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Climate of the Past Discussions

Interactive comment on "Sea-ice dynamics strongly promote Snowball Earth initiation and destabilize tropical sea-ice margins" *by* A. Voigt and D. S. Abbot

Anonymous Referee #3

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Review of CPD-8-2445-2012 By A. Voight and D.S. Abbot General Comments The authors describe a reanalysis of the snowball bifurcation point employing the European ECHAM5/MPI-OM model under conditions consisting of an approximate Marinoan distribution of the continents, and a 6% reduction in the solar constant, as a function of the atmospheric CO2 concentration. They characterize the bifurcation point by the latter concentration together with the fractional sea-ice cover at which the bifurcation occurs. They have modified their analyses in two ways from those previously published, respectively by reducing the value of the bare sea-ice albedo to the much lower value of 0.45 (from their previously assumed value of 0.75) in order to be consistent with the value assumed in CAM3, the atmospheric component of the NCAR CCSM3 structure

that has recently been employed by Yang et al (2012a,b) to address the same problem. The results obtained by Yang et al demonstrated that there existed a significant difference between the CCSM3 results and those obtained using ECHAM with its assumed high value of the bare sea ice albedo and traced these significant differences to this difference in this assumed albedo. Consistent with the Yang et al results, the authors find that this does make a highly significant difference in the bifurcation point, it then occurring only for a significantly reduced value of the atmospheric CO2 concentration, as demonstrated by Yang et al. Since the NCAR model(s) include a much more sophisticated representation of the albedos of both snow covered and bare sea ice and since the model much more accurately fits the observed diminution of sea ice cover over the Arctic ocean over the instrumental era, the Yang et al results should be accepted as the more accurate. The additional issue which the authors address concerns the ability of their model, under various operating conditions (including or excluding sea ice dynamics, including or excluding ocean heat transport) to embody the hysteresis which is clearly required to understand snowball Earth occurrence. This is the critical issue in the snowball earth debate. In the standard "hard" snowball Earth scenario, it is imaging that the entire earth became ice covered during both the Sturtian and Marinoan periods of the Neoproterozoic. The competing"soft" snowball scenario (eg. Hyde etal 2000, Liu et al, 2011), posits the continued existence of open water on the equator even under conditions in which low latitude ice sheets cover the low latitude continents. In the hard snowball scenario, the needed hysteresis is imagined to derive from the continuing flux of CO2 into the atmosphere that would be expected to exist even when the oceans were entirely covered by sea ice. In the soft snowball scenario, the needed hysteresis is provided by the dynamics of the continental ice-sheets themselves. The authors revisit in this paper, an additional mechanism for hysteresis that was previously suggested to exist in the ECHAM atmosphere only model which was referred to as involving a so-called Jormungand bifurcation that depended upon the difference between the albedo of bare sea ice and that of snow-covered sea-ice. In the current paper the new analyses demonstrate that the previously found hysteresis was an artifact of the exclusion of oceanic and sea-ice dynamical processes. The current paper then includes special pleading to the effect that the same source of hysteresis might be recovered as a consequence of processes not explicitly included in their model. From the perspective of this referee, the paper would be improved by entirely removing these poorly motivated speculations. The paper would also be significantly further improved by listing the specific differences between the co-ordinates of the bifurcation point found by Yang et al for both CCSM3 and CCSM4 under conditions of modern continental configuration AND by including results from ECHAM/MPI-OM for the modern distribution of the continents with the reduced value for the bare sea ice albedo so that direct comparison with the Yang et al results is possible. This would greatly help in sharpening-up the remaining issues in the literature and would lead to a much stronger publication. The following additional specific points should also be taken into consideration in the revision of this paper prior to acceptance for publication, assuming that the previously identified issue is also addressed:

Specific Points

1. Page 2470, Figure 5 Bottom: The figure caption is not consistent with the figure legends. From the figure caption, it is clear that the red line is supposed to indicate the influence of sea-ice dynamics, whereas in the figure legend the red line indicates the influence of melting and conversion. Confusions also exist for concerning the black and blue lines.

2. Page 2453, section 3: In Yang et al. (2012a, Figure 7), the dynamical and thermodynamical sea-ice thickness tendencies in CCSM3 had been analyzed n detail, ie the sea ice momentum budget has been fully analysed. The language in the text at this point suggests that this has not previously been done for any model In low- and mid-latitudes, the results of Yang et al. and in this paper are consistent. But for high latitudes of both hemispheres, Yang et al. demonstrated that the thermodynamic contribution is positive whereas the dynamical contribution is negative, meaning sea-ice is growing in these regions and is being transported equatorwards by dynamics. The results of this paper

(Fig. 4) suggest that both the thermodynamic and the dynamic contributions are positive. Since the results of Yang et al. are more reasonable on physical grounds this issue needs to be fully addressed prior to publication. Might the inconsistency be due to the cut-off imposed upon sea-ice thickness, that it be constrained never to exceed 8 m in ECHAM5/MPI-OM?

3. Page 2456, section 5: This section purports to demonstrate that ocean heat transport has a much smaller effect on the critical CO_2 level and the critical sea-ice cover relative to that of sea-ice dynamics. However, in the zero ocean heat transport experiments, sea-ice dynamics has already been disabled. A possible explanation for the weak effect of ocean heat transport is that disabled sea-ice dynamics has already driven the critical sea-ice cover significantly equatorward to the very high degree (85%), so that above this point the climate system enters a very unstable region; further reduced ocean heat transport therefore has nearly no effect on the critical sea-ice cover. If a group of experiments with zero ocean heat transport and active sea-ice dynamics were performed, the effect of ocean heat transport on the critical sea-ice cover would be directly revealed. These experiments should also be performed prior to publication, further strengthening what could be a strong contribution

4. Page 2458, section 6: In two groups of experiments with and without ocean dynamics, the authors found that there is no sign of the Jormungand bifurcation. Then, the authors concluded that the lack of the Jormungand bifurcation in ECHAM5/MPI-OM is not caused by ocean dynamics and the associated ocean heat transport. Abbot et al. (2011) concluded that the Jormungand bifurcation is due to the high albedo contrast between bare and snow-covered sea-ice, which also exists in the simulations of ECHAM5/MPI-OM of this paper. Do the results of this paper suggest that the high albedo contrast is not the reason for the Jormungand bifurcation, OR whether the high albedo contrast can generate the Jormungand bifurcation or not depends on the model employed?

Minor issues: Page 2451, second last pp., the sentence beginning “the simulations apply exactly the same scheme sea-ice the thermodynamic scheme as the other simulations"âĂŤplease fix the English in this sentence Conclusions, the sentence "Our results represent and important extension of these studies as we quantify the impact of sea-ice dynamics on the Snowball Earth bifurcation in an AO-GCM that includes interactive surface wind". This influence has already been analysed in detail in the Yang et al (2012a,b,c) papers. Furthermore Yang et al do not need to disable sea ice dynamics to find solutions with stable sea ice margins at very low latitude

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