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Reply to comment by E. T. DeWeaver et al. on "On the reliability of simulated Arctic sea ice in global climate models"

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[1] In a recent paper we used thermodynamic calculations to suggest that differences in simulated Arctic downwelling longwave radiation have major implications for underlying sea ice in sixteen global climate models (GCMs) being evaluated for the IPCC Fourth Assessment Report (AR4), and we discussed the possibility that albedo tuning may help explain the extent to which simulated present-day sea ice in these models agrees with observations despite the atmospheric model errors [*Eisenman et al.*, 2007]. *DeWeaver et al.* [2008] compare our albedo sensitivity calculations with simulations carried out using a version of CCSM3, which is one of the sixteen GCMs considered in our study. They find that CCSM3 is significantly less sensitive to sea ice albedo than our thermodynamic calculations demonstrated, and hence they conclude that ice albedo may not be as effective a GCM "tuning knob" as we suggested. We thank them for their comment and for the opportunity to discuss further the issue of sea ice sensitivity in GCMs.

[2] We recognize that more sophisticated models contain various processes that may mitigate the wide range of equilibrium thicknesses obtained in our calculations, and we agree that GCM simulations can provide a more detailed indication of the sensitivity of the AR4 GCMs than the thermodynamic model used in our calculations. However, we note that most of the AR4 GCMs may be expected to be more sensitive to albedo than CCSM3 because of a known shortwave radiation bias, as described below. DeWeaver et al. find that the 0.13 increase in CCSM3 bare ice albedo has the same effect on net surface shortwave radiation as increasing the albedo in our sensitivity calculations by 0.035. There are three factors responsible for this difference in net shortwave radiation, which are also mentioned by DeWeaver et al.: (1) the unchanged albedo of snow-covered ice (as well as leads) in their simulations, (2) the difference in incident shortwave radiation between their simulations and our calculations, and (3) the mitigating effect of cloud feedbacks and multiple cloud scattering in their simulations. We discuss these three factors below, noting the extent to which each depends on specifics of their simulations rather than being representative of typical albedo tuning of the AR4 GCMs.

[3] Because the snow-covered ice albedo was not adjusted in their simulations, the 0.13 bare ice albedo increase causes the effective annual albedo change in the perennial ice region to be only 0.073 (the ratio of annual upward and downward shortwave radiation fluxes listed in their Table 1). However, the albedo of snow-covered ice is often also tuned in GCMs. In the example considered in our study, the snow-covered ice albedo in MIROC3.1 was tuned by 0.05 between two different model resolutions.

[4] The annual mean surface shortwave radiation above perennial ice in their standard case simulation is $70\ \mathrm{Wm}^{-2}$, compared with $100\ \mathrm{Wm}^{-2}$ in our calculations, which reduces the albedo change that would lead to an equivalent radiative effect in our calculations from 0.073 to 0.051. Although CCSM3 is believed to be one of the most reliable current models of Arctic climate, *Collins et al.* [2006] report that cloud radiative forcing overestimates cause the annual mean Arctic downwelling shortwave flux in CCSM3 to be $13\ \mathrm{Wm}^{-2}$ lower than observations. Collins et al. explain that the CCSM3 cold snow-covered ice albedo parameter is reduced by 0.07 to compensate for this effect. Indeed, the annual surface Arctic shortwave radiation in CCSM3 is more than one standard deviation below the intermodel mean in the sixteen AR4 GCMs analyzed in our study. This suggests that the diminished CCSM3 albedo sensitivity due to the small surface shortwave flux is not characteristic of most of the AR4 GCMs. Note that the intermodel mean Arctic shortwave radiation is $90\ \mathrm{Wm}^{-2}$, which is lower than the observationally-based central Arctic value of $100\ \mathrm{Wm}^{-2}$ [*Maykut and Untersteiner*, 1971] used in our calculations, and this may give our calculations a slight oversensitivity bias compared to the AR4 GCMs.

[5] When the albedo is increased in their simulations, the simulated cloudiness decreases, allowing more shortwave radiation to reach the surface. Additionally, multiple scattering associated with cloud shortwave reflectivity causes the total downwelling shortwave radiation to increase in response to the increase in albedo. Both of these cloud effects mitigate the reduction in net surface shortwave radiation in response to the increased albedo; an albedo change of only 0.035, instead of 0.051, gives an equivalent change in net surface shortwave radiation in our calculations. We agree with DeWeaver et al. that this cloud feedback and the effect of multiple scattering may both be interesting potential mechanisms to mitigate the response of simulated sea ice to changes in forcing. However, while some level of albedo sensitivity mitigation due to multiple scattering may be expected to occur in all of the GCMs considered in our study, we emphasize that these cloud

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effects should not be expected to occur similarly among these GCMs because of the large intermodel spread in Arctic cloud conditions. Disparities in simulated Arctic cloudiness appear to be a significant source of differences in the AR4 GCMs [*Eisenman et al.*, 2007, Figure 1].

[6] When the difference in incident shortwave radiation associated with these factors is neglected, the CCSM3 simulations imply an ice thickness sensitivity to albedo that is roughly half as large as the sensitivity in our thermodynamic calculations, as noted by DeWeaver et al. Reasons for this difference in sensitivity may include the lack of horizontal structure and ice dynamics in our thermodynamic calculations. We note, however, that the range of ice thickness sensitivities to albedo in these GCMs may be expected to be large based on the wide intermodel range of simulated ice extents in response to a change in forcing conditions. Similar to the results reported by *Zhang and Walsh* [2006] and *Arzel et al.* [2006], we find that the range of A1B scenario projections from the 16 GCMs considered in our study span from ice-free Septembers by 2030 (MIROC3.2 high resolution) to a September ice extent that diminishes by only 10% between year 2000 and year 2100 (GISS ER). It is thus unlikely that the CCSM3 simulated albedo sensitivity would agree very much better with the other GCMs than the factor of two difference in sensitivity to net shortwave radiation compared with our calculations. Nonetheless, we agree that feedbacks and other processes beyond albedo tuning are likely contributing to the relative agreement in simulated present-day sea ice conditions in the AR4 GCMs.

[7] In closing, we would like to take this opportunity to discuss a more general point relevant to the broader context of this exchange. During August and September of 2007, sea ice in the Pacific sector of the Arctic Basin experienced an unprecedented, enormous loss. This observed loss was outside the range of AR4 GCM projections [cf. *Stroeve et al.*, 2007]. A recent study [*Nghiem et al.*, 2007] has attributed it to several preceding years of increased ice export through Fram Strait, resulting in a growing amount of first-year ice that is capable of being melted in one summer. In addition, continuing intrusions of warm Atlantic water into the Arctic Basin [e.g., *Polyakov et al.*, 2007] and the destruction of thin ice by deformation may have accelerated the process. GCMs strive to predict sea ice changes as one of the consequences of increasing greenhouse gas forcing. Owing to the great sensitivity of the ice thickness to the surface heat balance, it has not been possible to attribute a specific cause to the observed in-situ thinning of the ice in the nineties, but it may well have been a consequence of greenhouse gases [e.g., *Rothrock et al.*, 1999]. Thinner and hence weaker ice with low internal stress will become predominantly wind-driven, even in winter. Indeed, the International Arctic Data Buoy Program documents generally increased ice velocities, and thus export, during the past few years, leading to the enormous loss of ice in summer 2007. With sea surface temperatures at +5°C in the open water during September 2007, it remains to be seen how the growth of ice this winter will influence the thin end of the thickness distribution, which is expected to play an important role in determining how much of the ice cover survives next summer's melt season. Even if the ice remains fairly thin, however, a change in the wind stress field may reduce the future ice export, giving the ice a longer residence time in the Arctic Basin and a greater chance to grow to multi-year thickness. While some GCM simulations demonstrate abrupt sea ice retreat associated with factors such as an increase in ocean heat transport to the Arctic [e.g., *Holland et al.*, 2006; *Winton*, 2006], it remains to be studied how well the range of current GCMs compare with observations in modeling these oceanographic intrusions.

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