The Initiation of modern "soft Snowball" and "hard Snowball" climates in CCSM3

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Abstract

The problem of the forcing required for the Earth to enter a state of complete glaciation is examined using the Community Climate Model System (CCSM3). All of these simulations performed to address this issue employ the combination of factors, consisting of total solar luminosity, CO2 concentration, and sea-ice/snow albedo parameterization. Our analyses demonstrate that the critical conditions beyond which runaway ice-albedo feedback will lead to global freezing include a 10-10.5% reduction in solar radiation with pre-industrial greenhouse gas concentrations; a 6% reduction in solar radiation with 17.5 ppm CO2; or a 6% less solar radiation and 266 ppm CO2 if sea-ice albedo is equal to or greater than 0.60 with a snow albedo of 0.75; or sea-ice albedo is 0.80 with a snow albedo equal to or greater than 0.80. These transition thresholds are very sensitive to the sea-ice and snow albedos. With a 5% reduction in solar radiation, as was approximately the case for the Neoproterozoic glaciation of the Representative Era, and CO2 concentration between one-eighth and two times pre-industrial level, when the sea-ice albedo is equal to or less than 0.60, "soft Snowball" solutions are preferred with tropical open-water oceans in the tropics, coexisting with year-round snow-covered continents (implying that tropical continental ice sheets would actually be present). We conclude that a "soft Snowball" is entirely plausible, in which the global sea-ice fracion may reach as high as 76% and sea-ice margins may extend to 10°S and 10°N latitude.

1. Introduction

During the Neoproterozoic era, it is generally argued that two or more global-scale glaciations occurred, one that dated at ~716 Ma (Ma = million years ago), the Sturtian glaciation (and a second that dated at ~835 Ma (the Marinoan glaciation), during which heavy land glaciers reached low latitudes and the ocean was completely covered by thick sea-ice. This has been referred to as the "hard Snowball" hypothesis (Hoffman et al. 1998). An alternative to the hard Snowball hypothesis was first proposed by Hyde et al. (2000) and further developed in Peltier et al. (2007), the "soft Snowball" or "Shuabian" hypothesis. In the latter model, although the continents are covered by thick continental ice-sheets, stable states are imagined to exist in which open water in the tropics may coexist with low latitude continental glaciation. Here, we use the coupled ocean-atmosphere model CCSM3 to examine the conditions required for the initiation of either a soft Snowball state or a hard Snowball state for an Earth with modern geodaphy and topography.

2. The Influence of Solar Radiation and CO2 Concentration

Sea-ice evolution in the reduced solar radiation experiments is showed in Fig. 2. The control experiment with the present solar constant and greenhouse gases, the global mean surface air temperature (T2m) of 287.1 K and sea-ice cover of ~6% are close to modern values. After 1% reduction in solar radiation and 69 ppmv decrease in CO2, the global mean T2m decreases by 3.2 K and the global mean sea-ice cover increases by 5%. In the further experiments, we simply reduce the solar radiation in a series of successive steps while keeping the CO2 concentration fixed at 266 ppmv. Our analyses demonstrate that runaway albedo feedback occurs after a 10.5% reduction in solar luminosity. From 0.09TTSI to 0.89TTSI (the solar irradiance, the number in front of "TTSI" is the normalized solar radiation) the T2m decreases by 23 K and the global sea-ice fraction jumps from 49% to 100%. By fixing solar radiation to 96% of the present level, the sea-ice cover response to CO2 reduction is shown in Fig 2. As a decrease of the atmospheric CO2 concentration from 355 ppmv to 17.5 ppmv, the ocean becomes totally ice-covered at model year 450. Importantly, when the CO2 concentration is between 50 ppmv and 20 ppmv, the maximum-stable sea-ice cover (above which runaway albedo feedback occurs) may be as high as 76%, and the sea-ice-albedo "soft Snowball" solutions are preferred to close to 1%S and 10°N latitude. In the further experiments, in which open oceans can stably coexist with year-round snow covered continents (Fig 3), this state is consistent with the spatial distribution of Neoproterozoic continental glacial deposits (Hoffman et al. 1998) and also consistent with recent observations which imply that some oceans should be ice-free during the glaciations (Allen and Etienne 2003).

3. Sea-ice/snow Albedo Sensitivity

It is clear on physical grounds that increasing the sea-ice albedo and/or snow albedo will enhance albedo feedback and promote the formation of a hard Snowball Earth. As shown in Fig 4, the results are very sensitive to the sea-ice/snow albedo. In the range of CO2 concentration between one-eighth and two times pre-industrial level for a sea-ice albedo at or below 0.60 and a snow albedo of 0.80, soft Snowball solutions exist. It is worth noting that these sea-ice and snow albedos are comparable to the observations in the Arctic on present-day conditions (developed by Warren et al. 2002).

4. Forcing and Feedbacks

As reduction in solar radiation and CO2 concentration, it is found that (1) the amount of atmospheric water-vapor and its attendant greenhouse effect decrease with the logarithm of sea-ice; (2) the changes of net cloud forcing are on the order of 10 W m-2; (3) the strengths of the atmospheric Hadley cells and the wind-driven ocean circulations increase by a factor of 2-3 in the Southern Hemisphere. As shown in Fig 5, the major controlling factors in producing completely ice-cover state are ice-albedo feedback (see 3 above) and water-vapor feedback.

References