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GCM Response to Late Precambrian (~590 Ma) Ice–Covered Continents

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Abstract. Recent coupled energy balance/ice sheet modeling studies indicate that ice-covered continents can be simulated for the Late Precambrian with 6% solar constant reduction. We examine the ocean mixed layer response to such an ice sheet with the GENESIS 2 general circulation model and CO_2 levels varying from 0.5–2.5 times present. The ocean ices over completely at 0.5–1.0X present levels, with the final phase of sea ice growth occurring within a single model year. A qualitatively different 2.5X CO_2 solution is close to equilibrium and yields open water between ~25 °N and ~25 °S paleolatitude. The prevailing wind patterns suggest that an equatorial Pacific–type circulation may have developed in part of the Neoproterozoic ocean.

Introduction

Ice sheets apparently extended to the equator at the end of the Proterozoic Era (~800–540 Ma, Mega anna, million years ago). Based on δ^{13}C data, *Hoffman et al.* [1998] hypothesize a completely ice–covered planet or "Snowball Earth." Early work on this problem with an energy balance model (EBM) [*Crowley and Baum*, 1993] and general circulation models (GCM) [*Jenkins and Frakes*, 1998; *Oglesby and Ogg*, 1998] had difficulty obtaining snow covered solutions for continents. However, a recent modeling study [*Hyde et al.*, 2000] with an EBM coupled to a dynamic ice sheet model [*Tarasov and Peltier*, 1997] simulates ice sheets extending to the equator when the solar luminosity is reduced to 6% below present [*Crowley and Baum*, 1993] and CO_2 levels were ±50% of present. A GCM sensitivity test with a fixed ice sheet indicates that open water in low latitudes can coexist with ice–covered landmasses at CO_2 levels 2.5X present [*Hyde et al.*, 2000]. Previous modeling studies for the last glacial maximum [*Manabe and Broccoli*, 1985; *Hyde et al.*, 1989] suggest that such results are not entirely unexpected, as there is a characteristic length scale of approximately 1500–2000 km in both EBMs [*North*, 1984] and GCMs [*Crowley et al.*, 1994] that constrains the influence of an ice sheet on far–field temperatures.

The possibility of open water coexisting with ice-covered continents is of more than academic interest because this interval represented a critical bottleneck in the evolution of life. Several lines of evidence suggest that metazoans (multi-celled animals) may have evolved before the final "Varanger" glaciation at about 600 Ma. If so it is hard to contemplate such higher lifeforms surviving a completely ice-covered Earth.

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In this paper we examine a suite of Precambrian GCM runs and discuss fields not reported on in *Hyde et al.* [2000]. The purpose is to better constrain the threshold level between full and partial glaciation, as well as describe the rapid transition into a full-glacial state and selected meteorological fields.

Model

The GENESIS 2 GCM consists of coupled global models of the atmosphere, ocean, land surface and sea ice [*Thompson and Pollard*, 1995]. The atmospheric GCM has diurnal forcing, interactive clouds, penetrative plume convection, boundary layer mixing, and a semi–Lagrangian water vapor transport scheme. The ocean component is a slab 50 m thick, i.e. no ocean currents are simulated. Horizontal heat transport by the ocean is modeled as linear diffusion down the local gradient of ocean temperature. The diffusion coefficient is constant in time and depends on both the latitude and zonal land–ocean fraction. Simulations used an atmospheric resolution of T31 (3.75° X 3.75°) and surface model resolution of 2° X 2° and span a range from 0.5–2.5X present. The model has a sensitivity of about 2 °C for a doubling of CO_2.

Land and sea ice are assigned different albedos, with the latter being less due to leads, meltwater and ridging. Sea ice albedo is partitioned into visible and near infrared components, with the former varying between 0.7–0.8 and the latter between 0.4–0.5 (the comparable land ice ranges are 0.7–0.9 and 0.5–0.7). These ranges are temperature dependent, varying according to where the temperature falls 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.

The paleogeographic reconstruction is that of *Dalziel* [1997]. Land ice extent and topography are specified from the dynamic ice sheet model simulation results of *Hyde et al.* [2000] for a 6% reduction in the solar constant, i.e. all land points are covered by ice to a maximum thickness of 4–5 km. The specified orbital parameters for the GCM simulations are that of the present; the *Hyde et al.* [2000] results indicate that orbital variations have little effect on ice sheets of this size and extent.

Results

The initial simulation with a CO_2 concentration 50% that of present was started from a zonally–averaged state with an average temperature of 0° C, and reached an equilibrium temperature of -61° C after 25 years of integration (Figure 1). During the first 19 years the temperature dropped about 0.15° C per month, after which it started decreas-

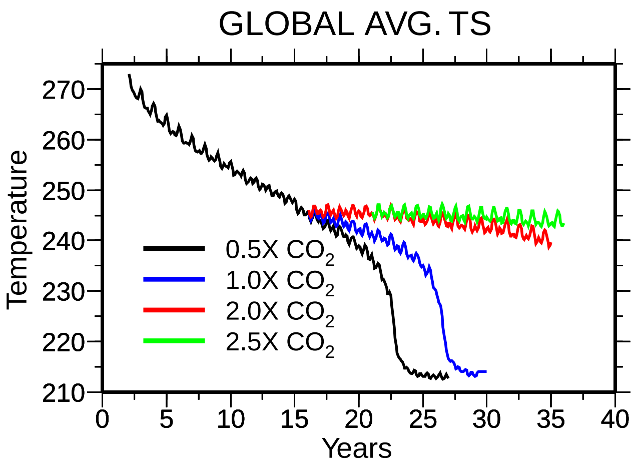

Figure 1. Time series of global average surface temperature for 0.5X (black), 1.0X (blue), 2.0X (red) and 2.5X (green) CO_2 simulations.

ing more dramatically. The most precipitous phase featured a 15° C decrease in a single year. This is suggestive of a climate instability previously found in EBMs and GCMs [*Baum and Crowley*, 1991; *Crowley et al.*, 1994; *Otto-Bliesner*, 1996] and is consistent with the rapid final phase of glaciation postulated by *Hoffman et al.* [1998].

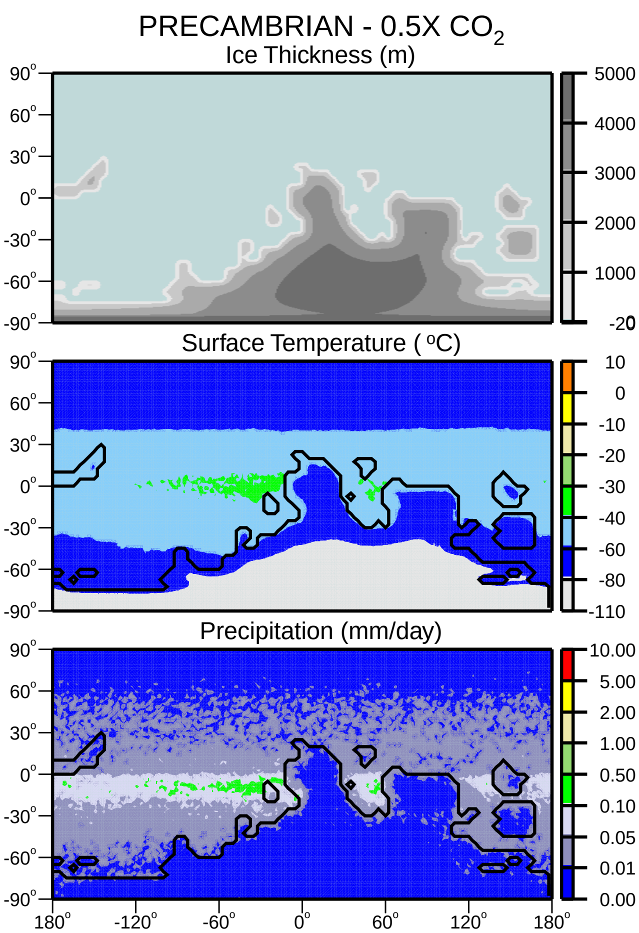

Figure 2. Ice sheet height (m), surface temperature (TS) and precipitation (PPT) fields for 0.5X CO_2 simulation.

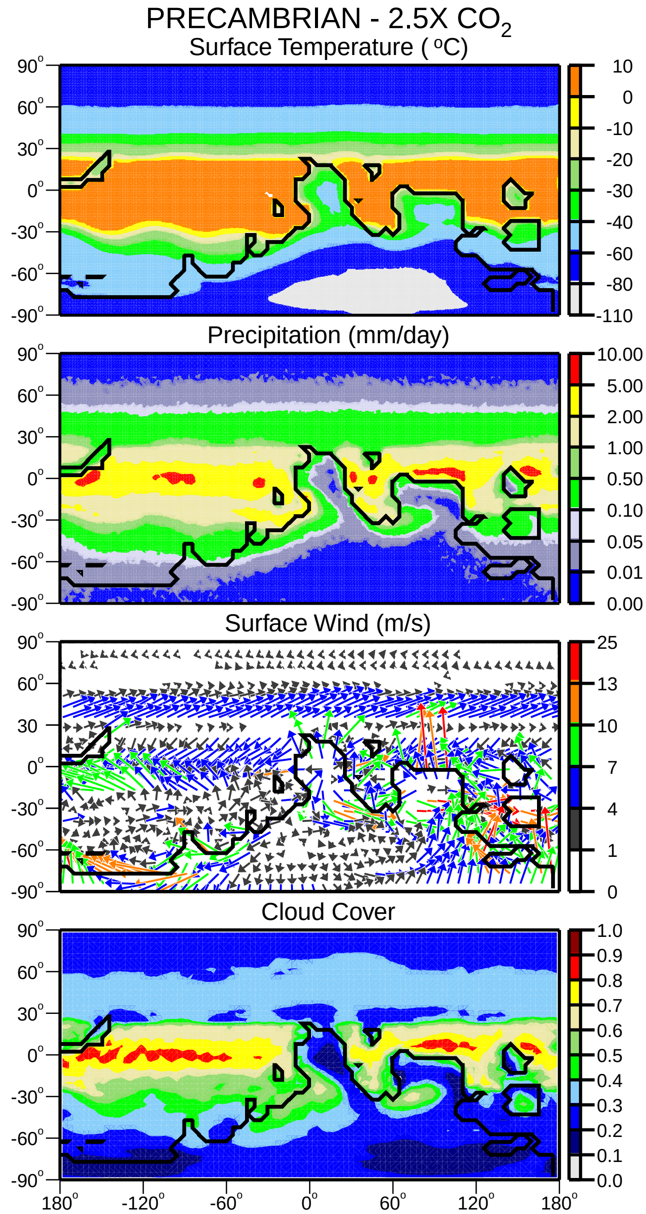

Figure 3. Surface temperature (TS), precipitation (PPT), surface wind (ms^{-1}) and cloud cover fields for 2.5X CO_2 simulation.

The four–year average of the equilibrium surface temperature distribution for the 0.5X CO_2 simulation (Figure 2) shows an ice-covered Earth with minimum temperatures approaching -110° C over the south polar ice cap and maximum temperatures no greater than -37° C at the equator. The accompanying precipitation field supports the radical reduction in precipitation predicted by *Hoffman et al.* [1998] for an ice-covered planet. Nearly all land areas receive less than 0.01 mm/day, with the majority receiving an even smaller amount (0.005 mm/day). A small belt at the equator has 0.05 mm/day, with around 10% of that reaching over 0.1 mm/day in a snowball "Intertropical Convergence Zone" (ITCZ).

A 1.0X CO_2 simulation (Figure 1) was initiated at the end of the 16th year of the 0.5X simulation. It reached the snowball earth state about 8 years after the 0.5X simulation

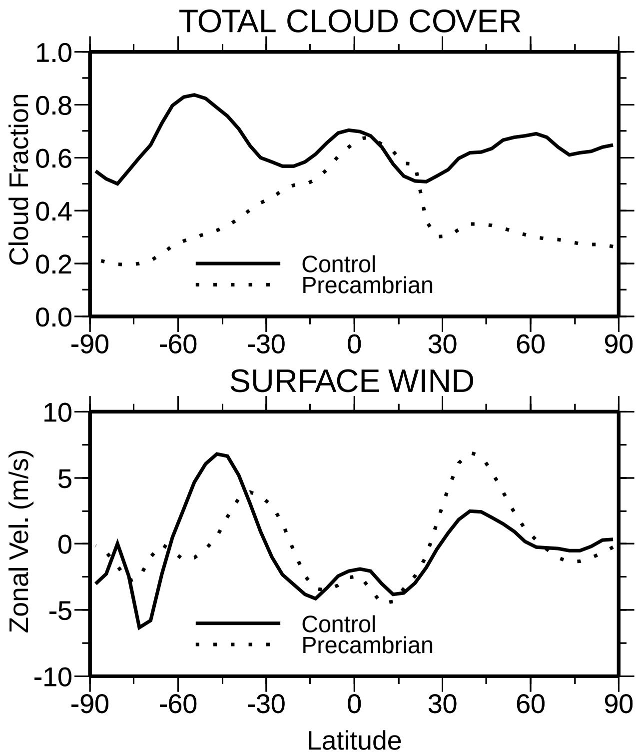

Figure 4. Zonal average of zonal wind component (upper) and total cloud cover (lower) for control and 2.5X CO_2 Neoproterozoic runs.

and experienced a similar final rapid glaciation phase with a final global average temperature about a degree higher (i.e., 214 °C). A 2X CO_2 simulation (also initiated at the end of year 16) exhibited a slow downward temperature trend (Figure 1); this run was therefore truncated. However, a 2.5X CO_2 simulation (Figure 1) is closer to equilibrium. It exhibits no trend until year 27, at which point it trends downward about 0.1 ° C/yr until year 35 when the downward trend flattens out and even begins to reverse. This behavior is qualitatively different from that seen in the 2.0X CO_2 simulation. Although we cannot state with certainty that we have achieved an equilibrium state, we can state that we seem to be either near such a state or have reached it, with the model's internal variability providing oscillations about the mean. We are continuing this simulation as resources permit.

The surface temperature distribution for the 2.5X CO_2 simulation (Figure 3) shows an area of around 150 million square kilometers of open ocean area, about 40% of the present ocean area. The near–zonally symmetric response occurs because the very large atmospheric Rossby radius of deformation at the equator enables the efficient propagation of thermal perturbations in the low latitudes. This pattern is different than the coupled EBM/ice sheet runs (not shown), which only show open water in the equatorial region most distant from the land.

In the 2.5X CO_2 run, sea ice extends to about 25° paleolatitude and reached a maximum thickness of 11 m (the cutoff limit in the model). The coldest temperatures over the ice sheet still approach -110° C, although the maximum temperature at the equator is about +10° C, nearly 40° C higher than for the 0.5X simulation (Figure 2). Maximum precipitation in the same area has increased about two orders of magnitude to around 10 mm/day over that of the 0.5X simulation, with the ITCZ moderately well developed. However, surface temperatures over the ice sheet are below 0° C, indicating that higher CO_2 levels and open water are consistent with ice–covered land areas.

An important result is that global average cloudiness decreases from 0.64 in the control run to 0.44 in the 2.5X CO_2 run. Zonal profiles (Figure 4a) indicate the most dramatic decreases occur in mid-high latitudes. This response reflects the lower water vapor content of the cold Precambrian atmosphere [cf. *Jenkins,* 1993; *Chandler and Sohl,* 2000]. The substantial increase in shortwave radiation receipt at the surface offsets in part the higher albedo of the GENESIS sea ice (vis–á–vis the EBM), thereby limiting equatorward expansion of sea ice. This response could allow an open ocean area to exist, with the AGCM dynamical processes providing an efficient mechanism for spreading the heat zonally.

Mean annual surface winds in the open–water simulation (Figure 3c) illustrate the standard pattern expected for equatorial regions, with trade wind velocities comparable to the control run (Figure 4b) within 15° of the equator, 100% stronger in northern mid–latitudes, and the southern midlatitude westerlies shifted about 15° equatorward in the ice–covered hemisphere. It may seem surprising that zonally–averaged southern hemisphere westerlies are stronger in the control run than in the late Precambrian, but it is necessary to recall that at present the westerly maximum is at a latitude with virtually unrestricted flow. In contrast, the anticyclonic winds of the the polar high over the large Precambrian ice sheet blow opposite to the westerlies at their latitude of maximum velocity (cf. Figure 3c).

The hemispheric asymmetry of the land masses and resulting wind patterns would be expected to produce an east–west asymmetry in tropical SSTs, with colder waters in the eastern part of ocean basins and warmer waters in the west. Cold air outbreaks from the ice sheets could also cause deep–water convection at some low latitude sites. Some of the geological evidence for sea level ice from Australia (approximately 5° N, 20° E) at the equator suggests open–water peritidal deposits [*Williams*, 1998]. The modeled wind fields in the oceanic region east of this land mass could conceivably have supplied the warmth needed to keep the continental shelf sufficiently free of ice (at least seasonally) to allow the formation of such deposits. Dynamic ocean model simulations are planned to investigate the role of the ocean in such open–water solutions.

Discussion and Conclusion

To summarize, GCM experiments narrow the transition CO_2 level from partially ice–covered to fully snowball Earth conditions to slightly greater than twice the present level. The final transitions into the snowball Earth are very abrupt (on the order of one year) and support the basic concept of the snow/ice instability discussed in the above. Our 2.5X CO_2 GCM results show an equatorial ice–free ocean belt; we suggest the open water solution occurs even with the higher sea ice albedo because of significantly reduce cloudiness.

Jenkins and Smith [1999] previously found that a 5X CO_2 level prevented glaciation (with idealized geography). Our results for the 2.5X CO_2 simulation suggest an intermediate state where ice on land can coexist with some open water.

Our results are therefore broadly consistent with Jenkins and Smith as well as with coupled EBM/ice sheet model simulations for this interval [*Crowley et al.*, 2000]. The agreement among these different approaches therefore suggests a region in parameter space between ∼2.5–4.5X CO_2 where CO_2 forcing could have led to an open–water solution coexisting with low latitude glaciation. This range represents a good target for geochemical modelers to determine whether there is perhaps a "CO_2 attractor" in this area of parameter space that might prevent the Earth from plunging into a full Snowball state

Some obvious limitations to this study include: (1) the atmospheric field does not interact with the ice sheet and meltwater discharge; (2) as discussed above, the zonally uniform ocean conditions would be further modified by the easterly wind fields, implying the eventual need for a dynamical ocean model simulation (which we are presently initiating); and (3) deep–ocean convection might occur as a result of cold–air outbreaks from the ice sheet. All of these changes might further modify the patterns we simulate here. A particularly intriguing feature of our results is that the open–water solution may have had the equivalent of an Antarctic katabatic wind/deep–water formation pattern superimposed on an equatorial Pacific–like ocean circulation. We look forward with no small interest to assessing the response of a dynamic ocean model to such forcing.

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