CO$_2$ CLIMATE SENSITIVITY AND SNOW-SEA-ICE ALBEDO PARAMETERIZATION IN AN ATMOSPHERIC GCM COUPLED TO A MIXED-LAYER OCEAN MODEL

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Abstract. The snow-sea-ice albedo parameterization in an atmospheric general circulation model (GCM), coupled to a simple mixed-layer ocean and run with an annual cycle of solar forcing, is altered from a version of the same model described by Washington and Meehl (1984). The model with the revised formulation is run to equilibrium for 1 x CO$_2$ and 2 x CO$_2$ experiments. The 1 x CO$_2$ (control) simulation produces a global mean climate about 1 °C warmer than the original version, and sea-ice extent is reduced. The model with the altered parameterization displays heightened sensitivity in the global means, but the geographical patterns of climate change due to increased carbon dioxide (CO$_2$) are qualitatively similar. The magnitude of the climate change is affected, not only in areas directly influenced by snow and ice changes but also in other regions of the globe, including the tropics where sea-surface temperature, evaporation, and precipitation over the oceans are greater. With the less-sensitive formulation, the global mean surface air temperature increase is 3.5 °C, and the increase of global mean precipitation is 7.12%. The revised formulation produces a globally averaged surface air temperature increase of 4.04 °C and a precipitation increase of 7.25%, as well as greater warming of the upper tropical troposphere. Sensitivity of surface hydrology is qualitatively similar between the two cases with the larger-magnitude changes in the revised snow and ice-albedo scheme experiment. Variability of surface air temperature in the model is comparable to observations in most areas except at high latitudes during winter. In those regions, temporal variation of the sea-ice margin and fluctuations of snow cover dependent on the snow-ice-albedo formulation contribute to larger-than-observed temperature variability. This study highlights an uncertainty associated with results from current climate GCMs that use highly parameterized snow-sea-ice albedo schemes with simple mixed-layer ocean models.

1. Introduction

The importance of snow-sea-ice albedo feedback to global climate and climate change has long been recognized from the earliest days of simple climate models (e.g., review by Meehl, 1984). Snow-ice albedo processes continue to play a critical role in present-day atmospheric general circulation models (GCMs) coupled to interactive ocean formulations, as they are applied to the study of climate sensitivity to increased carbon dioxide (CO$_2$) (e.g., dating from the pioneering study by Manabe and Wetherald, 1975, and simulations since then summarized by Schlesinger and Mitchell, 1987). For example, Dickinson et al. (1987) estimated...

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that about 1.3 of the 3.5 °C global warming in the Washington and Meehl (1984) CO₂ simulation could be attributed to ice-snow feedback. Ingram et al. (1989) removed all sea-ice feedbacks in a doubled CO₂ experiment and global warming was reduced by about 20%. In a study of changes of persistent atmospheric circulation patterns in the Washington and Meehl (1984) model due to increased CO₂, Bates and Meehl (1986) concluded that most of the shift of regions of blocking activity in the Northern Hemisphere could be linked to the retreat of overextensive sea ice in the model.

Climate simulations with GCMs so far have necessarily represented compromises between explicitly resolved processes and parameterizations due to limitations of computer resources and the need to perform long integrations with models that include interactive ocean representations. Explicit models of sea ice have been developed to realistically take into account most of the relevant dynamical and thermodynamical processes (Hibler, 1979; Parkinson and Washington, 1979; Semtner, 1987). Because these models are time-consuming, other more computationally efficient parameterized schemes have been devised to be used with current climate GCMs (Bryan, 1969; Semtner, 1976). Most of these involve some type of thermodynamic formulation for sea ice with a temperature-dependent ice-albedo threshold. Although these schemes reproduce many features of the seasonal growth and decay of sea ice (Semtner, 1984), they are highly parameterized versions of more realistic sea-ice models, and uncertainty about the parameters used with such thermodynamic sea-ice models still exists. It is possible that the inclusion of more realistic sea-ice formulations with ice dynamics and ocean-heat transport will have an impact on the ice-albedo feedback. The present purely thermodynamic sea-ice scheme should provide a measure of the upper limit of sea-ice sensitivity to CO₂ climate change.

Washington and Meehl (1986) addressed this problem with several integrations of an atmospheric GCM coupled to a swamp ocean and run with annual mean solar forcing (SSTs computed using surface energy balance only, no ocean heat storage or transport included). They showed the critical dependence of global climate and climate sensitivity on the sea-ice formulation used. In particular, they compared a scheme whereby the ice albedo dropped from its ice value of 0.7 to its much lower ocean value only when all the ice melted at a given grid point to one where the ice-albedo value of 0.7 dropped to 0.35 if the surface temperature reached 10 deg below the freezing point of sea ice. An albedo change at a temperature less than freezing accounts for subgrid-scale temperature where temperatures are often above and below the grid-scale freezing point. If all ice at a grid point melted, the albedo was set to its lower ocean value (dependent on solar zenith angle – see explanation in Washington and Meehl, 1984). For the annual mean swamp-ocean model, Washington and Meehl (1986) found that the latter scheme was more conducive to ice melting, produced a warmer global mean control climate (less sea ice), and was evidenced by a greater global mean sensitivity to increased CO₂. However, the results with the swamp ocean could only be con-