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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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Reply to the comments of J. Kasting on "The initiation of modern soft and hard Snowball Earth climates in CCSM4" (Clim. Past Discuss., 8, 1–29, 2012)

We are very grateful for the review provided by the referee, James F. Kasting. We address Kasting's comments and questions point for point. Our answers are preceded by "Reply". We will also modify the text of the manuscript to take these comments into account.

1) Comment: "That said, the authors fail to point out an important difference between their "soft Snowball" model and the "Jormungand" model of Abbot et al. (2011). These two models differ significantly in the percentage of the ocean covered by ice and pre-

sumably in the way that they would deglaciate. Generally, the big criticism of the soft Snowball model is that it exhibits either weak, or no, hysteresis with respect to CO2 levels; hence, it makes it more difficult to account for the presence of cap carbonates. If pCO2 does not overshoot its original concentration during the recovery phase, then there is no reason that such cap carbonates should exist. The Jormungand model, on the other hand, exhibits significant hysteresis because it is much closer to a full Snowball state. The hard Snowball model of Hoffman et al. exhibits the most hysteresis, i.e., it requires the highest CO2 levels to deglaciate, because the albedo is assumed to be high everywhere."

Reply: As presented in Abbot et al. (2011), global sea-ice coverage is approximately 80% for the Jormungand climate state; although this is much higher than that for the soft Snowball state obtained in Ice-sheet/EBM climate models (e.g., Peltier et al., 2007). This is nevertheless close to that for the soft Snowball Earth state obtained in an atmospheric general circulation model with specified ice-sheet covered continents (Baum and Crowley, 2001) and in the coupled atmosphere-ocean model CCSM3 (Yang et al., 2012) and CCSM4 (this manuscript). Abbot et al. (2011) thought that the hysteresis associated with the Jormungand climate state would be much stronger for the soft Snowball state, which we believe to be somewhat misleading. The Jormungand state occurs for CO2 values of 1750-15000 ppmv (Abbot et al., 2011), and the soft Snowball Earth state occurs for CO2 levels of 100-1000 ppmv (e.g., Liu and Peltier, 2010). Although the absolute values are quite different, the upper limit is approximately ten times the lower limit for both of these two climate states. The strength of the hysteresis associated with these two states is therefore similar because of the logarithmic dependence of radiative forcing on CO2. Moreover, the absolute value for CO2 concentration is not expected to be important primarily due to the absence of ocean heat transport in the simulations of Abbot et al. (2011). For example, the CO2 threshold of 1500-1750 ppmv required for the initiation of a hard Snowball in the atmospheric general circulation model CAM3 (Abbot et al., 2011) is much greater than that of 17.5-20 ppmv in the coupled version CCSM3 (Yang et al., 2012). Ocean heat transport plays an important role in weakening the influence of ice-albedo feedback and stabilizing the latitudinal location of the sea-ice front. We agree that the soft Snowball state and the Jormungand climate state should be viewed as distinct climate states and we will address this fully in the revised version of the paper.

2) Comment: "I will make one other substantive point. The fact that CCSM4 does not predict global glaciation for reasonable Late Proterozoic solar luminosity and CO2 does not imply that global glaciation is impossible, or even unlikely. CCSM4 may be better than CCSM3, but it is not a perfect climate model, and it does not even include simulated Late Proterozoic geography. The authors are aware of these limitations, and they are careful to state their conclusions with appropriate caution. I see the utility of this paper in elucidating the differences between different versions of CCSM, not in convincing people that soft Snowballs are the right solutions."

Reply: We agree that our results cannot be taken to imply that a global glaciation is impossible and we have addressed this clearly in the 'Discussion and Conclusions' section of our manuscript. In addition, we will more clearly emphasize this point in the 'Abstract' of the revised version of the paper.

3) Comment: "Doesn't it seem weird that CO2 needs to have been only 12 times higher than today in the early Neoproterozoic, but 15 times higher in the early Cambrian when solar luminosity was higher? What kind of climate does CCSM4 predict under these circumstances? This might be a way to test whether this climate model is really appropriate for simulating the glaciations in between."

Reply: Following Pierrehumbert et al. (2011), it requires 12 times the preindustrial level to compensate the effect of a relatively faint sun in order to keep the Neoproterozoic temperature close to present, based on global energy conservation calculations and climate feedbacks (Ray T. Pierrehumbert, personal communication, 2011). For the early Cambrian, it was suggested that the CO2 concentration is about 15 times the present level, based on results of a geochemical model (Berner, 2006). We do not

insist that the CO2 in the early Cambrian must have been significantly higher than the Neoproterozoic era, since these results for the early Cambrian are based on a relatively simple but nevertheless interesting model. This issue will be more clearly addressed in the revised version of the paper. Our recent work with CCSM3 has demonstrated that the CO2 level required to compensate the effect of a relatively faint sun in order to keep the Neoproterozoic surface temperature close to present is approximately ten times the pre-industrial level, i.e., $\sim$3000 ppmv (Yonggang Liu and Wm. Richard Peltier, in preparation, 2012).

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