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Climate of the Past Discussions

Interactive comment on "The initiation of modern soft and hard Snowball Earth climates in CCSM4" *by* J. Yang and W. R. Peltier

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We are very grateful for the comments provided by anonymous referee #2. In the two companion papers of the Journal of Climate, we discussed in detail the stability boundaries across which the modern Earth would transition into a hard snowball state of complete ice cover. These analyses were performed using the NCAR CCSM3 model, one of the few able to reasonably account for the variation of Arctic sea ice cover over the past 33 years since satellite data first became available. The present paper repeats the critical analyses presented in those papers using the considerably more sophisticated CCSM4 version of the model. This model contains significant changes to the sea ice component of the modeling structure, which we have shown to be critical to the determination of the thresholds for hard snowball transition. The current paper

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demonstrates that, in spite of these significant changes to this critical component of the model, the transition thresholds are only moderately shifted. However the shift is in the direction of making the transition into the hard snowball state easier to achieve, which we view as an extremely important result. Our responses to the two primary issues raised in this review are repeated below, following which we provide specific replies.

Key comments of the referee

1. "I don't doubt that the implications of the differences in CCSM3 vs. 4 cryospheric parameterizations (in particular) for exploring the dynamics of past systems such as 'snowball Earth' are very important to assess and present, but without additional (paleo) 'science' results, I must question whether this paper is really suitable, or rather, does it contain sufficient new paleo-orientated findings, for subsequent publication in Climate of the Past?"

2. "In particular: what is the role of continental configuration? ... What role does the distribution of continents play? E.g. what is the difference between polar and equatorial super-continents (if any) in terms of sea-ice thresholds, what is the position, response, and influence of the Hadley Cell in cooling feedbacks? What is the importance (if any) of fragmented landmasses vs. a super-continent?"

Reply

1. Previous work of various authors has suggested there exists no soft Snowball Earth solutions in fully coupled ocean-atmosphere models, including the FOAM model (Poulsen and Jacob, 2004), the MIROC-lite model (Oka et al., 2010), and the ECHAM5/MPI-OM model (Voigt and Marotzke, 2010; Voigt et al., 2011). The only exception to this appears to be the more fully articulated CCSM3 model (Yang et al., 2012a). It is clearly important to understand whether the CCSM3 result is an aberration. The fact that this model has been significantly further improved and its current CCSM4 version has provided the opportunity for us to enquire as to whether the CCSM3 results concerning the existence of solutions characterized by the presence of

CPD
8, C262–C265, 2012

(implicit) low latitude land ice but open water on the equator are truly anomalous. We show in the present paper that these earlier results concerning the existence of soft snowball solutions are only further reinforced by the results of the CCSM4-based analyses. We view this as critical support for the validity of the conclusions documented in the two companion papers in the Journal of Climate.

2. As demonstrated in the draft of the current paper, the parameterizations employed previously of sea-ice and snow albedo in investigations of the Snowball Earth issue all are overly simplified and demonstrably inconsistent with observations. In comparison with observations, the sea-ice albedo is higher in the ECHAM5/MPI-OM model and lower in CCSM3. It is therefore not surprising that the former model aids and abets the transition to hard snowball conditions. The CCSM4 model employs even more realistic sea-ice/snow albedo than does CCSM3 and therefore should even more accurately capture the transition thresholds of interest. We find the hard snowball transition threshold to shift.

3. The greatest divergence between the different models that have been employed in previous snowball Earth analyses, however, involve the influence of cloud cover and cloud radiative forcing. Although previous simulations with different models seem to indicate that there are significant differences in cloud radiative forcing between different models for the Snowball Earth simulations, no previous paper has seriously investigated this problem. In the current paper, we have carefully compared the cloud radiative forcing between the CCSM3 and CCSM4 models, as well as the differences in the ocean circulation and meridional atmosphere/ocean energy transports. These are original results, which we also view as important.

4. We agree that the issue of continental configuration may prove to be very important for the issue of the initiation of a soft or hard Snowball Earth under true Neoroterozoic conditions in which the land-sea distribution is more accurately represented. Very detailed recent analyses of the impact of such realistic paleogeography have recently been published by Liu and Peltier (2010, 2011 JGR-Atmospheres) using a fully coupled

CPD
8, C262–C265, 2012

EBM-land ice-carbon cycle model as a first step towards a complete investigation of this influence. In these models, as we have demonstrated, the soft snowball solutions continue to exist for either Marinoan or Sturtion distributions of the continents. High resolution analyses are currently being performed for both land-sea distributions, the results for which will be submitted for publication in due course. These analyses, to be credible, require the results of the modern snowball initiation experiments discussed in the present paper to serve as a basis on which the distinct effects associated with continental configuration may be isolated.

5. One of the goals of CP is "simulation of past climate and model-based interpretation of palaeo climate data for a better understanding of present and future climate variability and climate change." We believe our paper contributes significantly to this important goal.

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