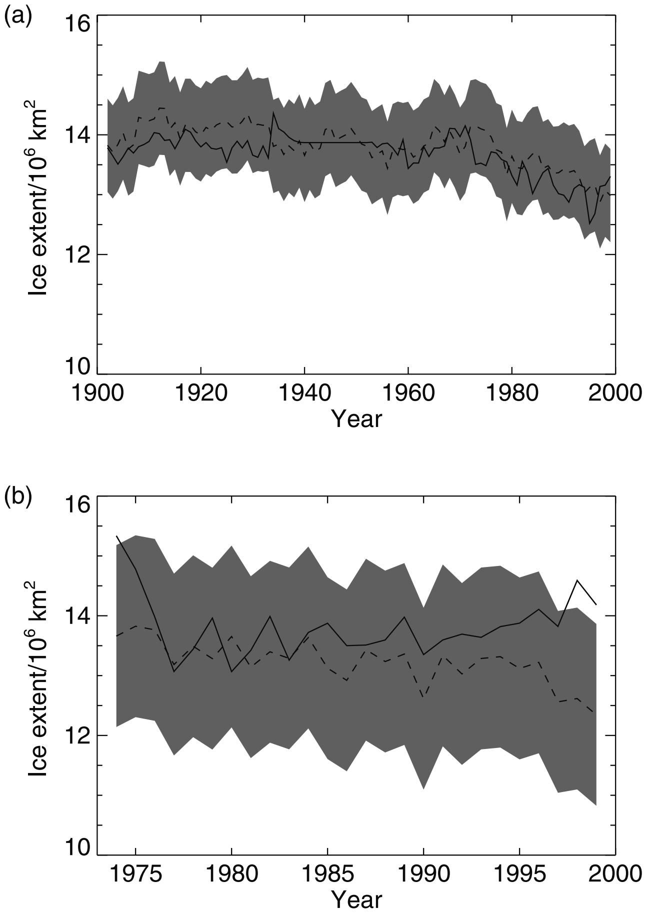

Figure 1. Observed (solid) and simulated (dashed) sea ice extent changes in recent decades: (a) Arctic; (b) Antarctic. (See section 5 summary for discussion of the Antarctic.) For 1940–1952 a climatology was used for the observed Arctic extent. On the basis of internal variability simulated by the control run, 90% of observed values should fall within the shaded region if the model ensemble mean gives an accurate indication of changes due to anthropogenic and natural forcings.

30 years, implying an anthropogenic rather than a natural cause for the observed trend (Table 1).

[9] The strongest decrease in ice extent is observed in summer and the weakest in winter. In HadCM3, the seasonal variation of trends is less pronounced, but the simulated climatological cycle of extent has too large an amplitude. [see, *Gordon et al.*, 2000, for further details.] As such discrepancies may be related to the simulation of summer melting, we are currently comparing simulated changes in the melting season with observations, following *Smith* [1998].

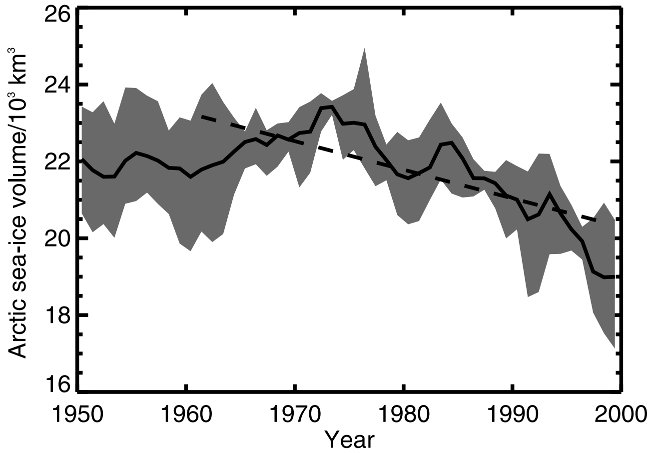

Figure 2. Simulated sea ice volume changes in recent decades. The solid line is the ensemble mean, and the dashed line is a least-squares linear fit to it. The shaded region delimits the envelope of the four ensemble members.

3. Recent Changes in Thickness

[10] In concert with the reduction in extent, Arctic sea ice volume declines in the recent decades of the simulations (Figure 2). Sea ice volume changes are relatively poorly known from observations, since thickness data derive principally from submarine sonar measurements, which do not have the coverage of the remotely sensed concentration data. *Rothrock et al.* [1999] calculated a reduction of roughly 40% in volume over the last two to four decades, affecting all sampled regions of the Arctic. *Tucker et al.* [2001] demonstrated a reduction in ice thickness for the western Arctic between the mid-1980s and early 1990s, attributing this to circulation changes. *Winsor* [2001] found no evidence of thinning during the 1990s alone.

[11] Various workers have undertaken integrations of dynamic–thermodynamic sea ice models over recent decades with surface boundary conditions taken from NCEP reanalyses. *Hilmer and Lemke* [2000] obtained a statistically significant simulated volume trend of −4% per decade for 1961–1998. *Lisaeter et al.* [in press] reported a simulated area-average trend in multiyear ice thickness for 1958–1998 of about half the size of that estimated by *Rothrock et al.* [1999], while at the same time demonstrating a high

Table 1. Sea Ice Extent and Volume in Recent Decades, as Observed and Simulated

	Arctic extent 1970–1999		Arctic volume 1961–1998		Antarctic extent 1974–1999	
	Trend	Average	Trend	Average	Trend	Average
HadISST1	−0.33[a]	13.3	—	—	0.0	13.8
Hilmer and Lemke [2000]	—	—	−4	30	—	—
HadCM3 all-forcings	−0.34 ± 0.07[a,b]	13.4	−3.4 ± 0.8[b]	23	−0.35 ± 0.07[b]	13.1
HadCM3 natural	−0.05	—	—	—	—	—
HadCM3 control 5-percentile	−0.28	—	−2.8	—	−0.30	—

We include all Northern Hemisphere sea ice in HadISST1 and HadCM3 figures for the Arctic.
Extent trend is in 10^6 km^2 per decade, average extent in 10^6 km^2, volume trend in % per decade, average volume in 10^3 km^3.
[a]The HadISST1 Arctic ice extent trend is equivalent to −2.5% per decade and the HadCM3 to (−2.5 ± 0.5)% per decade.
[b]The uncertainty is the standard error based on the variance of trends within the ensemble.

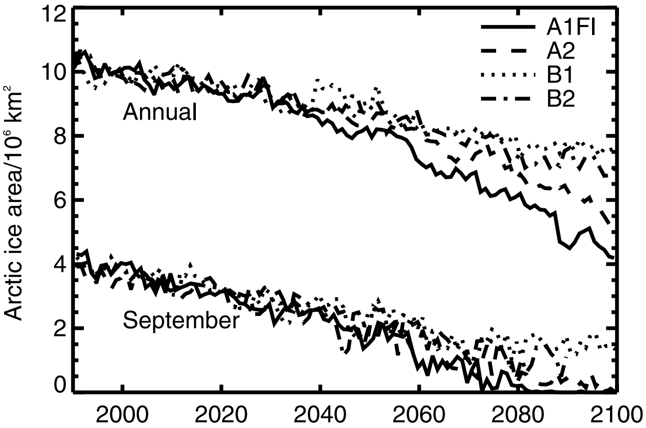

Figure 3. Simulated Arctic sea ice area in four illustrative SRES scenarios.

level of agreement with thickness measured along a number of submarine tracks in the 1980s and 1990s. *Holloway and Sou* [2002] found a simulated volume reduction over 1948–1999 of 45% when sampled at the submarine locations of *Rothrock et al.* [1999], but only 12% for the entire Arctic. These model studies suggest that the result of *Rothrock et al.* [1999] may have been enhanced by decadal variability, which can have a substantial influence on regional trends [*Zhang et al.*, 2000].

[12] For 1961–1998, the HadCM3 ensemble-mean trend in Arctic ice volume (Figure 2) is about −3.4% per decade, in statistical agreement with the result of *Hilmer and Lemke* [2000]. This trend is more negative than the lower 5-percentile of trends over periods of similar length from the control run, and is therefore inconsistent with simulated internal variability (Table 1).

[13] The annual standard deviation of ice volume in the HadCM3 all-forcings ensemble is 6% of the long-term average ice volume, in agreement with the simulation of *Hilmer and Lemke* [2000]. The natural-forcings ensemble does not show any significant trend in ice volume over 1961–1998. However, comparing the ice volume fluctuations with the negative radiative forcing associated with volcanic stratospheric aerosols suggests that the ice volume may increase during the years following major eruptions, as a result of the cooling they produce. In recent decades the strongest forcings resulted from Agung in 1963, Fernandina in 1968, El Chichón in 1982 and Pinatubo in 1991. A statistical test (see Appendix) confirms that there is likely to be a significant signal of the natural forcings in the ensemble-mean ice volume.

4. Projected Future Changes

[14] During the 21st century, Arctic sea ice continues to decline in all four SRES scenarios considered (A1FI, A2, B1 and B2), as the temperature continues to rise (Figure 3). The results for the four scenarios do not diverge significantly until around 2040, but they show a considerable spread by the end of the century. The global average temperature difference between the 1990s and the 2090s ranges from 1.9 K in B1 to 4.2 K in A1FI, which is in all cases much larger than the rise over the last century of 0.6 ± 0.2 K [*Folland et al.*, 2001]. (These two illustrative scenarios bracket almost the entire range of the SRES scenarios in temperature change by 2100.) The reduction in annual-average Arctic sea ice area is correspondingly great, being in the range of 20–50%, the lower bound implying a loss at about the current rate. For the future we use sea ice area (the area-integral of the concentration) rather than extent because the area relates more directly to the concentration fields simulated by the model and is therefore more informative and convenient.

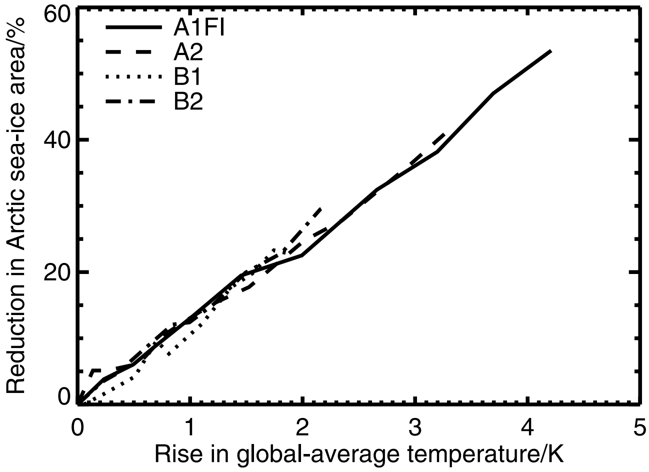

Figure 4. Relationship between simulated Arctic sea ice area and global-average surface air temperature changes with respect to 1990 in four illustrative SRES scenarios.

[15] Arctic sea ice reacts to climate change on the timescale of a few years, because much of the ice is renewed each year. Hence over decadal timescales the sea ice evolves along with the climate, not depending on its previous history. This leads to the appearance of a well-defined relationship between Arctic sea ice area reduction and global-average temperature rise (Figure 4), independent of climate scenario. The relationship is linear, with a slope of 13% K^{-1}.

[16] As in recent decades, the proportional reduction in Arctic sea ice volume is greater than in area. The relationship between them is also independent of scenario, but it is not linear (Figure 5). To begin with, the volume reduction is

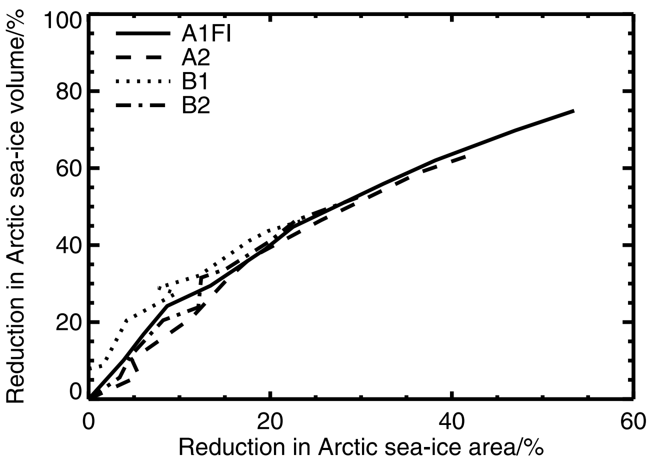

Figure 5. Relationship between simulated Arctic sea ice area and volume changes with respect to 1990 in four illustrative SRES scenarios.

about twice as great (for instance, a 40% reduction in volume accompanies 20% in area). For larger reductions in area, the volume loss is not so great. The relationship which emerges in HadCM3 between area and volume change must depend on the assumptions concerning the thickness PDF made in the sea ice thermodynamics model. Further investigation into the model sensitivity to these assumptions is warranted.

[17] The greatest proportional loss of thickness is in autumn, the least in spring. In scenario A1FI, which has the greatest warming, there is practically no Arctic sea ice by the end of the summer in the climate of 2070–2100 (Figure 3).

5. Summary and Discussion

[18] In common with other AOGCMs, HadCM3 employs rather unsophisticated sea ice schemes, and since it does not use flux adjustment its simulated climate has some biases [*Gordon et al.*, 2000]. Nonetheless, the decline in Arctic sea ice extent simulated by HadCM3 for recent decades (2.5% per decade) is very close to the observed trend. HadCM3 is also consistent with other model results in showing a somewhat greater reduction in Arctic sea ice volume (3.4% per decade). The latter is a quantity which is much less readily observable at present, and estimates based on submarine data are not in agreement over the size of the trend. The possible future use of satellite altimetry to estimate sea ice thickness is therefore particularly welcome. The simulated trends in extent and volume are too large to be attributed to internal or naturally forced variability as simulated by the model.

[19] HadCM3 exhibits a significant decline in Antarctic sea ice extent (Figure 1b) during recent decades, consistent with increasing temperatures in areas where the ice edge is retreating in the model, but HadISST1 shows no overall change since comprehensive Antarctic measurements began in 1973 (Table 1). The time-average of the HadCM3 Antarctic ice extent is nonetheless similar to the observed (Table 1), as is its seasonal cycle [see *Gordon et al.*, 2000], suggesting that the disagreement over the trend may be due to an unrealistic simulation of regional warming in the Southern Ocean around Antarctica rather than to a particular deficiency in the ice model. The reasons need to be investigated; unfortunately evaluation and improvement of AOGCM simulations for the Southern Ocean are hampered by a scarcity of data.

[20] Our projections for the 21st century indicate that Arctic sea ice area and volume will continue to decline as temperature rises, with the volume decreasing more rapidly. Continued monitoring of sea ice area and thickness will be valuable, sea ice being a sensitive indicator of climate change. Deficiencies in the seasonal cycle and in the geographical distribution of sea ice changes simulated by HadCM3 will probably have an effect on the reliability of the projections. More detailed studies are needed of the processes of past and future sea ice change and the causes of systematic errors in the simulation, with the aim of improving the AOGCM.

Appendix

[21] To test for a significant signal from the natural forcings, we use a bootstrap method. First, from annual means for 1978–1997 in the natural-forcings ensemble we calculate the ratio of the temporal variance of the ensemble-mean ice volume to the average intra-ensemble variance. This F-ratio will be large when the natural externally forced variability (solar and volcanic) is large compared with the internally generated variability of the climate system. We then construct 1000 "pseudo-ensembles" from the control run, each ensemble consisting of four randomly chosen 20-year segments of the run. Since the pseudo-ensemble members are independent, we do not expect them to show any coherence. From the pseudo-ensembles we can construct a sampling distribution for the F-ratio, and conclude that in the natural ensemble the ratio is larger than expected by chance at the 5% level of significance (one-tailed).

[22] **Acknowledgments.** We are grateful to John Mitchell, Geoff Jenkins, David Parker, Howard Cattle, Kostya Vinnikov, Greg Flato and an anonymous reviewer for helpful comments, and to Steven Hill and Jason Lowe for assistance with data processing. This work was supported by the UK Department of the Environment, Food and Rural Affairs under contract PECD 7/12/37 and by the Government Meteorological Research contract.

References

Folland, C. K., et al., Observed climate variability and change, in *Climate change 2001: The scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C. I. Johnson, Cambridge University Press, 2001.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, *16*, 147–168, 2000.

Hilmer, M., and P. Lemke, On the decrease of Arctic sea ice volume, *Geophys. Res. Let.*, *27*, 3751–3754, 2000.

Holloway, G., and T. Sou, Has Arctic sea ice rapidly thinned?, *J. Clim.*, *15*, 1691–1701, 2002.

Johns, T. C., et al., Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, *HCTN 22*, available from the Hadley Centre, 2001.

Lisæter, K. A., O. M. Johannessen, H. Drange, G. Evensen, and S. Sandven, Comparison of modeled and observed sea ice concentration and thickness fields in the Arctic, *J. Geophys. Res.*, in press.

Nakićenović, N., et al., Special report on emissions scenarios, 599 pp., Cambridge, 2000.

Rayner, N. A., D. E. Parker, C. K. Folland, E. B. Horton, L. V. Alexander, and D. P. Rowell, Globally complete analyses of SST, sea ice and night marine air temperature, 1871–2000, in preparation.

Rothrock, D. A., Y. Yu, and G. A. Maykut, Thinning of the Arctic sea-ice cover, *Geophys. Res. Let.*, *26*, 3469–3472, 1999.

Smith, D. M., Recent increase in the length of the melt season of perennial Arctic sea ice, *Geophys. Res. Let.*, *25*, 655–658, 1998.

Stott, P. A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins, External control of 20th century temperature by natural and anthropogenic forcings, *Science*, *290*, 2133–2137, 2000.

Tucker, W. B., J. W. Weatherly, D. Eppler, L. D. Farmer, and D. L. Bentley, Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s, *Geophys. Res. Let*, *28*, 2851–2854, 2001.

Vinnikov, K. Y., A. Robock, R. J. Stouffer, J. E. Walsh, C. L. Parkinson, D. J. Cavalieri, J. F. B. Mitchell, D. Garrett, and V. F. Zakharov, Global warming and Northern Hemisphere sea ice extent, *Science*, *286*, 1934–1937, 1999.

Winsor, P., Arctic sea ice thickness remained constant during the 1990s, *Geophys. Res. Let.*, *28*, 1039–1041, 2001.

Zhang, J. L., D. Rothrock, and M. Steele, Recent changes in Arctic sea ice: The interplay between ice dynamics and thermodynamics, *J. Clim.*, *13*, 3099–3114, 2000.

J. M. Gregory, P. A. Stott, N. A. Rayner, C. Gordon, and D. M. H. Sexton, Hadley Centre for Climate Prediction and Research, Met Office, London Road, Bracknell, Berkshire, RG12 2SY, UK. (jonathan.gregory@metoffice.com)

D. J. Cresswell, Centre for Polar Observation and Modelling, Department of Space and Climate Physics, University College London, Gower Street, London, WC1E 6BT, UK.