On the reliability of simulated Arctic sea ice in global climate models

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[1] While most of the global climate models (GCMs) currently being evaluated for the IPCC Fourth Assessment Report simulate present-day Arctic sea ice in reasonably good agreement with observations, the intermodel differences in simulated Arctic cloud cover are large and produce significant differences in downwelling longwave radiation. Using the standard thermodynamic models of sea ice, we find that the GCM-generated spread in longwave radiation produces equilibrium ice thicknesses that range from 1 to more than 10 meters. However, equilibrium ice thickness is an extremely sensitive function of the ice albedo, allowing errors in simulated cloud cover to be compensated by tuning of the ice albedo. This analysis suggests that the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice. **Citation:** Eisenman, I., N. Untersteiner, and J. S. Wettlaufer (2007), On the reliability of simulated Arctic sea ice in global climate models, *Geophys. Res. Lett.*, *34*, L10501, doi:10.1029/2007GL029914.

1. Introduction

[2] Simulations of Earth's climate during the 20th and 21st centuries under several future greenhouse gas emission scenarios have recently been carried out with a selection of coupled global climate models (GCMs) as part of the ongoing evaluations for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). Although intermodel differences in GCMs have typically been greatest in the polar regions [*Houghton et al.*, 2001], most of the models being evaluated for the AR4 have been reported to simulate present-day sea ice extent in reasonable agreement with observations [*Parkinson et al.*, 2006; *Zhang and Walsh*, 2006]. The reliability of simulated Arctic sea ice cover in these GCMs is particularly relevant in light of the observed recent sea ice retreat, which is one of the most significant signals of 20th century climate change.

[3] Coupled GCMs simulate the circulation and thermodynamics of the global atmosphere, ocean, and sea ice. The extreme sensitivity of sea ice to atmospheric and oceanic forcing, and the powerful feedback mechanisms involved, have long been recognized and studied [*Maykut and Untersteiner*, 1971; *Ebert and Curry*, 1993]. However, in light of the emphasis placed on recent GCM simulations, it appears timely and informative to perform systematic sea ice sensitivity calculations with specific emphasis on the Arctic.

[4] Here we consider intermodel differences in simulated Arctic cloud cover, which are large in the AR4 simulations and produce significant differences in downwelling longwave radiation. At the time of this analysis, relevant GCM output fields were available from 16 of the 23 GCMs being evaluated for the IPCC AR4 (Figure 1 legend). Included in the range of simulated fields in the GCMs are the fractional cloud cover and downwelling longwave radiation at each vertical level in the atmosphere. As an indication of the broad intermodel spread in cloudiness, the 1980–1999 mean seasonal cycle in total vertically integrated cloud fraction is plotted for each GCM in Figure 1a. This spread in cloudiness is associated with a 40 Wm^{-2} intermodel range in downwelling longwave radiation incident at the surface (Figure 1b).

[5] We use two standard thermodynamic models of sea ice to calculate the equilibrium ice thickness, and we find that the GCM-generated spread in longwave radiation produces thicknesses that range from 1 to more than 10 meters. However, equilibrium ice thickness is an extremely sensitive function of the ice albedo, thereby allowing errors in simulated cloud cover to be compensated by tuning of the ice albedo. This implies that the simulated cloud cover and associated downwelling radiation in most of the GCMs analyzed here would have caused dramatically unrealistic sea ice thickness. However, adjustments to model parameters such as the ice albedo are sufficient to compensate these errors, thereby leading to unrealistically good simulations of present-day ice conditions.

2. Models

[6] The first model we use is a modified version of the 2-season thermodynamic model of *Thorndike* [1992], which provides an approximate analytical equation for the equilibrium ice thickness. The total energy flux for melting or growing ice is the sum of downward and upward longwave radiation (F_{LW} and F_{UP}), absorbed shortwave radiation ($(1-\alpha) F_{SW}$ with snow/ice albedo α), and the oceanic heat flux at the ice-ocean interface (F_W). We neglect the turbulent surface fluxes of sensible and latent heat, which are well known to be much smaller than the radiative components [*Maykut and Untersteiner*, 1971]. Linearizing the Stefan-Boltzmann law about the bulk freezing temperature, the upward longwave radiation can be written $F_{UP} = A + BT$, where T is the departure of the surface temperature of the ice from the freezing point (e.g., the temperature measured in °C). This leads to a change in thickness during winter or summer of

$$\Delta h = \frac{\tau}{L}[F_{LW} - (A + BT) + (1-\alpha)F_{SW} + F_W] \tag{1}$$

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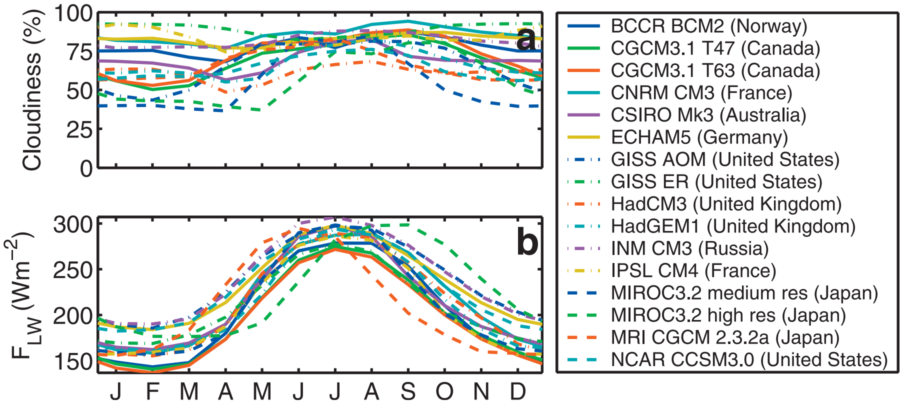

Figure 1. Simulated Arctic (70–90°N area average) 1980–1999 mean seasonal cycle in "Climate of the 20th Century" GCM simulations for the IPCC AR4. (a) Total vertically integrated cloudiness. (b) Downward longwave radiation incident at the surface. Only Run 1 was considered for models with multiple ensemble members available.

where τ is one half year and L is the latent heat of fusion for sea ice. Following *Thorndike* [1992], we represent the seasonal cycle as a step function with melting during one half of the year (in which all the shortwave radiation occurs) and freezing during the other half of the year. During the summer melt season, in which the surface temperature is taken to be at the melting temperature ($T = 0$), we specify the downward longwave radiation to be $F_{LW} = F_{LWs}$ and the shortwave radiation to be $F_{SW} = F_{SWs}$. In the winter freezing season, $F_{LW} = F_{LWw}$, $F_{SW} = F_{SWw} = 0$, and T is found by solving

$$\frac{dT}{dt} = 0 = F_{LWw} - (A + BT) - \frac{kT}{h}, \qquad (2)$$

which is derived by integrating the vertical heat diffusion equation under the quasi-stationary approximation and assuming that T is in steady state with the surface forcing. Setting summer melt $-\Delta h$ equal to winter growth Δh and solving for $h \equiv h_{eq}$ leads to a solution for equilibrium ice thickness,

$$h_{eq} = \frac{k}{B}\left(\frac{-W - S - 2F_W}{S + 2F_W}\right), \qquad (3)$$

with $W \equiv F_{LWw} - A$ and $S \equiv F_{LWs} - A + (1 - \alpha)F_{SWs}$.

[7] This solution (equation 3) can be compared with equation (31) of *Thorndike* [1992]. The principal distinction is that here we specify F_{LW} based on the GCM output (which implicitly contains the contribution from meridional advection of moist static energy), whereas in Thorndike's model F_{LW} is computed as a function of T (which is itself a function of h) using a gray-body radiative balance atmosphere. We use the parameter values $F_{LWw} = 158$ Wm^{-2}, $F_{LWs} = 272$ Wm^{-2}, $F_{SWs} = 200$ Wm^{-2}, $A = 320$ Wm^{-2}, $B = 4.6$ Wm^{-2} K^{-1}, $k = 2$ Wm^{-1} K^{-1}, $F_w = 0$, and $\alpha = 0.65$; this produces the observed equilibrium thickness, $h_{eq} = 2.8$ m [*Thorndike*, 1992]. Note that h_{eq} represents the approximate annual mean thickness at equilibrium since it comes from assuming that the typical winter surface temperature is maintained by a flux of heat upward through the ice of kT/h_{eq}.

[8] The second model used in this study is the more physically complete numerical sea ice thermodynamic model of *Maykut and Untersteiner* [1971], which we run to equilibrium. This single-column model simulates vertical heat diffusion throughout the depth of the snow/sea-ice system with specified surface fluxes based on observations. It produces ice thickness and temperature in good agreement with observations [e.g., *Untersteiner*, 1961; *Wensnahan et al.*, 2007].

3. Discussion

[9] To investigate the effect of the 40 Wm^{-2} intermodel spread in downward longwave radiation simulated in the GCMs (Figure 1b), we add an annually constant term ΔF_{LW} to the standard case longwave radiation in both of the sea ice models. For a ±20 Wm^{-2} range of ΔF_{LW}, we find in both models that equilibrium ice thickness runs from 1 to more than 10 m. This is illustrated in Figure 2. A modification to the *Maykut and Untersteiner* [1971] model suggested by *Bitz and Lipscomb* [1999] leads to equilibrium ice thickness that is slightly more sensitive to longwave radiation (C. Bitz, personal communication, 2007).

[10] Dynamic and thermodynamic forcing gives the present-day thickness of Arctic sea ice a distribution that has been documented by various remote sensing methods, especially submarine upward-looking sonar [*Wensnahan et al.*, 2007]. Most of the ice in the North American sector (longitude 30°W–150°W) has a residence time of at least 5–10 years [*Rigor and Wallace*, 2004] and has therefore reached an equilibrium thickness—where annual ablation balances annual accretion—of approximately 3 m. The range of 1 to 10 meters in Figure 2 constitutes greater than 90% of the observed sea ice thickness distribution [*Wensnahan et al.*, 2007], the thick end of which is dominated by mechanical deformation rather than thermodynamic growth, and hence this spread in ice thickness implied by the intermodel variance in longwave radiation is strikingly large. It should be borne in mind that, at a mean annual thickness of 1 m, the annual minimum thickness will

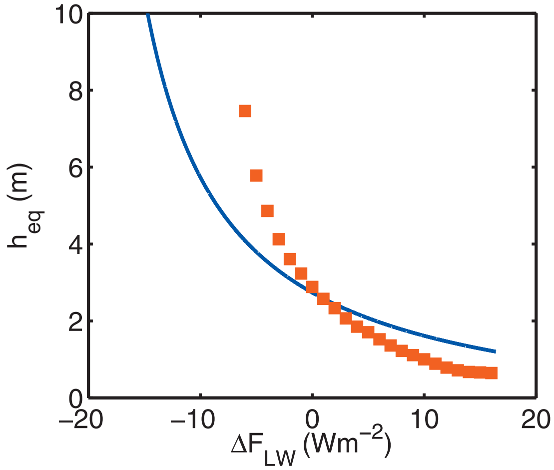

Figure 2. Equilibrium ice thickness (h_{eq}) as a function of downwelling longwave radiation in terms of annually constant departures (ΔF_{LW}) from standard case values. The line represents the solution using the idealized analytical model in equation (3) and the squares indicate 23 simulations with the more complete numerical model of *Maykut and Untersteiner* [1971].

be about 0.5 m. On the approach to that point, the ice will have melted through in many places, causing major changes to the surface albedo and limiting the relevance of these thermodynamic calculations which assume complete ice cover.

[11] The 16 GCMs considered here simulate 1980–1999 mean Northern Hemisphere sea ice extent (area of grid boxes with at least 15% ice cover) ranging among the models from 10.3 to 14.8 × 10^6 km^2 [cf. *Parkinson et al.*, 2006; *Zhang and Walsh*, 2006]. The simulated 1980–1999 mean Arctic (70–90°N area average) ice thickness in the GCMs ranges from 1.0 to 3.9 m. This intermodel spread in ice thickness is far smaller than the 1 to >10 m range which we suggest would be implied by the intermodel spread in longwave radiation. Hence we are forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes? A frequently used approach in GCM sea ice components is to tune the parameters associated with the ice surface albedo.

[12] The equilibrium ice thickness computed using equation (3) as a function of albedo (α) for the same range of downwelling longwave radiation (ΔF_{LW}) is plotted in Figure 3. If the albedo in these GCMs has been tuned by just ±0.1, this would be sufficient to eliminate the enormous differences in ice thickness implied by the spread in downward longwave radiation.

[13] Due to the fact that GCMs use varied albedo parameterizations that typically depend on fields such as ice thickness, snow thickness, surface temperature, and spectral band, a direct intermodal comparison of albedos is presently an unpractical method of assessing the extent to which albedo tuning is compensating the spread in longwave radiation. In multiple resolutions of the same GCM, however, the functional form of the ice albedo is the same and the parameter values are sometimes tuned differently in each resolution to produce observationally reasonable present-day simulation results [e.g., *Yeager et al.*, 2006]. Two of the IPCC AR4 GCMs analyzed here have results available for multiple resolutions (Figure 1 legend). In MIROC3.2, the annual average longwave radiation is 15 Wm^{-2} lower in the medium resolution version than in the high resolution version (Figure 1b). *Hasumi and Emori* [2004] report that MIROC3.2 uses a temperature-dependent albedo of snow-covered sea ice which is 0.05 lower in the medium resolution version than in the high resolution version, in qualitative agreement with the albedo tuning that this analysis suggests would be necessary to compensate for the longwave difference (Figure 3). The T47 and T63 resolutions of CGCM3.1 differ in annual average longwave radiation by only 3 Wm^{-2} (Figure 1b), and both versions use the same ice albedo parameter values (G. Flato, personal communication, 2007).

[14] The range in simulated cloudiness between the IPCC AR4 models also leads to a spread in shortwave radiation incident at the ice surface [cf. *Gorodetskaya et al.*, 2007]. Could this be enough to cancel out the differences in simulated longwave radiation? The intermodel spread among the 16 GCMs in Arctic surface downwelling shortwave radiation (not shown here) is roughly ±30 Wm^{-2}. Changes in incident shortwave radiation and surface albedo both equivalently affect the flux of absorbed shortwave radiation, $(1-\alpha)F_{SW}$. Specifically, varying F_{SW} in 200 ± 30 Wm^{-2} is equivalent to varying α in 0.65 ± 0.05, or about half the range plotted in Figure 3. Hence the intermodel range in shortwave radiation is not sufficient to rectify the spread in equilibrium ice thickness implied by the intermodel range in longwave radiation.

4. Conclusions

[15] Recent GCM simulations for the forthcoming IPCC AR4 display large intermodel differences in Arctic cloud cover which are associated with significant differences in downwelling longwave radiation. Using two standard ther-

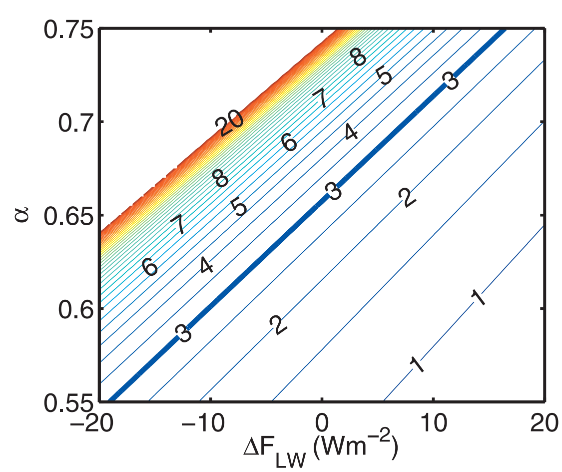

Figure 3. Equilibrium ice thickness in the idealized analytical model (equation 3) as a function of absorbed radiation for the range of downwelling longwave radiative fluxes predicted by GCMs (ΔF_{LW}) and varying ice albedo (α). Ice thickness contours are plotted in 0.5 m intervals up to h_{eq} = 20 m. The thick contour line represents a realistic present day equilibrium thickness of 3 m.

modynamic sea ice models [*Maykut and Untersteiner*, 1971; *Thorndike*, 1992], we have shown that ice thickness is highly sensitive to these variations in longwave radiation: forcing these models with the inter-GCM spread in downwelling longwave radiation leads to a range in equilibrium ice thicknesses from 1 to over 10 m. However, all of these GCMs appear to be simulating present-day sea ice conditions in reasonable agreement with observations [cf. *Parkinson et al.*, 2006; *Zhang and Walsh*, 2006]. Our analysis shows that ice albedo would need to be tuned by only ±0.1 if this parameter alone were used to compensate the effects of the spread in longwave radiation and explain the intermodel agreement in simulated present-day sea ice.

[16] The agreement between the models may also rely on the tuning of other model parameters to match observations. For example, the sensitivity of equilibrium ice thickness (h_{eq}) to the magnitude of the oceanic heat flux (F_W) is $0 \leq h_{eq} \leq 6$ m for $6\ \mathrm{Wm}^{-2} \geq F_W \geq 0$ in the model of *Maykut and Untersteiner* [1971]. Although this spread in equilibrium thickness is smaller than that implied by the intermodel variance in longwave radiation, we suggest that the study of this effect in GCMs would be a useful exercise. Nonetheless, we emphasize here that a sufficient explanation of the relative intermodel agreement in simulated present-day sea ice is the extreme sensitivity of ice thickness to albedo.

[17] These results suggest that most state-of-the-art GCMs are simulating observationally consistent present-day ice cover because the model errors associated with simulated cloudiness are being compensated by tuning parameters such as the ice albedo. In other words, errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components. Hence the widely anticipated and advertised demise of multi-year sea ice in the Arctic Ocean cannot be effectively argued on the basis of GCM predictions taken at face value. This analysis also implies that the thinning of Arctic sea ice over the past half-century [*Rothrock et al.*, 1999] can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields. The hope is that these results may be helpful in the development of future generations of GCMs. Furthermore, this analysis may help provide a context by which the widely differing IPCC AR4 GCM predictions of 21st century Arctic sea ice retreat can be interpreted.

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