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The snow/ice instability as a mechanism for rapid climate change: A Neoproterozoic Snowball Earth model example

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[1] Paleoclimate data increasingly suggest the likelihood of abrupt transitions due to instabilities in the climate system. Several previous studies offer support for the snow/ice instability mechanism as an explanation for some of these changes. However, most of these studies have either employed simple models or not closely examined the details of the transition. Herein we revisit this issue using a general circulation model (GCM) simulation for the late Precambrian, a time when glaciers may have reached the equator. Our results indicate that for CO_2 concentrations near present levels the snow/ice instability occurs in one model year. The width of open water associated with the onset of instability agrees with theoretical calculations of the critical length scale predicted for this behavior. These results strengthen support for the existence of this phenomenon as a mechanism for rapid climate change. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 5416 Planetology: Solid Surface Planets: Glaciation; 9699 Information Related to Geologic Time: General or miscellaneous. **Citation:** Baum, S. K., and T. J. Crowley, The snow/ice instability as a mechanism for rapid climate change: A Neoproterozoic Snowball Earth model example, *Geophys. Res. Lett.*, *30*(20), 2030, doi:10.1029/2003GL017333, 2003.

1. Introduction

[2] In the last two decades there has been increasing evidence supporting abrupt climate transitions in the paleoclimate record. Although many discussions of causes for such transitions involve the ocean circulation, a separate line of inquiry extending back over thirty years involves the existence of multiple solutions due to the nonlinearity associated with snow/ice feedback [*Budyko*, 1969; *Sellers*, 1969]. Gradually decreasing temperatures due to, for example, decreasing carbon dioxide or summer insolation changes, lead to development of snow/ice cover in a small area. This patch of snow or ice suppresses temperatures for a finite distance outside the original area, with the distance determined by a balance between the radiative damping and transport of the atmosphere/ocean system [*North*, 1984]. Temperatures outside the area originally perturbed are then depressed, allowing for snow accumulation in these areas. A new solution with significantly greater snow area rapidly evolves.

[3] Although initial studies of the snowline instability involved one-dimensional models, research with increasingly more realistic EBMs and general circulation models provide further support for the existence of the phenomenon [*Huang and Bowman*, 1992; *Mengel et al.*, 1988; *Baum and Crowley*, 1991; *Crowley et al.*, 1994; *Otto-Bliesner*, 1996]. *North* [1984] formally demonstrated that the length scale was equivalent to $(D/B)^{1/2}$, where D represents heat transport in the earth-ocean system (modeled as a diffusive process) and B is the damping term for radiative perturbations. For values characteristic of the Earth, this length scale is on the order of 15–20° of latitude or 1500–2000 km [*North*, 1990]. Such a length scale has been found in EBM and GCM simulations for the Pleistocene [*Manabe and Broccoli*, 1985; *Hyde et al.*, 1989], and surface temperature data [*Hansen and Lebedeff*, 1987].

[4] The existence of abrupt transitions in snow/ice cover is of more than academic interest because of its potential role in explaining the onset/expansion of ice sheets in earth history [*North and Crowley*, 1985], e.g., Pleistocene glacial inception, expansion of Antarctic ice [*Huybrechts*, 1994; *DeConto and Pollard*, 2003] in the Oligocene (about 34 Ma, millions of years ago), and the major Carboniferous and late Precambrian glaciations [*Hyde et al.*, 1999; *Crowley et al.*, 2001]. *Baum and Crowley* [2001] have already demonstrated in simulations of the late Precambrian (Neoproterozoic, ~600 Ma) that, with fixed ice sheets and CO_2 levels near present, sea ice growth reaches a point where it expands very quickly (order 1–2 years) to yield a completely ice-covered planet—one of two possible solutions postulated for the Neoproterozoic [*Hoffman et al.*, 1998].

[5] In this study we carry the analysis of the snow/sea ice instability two steps further for the Neoproterozoic case: (1) we examine the onset and development of the instability in more detail to examine responses during the transition period; and (2) we compare the spatial scale at which the transition occurs in the GCM to that predicted by theoretical studies [*North*, 1984]. The net result of the investigation is not only a rare look at model behavior across a bifurcation point but also a further buttressing of the importance of the mechanism for explaining rapid climate change.

2. Model and Results

[6] The results discussed herein are based on the experiments described in *Baum and Crowley* [2001]. The GENESIS 2 GCM [*Thompson and Pollard*, 1995] was used in the model

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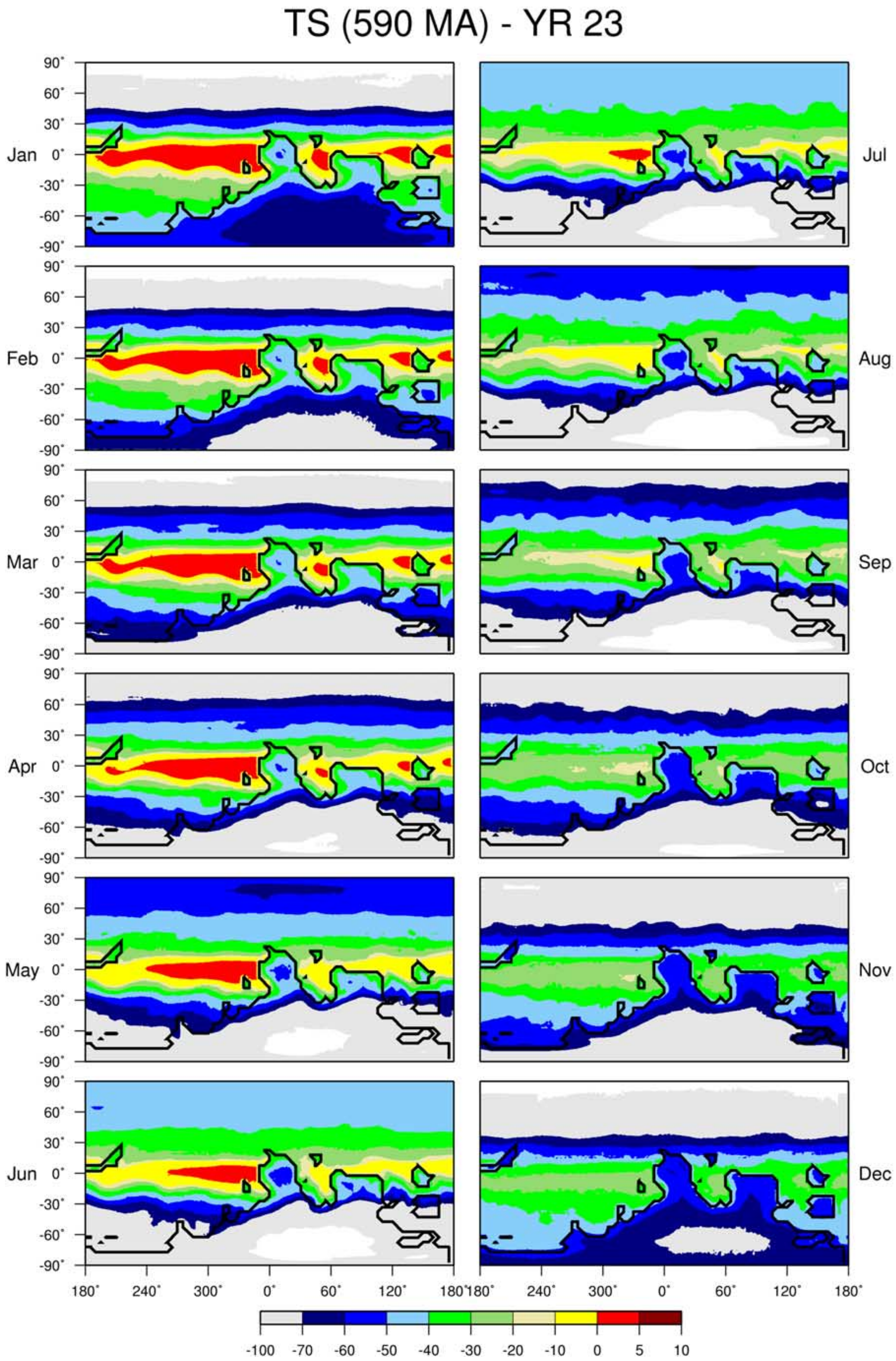

Figure 1. Monthly surface temperature (TS) for 23rd simulation year showing rapid sea ice closure of equatorial regions. The sea ice line is roughly coincident with the 0°C surface temperature line.

experiment. This is an atmospheric GCM coupled to a mixed-layer ocean. The model has diurnal forcing, interactive clouds, penetrative plume convection, boundary layer mixing, and a semi-Lagrangian water vapor transport scheme. The ocean component is 50 m thick, with horizontal heat transport modeled by linear diffusion; the diffusion coefficient is constant in time and depends on both the latitude and the zonal land-ocean fraction. The atmospheric model resolution is T31 (3.75° × 3.75°); surface resolution is 2° × 2°. The sea ice model is a six-layer thermodynamic model that predicts the local melting and freezing of ice. Heat diffuses linearly through the ice, and the total thickness changes by melting of the upper layer and melting or freezing of the bottom surface. The model is constrained to allow sea ice to become no thicker than 11 meters.

[7] Land and sea ice are assigned different albedos, with the latter being less due to the existence of leads, meltwater, and ridging. The sea ice albedo is partitioned into visible and near infrared bands, with the former varying between 0.7–0.8 and the latter between 0.4–0.5. These ranges are temperature dependent, varying between low (5°C less than the melting point) and high threshold (the melting point) temperatures. The total albedo at each ocean point is based on the sea ice fraction, itself dependent on the sea ice thickness.

[8] The paleogeographic reconstruction is after *Dalziel* [1997]. Topography is specificed from the dynamic ice sheet model simulation of *Hyde et al.* [2000] for a 6% reduction in the solar constant [*Crowley and Baum*, 1993]. The specified orbital parameters are those of the present. The model runs reached a completely snow-covered state for CO_2 levels 0.5 and 1.0X present values; a 2.0X run drifted very slowly towards a colder state and was terminated [*Baum and Crowley*, 2001]. We show the results from the 0.5X run, which was started from a zonally averaged state with an average temperature of 0°C, and reached an equilibrium of −61°C after 25 years of integration.

[9] As reported by *Baum and Crowley* [2001] (see Figure 1 therein) during the first 19 years the global temperature decreased about 0.15°C/month. Temperatures then started dropping more dramatically, with the most precipitous phase featuring a 15° decrease over a single year. The one year time scale is of course subject to some uncertainty—other simulations might reveal slightly longer times (D. Pollard, personal communication). The point is that the transition is very rapid - effectively instantaneous from the geologic viewpoint.

[10] Figure 1 shows a month-by-month documentation of the closure. The main area of interest is the ocean westward of the main landmasses; this basin is approximately the width of the present equatorial Pacific. The last area of open water occurs in the eastern side of this basin—an artifact that may partially reflect the lack of equatorial dynamics in the slab ocean model. Nevertheless the results indicate that once a critical point is reached the open-water area closes rapidly in both the east–west and north–south directions. The area of open-water is not isotropic because the large Rossby radius of deformation in the tropics "spreads out" the warm temperatures more in the west–east direction.

[11] Because the minor (north–south) axis direction should be most critical with respect to any length scale argument, we examined a box encompassing the arbitrary

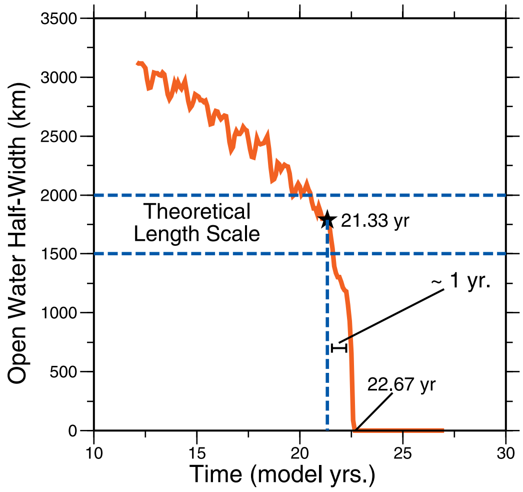

Figure 2. Open water half-width versus time as open ocean area closes. The rate of decrease drastically changes as the half-width shrinks to reach the theoretical length scale for onset of instability. The model rapidly evolves to a new equilibrium state.

longitudes 50°–100°W. Figure 2 illustrates the time series in model years of the half-width of open water across the minor axis of this box. The half-width is chosen because sea ice is encroaching from both the north and south, and the length scale argument should apply when the influence of the expanding ice suppresses temperatures from both sides. Also plotted on this figure is the 1500–2000 km theoretical length scale derived from energy balance models [*North*, 1984; *North*, 1990]. The onset of rapid reduction of ocean area agrees very closely with the prediction of an analytical model.

3. Discussion and Conclusion

[12] Late Precambrian modeling results suggest that with CO_2 levels 50% of present the transition to a completely ice-covered earth can occur rapidly and is consistent with the snow/ice instability mechanism. Previous analyses by *Crowley et al.* [1994] demonstrated that for the Carboniferous ice age there were few significant changes in atmospheric fields away from the region affected by the rapid transition. Ocean dynamics could however complicate the response we simulate for the Precambrian. For example, [*Poulsen et al.*, 2001] found that dynamical feedbacks in a coupled ocean-atmosphere model prevented the ocean from totally icing over. Additional work by *Peltier* [2001] with a coupled ocean-model and the ice sheet reconstruction of our study suggest that open water may still exist at present CO_2 levels due to an enhancement of poleward heat transport driven by deep convection near the ice sheets. But coupled models require a very long time for equilibration and we consider it entirely possible that over thousands of years cooling of water in high latitudes could lead to upwelling of near-freezing water in the tropics, eventually shutting down the ocean feedback loop. We therefore suggest that, although the present level of work on coupled ocean-atmosphere models is revealing, it cannot at this stage exclude the possibility of the snow/ice instability being applicable to the Neoproterozoic, especially if CO_2 levels could ever reach

values near present levels. Whether the latter could or did occur is a non-trivial question that can only be addressed with further geochemical modeling and data analyses. Our results indicate that the snow/ice instability warrants increased consideration as a mechanism for explaining some cases of rapid change in the paleoclimate record.

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