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Evaluation of the simulation of the annual cycle of Arctic and Antarctic sea ice coverages by 11 major global climate models

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[1] Comparison of polar sea ice results from 11 major global climate models (GCMs) and satellite-derived observations for 1979–2004 reveals that each of the models is simulating annual cycles that are phased at least approximately correctly in both hemispheres. Each is also simulating various key aspects of the observed ice cover distributions, such as winter ice not only throughout the central Arctic basin but also throughout Hudson Bay, despite its relatively low latitudes. However, some of the models simulate too much ice, others simulate too little ice (in some cases depending on hemisphere and/or season), and some match the observations better in one season versus another. Several models do noticeably better in the Northern Hemisphere than in the Southern Hemisphere, and one does noticeably better in the Southern Hemisphere. In the Northern Hemisphere all simulate monthly average ice extents to within $\pm 5.1 \times 10^6$ km^2 of the observed ice extent throughout the year; in the Southern Hemisphere all except one simulate the monthly averages to within $\pm 6.3 \times 10^6$ km^2 of the observed values. All the models properly simulate a lack of winter ice to the west of Norway; however, most obtain more ice immediately north of Norway than the observations show, suggesting an under simulation of the North Atlantic Current. The spread in monthly averaged ice extents among the 11 model simulations is greater in the Southern Hemisphere than in the Northern Hemisphere and greatest in the Southern Hemisphere winter and spring.

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1. Introduction

[2] Considerable attention has been drawn to the difficulties that models have in simulating the polar regions [e.g., *Serreze et al.*, 2000; *Proshutinsky et al.*, 2001; *Walsh et al.*, 2002]. In addition to numerical complications when the pole is treated as a singularity, these regions (Figure 1) also have the complication of having a variable, ever-changing sea ice cover spreading over much of the ocean area. This ice cover restricts exchanges of heat, mass, and momentum between the ocean and atmosphere, strongly reflects incoming solar radiation, provides a net transport of relatively fresh and cold water equatorward, and affects the salinity and density structure of the underlying ocean [e.g., *Gordon and Taylor*, 1975; *Aagaard and Carmack*, 1989; *Barry et al.*, 1993; *Parkinson*, 2004]. Because of the strong coupling between sea ice and the rest of the climate system, errors in the simulation of the sea ice cover will be propagated to errors in the simulated atmosphere and ocean as well.

[3] In this paper we examine how well 11 major global climate models (GCMs) are simulating the current sea ice covers of the two hemispheres, using as our comparative data set the observed sea ice coverages derived from satellite passive-microwave data. Specifically, we examine (1) the spatial distributions of the sea ice covers in March and September and (2) the monthly average sea ice extents throughout the annual cycle, in each case averaging for the 26-year period 1979–2004. The aim of the paper is to show how well the models are doing, including strengths and weaknesses, not to detail the underlying causes of the model differences.

2. Data and Methodology

[4] Simulation results were obtained from the following web site of the Intergovernmental Panel on Climate Change (IPCC): https://esg.llnl.gov:8443/home/publicHomePage.do. These results have been provided by the respective modeling groups for the ongoing evaluations for the IPCC Fourth Assessment Report, updating the earlier IPCC Third Assessment Report [*Houghton et al.*, 2001]. We selected all models with available output files for both sea ice concentration and sea ice thickness, although use only one run,

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"run1," for each of the models. These models are listed and briefly described in section 3. In each case we use the twentieth century simulation (20C3M) run 1 for the years 1979 through the end of the 20C3M run 1 (i.e., through 1999 or 2000, depending on the model) and its continuation, run 1 of "future climate simulations: scenario SRES A2", for the remaining years through 2004. Each of the 11 models incorporates greenhouse gases and the direct effects of sulfate aerosols in its twentieth century forcings. Some of the models also include additional forcings, as enumerated by *Santer et al.* [2005].

[5] The observational data used to compare with the model results come from the data of the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus 7 satellite and the Special Sensor Microwave Imagers (SSMIs) on the Defense Meteorological Satellite Program (DMSP) F8, F11, and F13 satellites. Details on the satellite data sets, their coregistration, and their use in Arctic and Antarctic sea ice studies can be found in the work of *Cavalieri et al.* [1999], *Parkinson et al.* [1999], and *Zwally et al.* [2002]. The SMMR data were collected on an every other day basis for most of the period November 1978 to August 1987, and the SSMI data have been collected on a daily basis for most of the period since the June 1987 launch of the first SSMI, on the DMSP F8. In this paper, we use the SMMR data for January 1979 to August 1987 and the SSMI data for August 1987 to December 2004.

[6] As in the work of *Parkinson et al.* [1999], *Zwally et al.* [2002], and others, ice extent is calculated from the satellite data as the sum of the areas of all grid cells having an ice concentration (percent areal coverage of ice) of at least 15%. For the models, we use the criteria that the ice concentration must be at least 15% and the ice thickness must be at least 6 cm, as the satellite instrument does not sense the extremely thin ice. The 26-year average ice extent, for each month, is calculated by averaging the 26 individual-year ice extents determined for that month. In addition to ice extents, our results (section 4) include maps of the average March and September ice distributions over the 26-year period. Using the 15% ice concentration and 6 cm ice thickness criteria in the individual years, for both March and September averages, we map a pixel as containing ice in the 26-year average March (or September) if and only if that pixel contains ice in at least half the Marches (or Septembers).

3. The Models

[7] The 11 GCMs employed in this study and their IPCC identifications (IDs) are as follows:

[8] 1. The United Kingdom Met Office (UKMO) Hadley Centre Coupled Model 3 (HadCM3) from the Hadley Centre for Climate Prediction and Research at the UKMO, United Kingdom, is a coupled atmosphere-ocean GCM with 19 vertical layers and a horizontal resolution of 2.5° latitude × 3.75° longitude in the atmosphere and 20 vertical layers and a horizontal resolution of 1.25° latitude × 1.25° longitude in the ocean. The sea ice formulation includes ice thermodynamic calculations, one ice layer in the vertical, and ice advection strictly with the ocean current. The ice calculations are divided between the atmosphere and ocean model components. The model shows little drift in surface climate in a control run of over a thousand years, despite not using flux adjustments. The model is described by *Gordon et al.* [2000] and *Pope et al.* [2000]. IPCC ID: UKMO-HadCM3.

[9] 2. The United Kingdom Met Office (UKMO) Hadley Centre Global Environmental Model version 1 (HadGEM1) from the Hadley Centre for Climate Prediction and Research at the UKMO, United Kingdom, is a new coupled climate model developed at the Hadley Centre starting in 2000 as an eventual replacement for the HadCM3 model, with advances in particular in the sea ice and atmosphere components. It has 38 vertical layers and a horizontal resolution of 1.25° latitude × 1.875° longitude in the atmosphere, while in the ocean it has 40 vertical layers, a zonal resolution of 1°, and a meridional resolution that is 1° poleward of 30° and smoothly varies from 0.333° at the equator to 1° at 30° latitude. The sea ice formulation includes ice thermodynamics, ice dynamics, one ice layer in the vertical, and multiple ice thicknesses allowed in a grid cell. The sea ice calculations in the HadGEM1 model, like those in the HadCM3 model, are divided between the atmosphere and ocean components. The HadGEM1 model is described by *Johns et al.* [2005]. IPCC ID: UKMO-HadGEM1.

[10] 3. The European Centre for Medium-Range Weather Forecasts (ECMWF) Hamburg Model version 5 (ECHAM5) from the Max Planck Institute for Meteorology (MPI), Hamburg, Germany, is a fifth-generation ECHAM model using a spectral, semi-implicit formulation for the atmosphere, with 31 vertical layers, and an ocean with 40 vertical layers and 1.5° latitude × 1.5° longitude horizontal resolution. The sea ice formulation includes ice dynamics, ice thermodynamics, one ice layer in the vertical plus an overlying snow layer, one ice thickness category, and 1.5° latitude × 1.5° longitude horizontal resolution. The sea ice calculations are done within the ocean component. The atmosphere component is described by *Roeckner et al.* [2003], and the ocean component is described by *Marsland et al.* [2003]. IPCC ID: ECHAM5/MPI-OM.

[11] 4. The Canadian Centre for Climate Modelling and Analysis (CCCma) Third Generation Coupled Global Climate Model (CGCM3) from the CCCma, Environment Canada, University of Victoria, Canada, is a third-generation model that has a substantially updated atmosphere component over the second-generation CGCM2, with details available at http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml. Results from two versions of the model, T47 and T63, were provided to the IPCC. We use the results from the lower-resolution T47 version, with 31 vertical layers and a spatial resolution of approximately 3.75° latitude × 3.75° longitude in the atmosphere and 29 vertical layers and a spatial resolution of approximately 1.85° latitude × 1.85° longitude in the ocean. The sea ice formulation includes ice thermodynamics, ice dynamics, and a single ice thickness per grid cell. Details on the model's ocean component can be found in the work of *Kim et al.* [2002]. IPCC ID: CGCM3.1.

[12] 5. The Commonwealth Scientific and Industrial Research Organization (CSIRO) Mark 3.0 model (CSIRO Mk3) from CSIRO, Australia, is a vintage 2001 model with 18 vertical layers and a horizontal resolution of approximately 1.875° latitude × 1.875° longitude in the atmosphere/land/ice component and 31 vertical layers and a horizontal resolution of approximately 0.84° latitude × 1.875° longitude in the ocean component. The sea ice formulation includes ice thermodynamics, ice dynamics, one or two ice layers in the vertical depending on ice thickness, and an overlying snow layer. The sea ice calculations are done as part of the atmosphere component, with the same spatial resolution. The CSIRO Mark 3.0 model is described in detail by *Gordon et al.* [2002]. IPCC ID: CSIRO-Mk3.0.