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Initiation of modern Soft Snowball and Hard Snowball in CCSM3

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During the Neoproterozoic era, the Earth experienced a series of extremely deep glaciations, two of which have been suggested to have been global in extent, with the oceans covered by sea-ice and the continents covered by thick ice-sheets. These events, the first of which began at ∼716 Ma (the Sturtian event), and the second began at ∼635 Ma (the Marinoan event), have been termed "Snowball" glaciations. The problem of the forcing required for the Earth to enter into such severe glacial states is examined using the Community Climate System Model (CCSM3). All the simulations we will present emply present Earth geography and topography and are used to explore the combination of forcings, consisting of solar luminosity decrease, atmospheric CO2 concentration, sea ice albedo, orbital configuration, and either including or excluding the influence of sea-ice dynamics that are able to drive the system into a "hard Snowball" state. The critical point at which runaway ice-albedo feedback will lead to formation of a hard Snowball Earth is found to correspond to (a) 10-10.5% reduction in solar radiation with pre-industrial greenhouse gas concentrations, (b) 6% reduced solar radiation with 17.5-20 ppmv CO2, or (c) 6% reduced solar radiation and 286 ppmv CO2 if sea-ice albedo is equal to or greater than 0.58.

However, the formation of melt ponds may signficantly decrease the sea-ice/snow albedo from 0.80 to 0.50 during the summer season. Especially when the sea-ice is entering the tropics, we expect that the melt ponds forming on the surface of the sea-ice would be deeper, greater in areal extent, and be longer lived than those that form in the Arctic and the Antarctic under present day conditions. When sea-ice albedo is below 0.58 or upon incorporation of the influence of melt ponds, we find soft Snowball solutions to be preferred. In the soft Snowball state, the global-mean sea-ice fraction may reach as high as 76%, the sea ice margins remain near 8oS and 15oN latitude, a state that is compatible with a tropical ice-free ocean and snow-covered continents. The absence of snow near the sea-ice margins, the melt ponds and the robust poleward atmospheric and oceanic heat transports together prevent the runaway sea-ice albedo feedback from occurring. We conclude that a soft Snowball Earth solution is entirely tenable, a result that is in conflict to some degree with the recently published results derived by the ECHAM5/MPI-OM analyzes of Voigt and Marotzke (2009) and Voigt et al. (2010) which were obtained using a relatively high sea-ice albedo (0.75). Moreover, we show that variations in the Earth's orbit have little influence on tropical sea surface temperature and thus on the expansion of sea-ice, implying that, under perturbations of Milankovitch type, the soft Snowball is a stable state.