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GCM simulations of Snowball Earth conditions during the late Proterozoic

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Abstract. In order to simulate the Snowball Earth conditions that may have existed during the late Proterozoic we have conducted a series of GCM simulations using a simple 50-meter slab ocean, a reduced solar constant of 6% and varied CO_2 concentrations. In this study, we vary the CO_2 concentration from 100 to 3400-ppmv and use rotation rates corresponding to 18 and 24-hour day-lengths. We also examine the effects of increasing the poleward transport of heat by the oceans. Our results show that below a critical value of approximately 1700 ppmv of atmospheric CO_2, sea-ice and sub-freezing temperatures occur from the poles to the Equator. A global mean annual two meter air temperature of 221°K is found for boundary conditions of 100 ppmv atmospheric CO_2, 6% reduction in solar forcing and a rotation rate corresponding to an 18 hour day. These results confirm those of earlier studies suggesting or implying that low-latitude glaciation occurred during the late Proterozoic. However, since the ocean is the critical factor for low-latitude glaciation, the results should be view cautiously because of the simple slab-ocean used in this study.

1. Introduction

Glaciation has occurred numerous times throughout the Phanerozoic, but rarely in the tropics or on a global scale. In the late Proterozoic, however, there is evidence of glacial deposits on the super-continent, Rodinia, that was apparently located in the tropics. Several studies have suggested that the glacial deposits imply that either the entire Earth was glaciated [*Hoffman*, 1998] or that the glaciation occurred primarily in the tropics [*Williams*, 1993; *Williams et al.*, 1998]. In the case of global glaciation the Neoproterozic Snowball Earth was initiated by a drawdown of atmospheric CO_2 associated with the breakup of the super- continent [*Hoffman*, 1998]. *Williams* [1993] suggest that tropics were subject to glaciation because Earth's obliquity was much higher in the Archean and Proterozoic than present. A high obliquity early in Earth's history was caused by a collision between the Earth and a planetesimal. The high obliquity was reduced in the late Proterozoic by core-mantle dissipation [Williams 1993] or an obliquity-oblateness feedback [*Williams et al.*, 1998].

Jenkins and Scotese [1998] note that a Snowball Earth is not likely in part because of difficulty in shutting down the global ocean because of its large thermal capacity, the wind driven and Thermohaline circulation. *Hoffman et al.* [1998] proposed that sea-ice of 1-kilometer thickness covered the Earth, however, the growth of sea-ice would have been limited by its thickness. As sea-ice thickens the ocean becomes insulated from the atmosphere and eventually there is no communication between sea-ice/ocean and the sea-ice/atmosphere interfaces (.i.e. the conductive heat flux approaches zero). Furthermore in order to produce one kilometer thick sea-ice, the entire column of water (up to 4 km) would need to be cooled to or near the freezing point of water [*Washington and Parkinson*, 1986].

In *Jenkins and Frakes* [1998], we examined the surface climate of an idealized tropical/sub-tropical super-continent when subject to a faster rotation rate, lower solar forcing and lower CO_2 concentrations using the GENESIS GCM. However, we prescribed sea surface temperatures (SSTs) for this set of simulations to examine the climate of the super-continent. We also included a 2-km north-south mountain chain in the hope of producing some region that had sub-freezing temperatures on a year-round basis. We found, however, that sub-freezing continental temperatures could not be maintained with a 6% reduction in the external solar forcing and atmospheric CO_2 concentrations of 100 ppmv. Further, we found the greatest snow depths were along the 2-km mountain chain. We would like to address several questions in this paper. Is global glaciation possible? Are sub-freezing temperatures and snow cover maintained over land area throughout the year? What is the approximate critical threshold of atmospheric CO_2 concentrations needed to counterbalance the reduced solar forcing of the late Proterozoic? What are the limitations of using a simple slab ocean? What additional work is needed for understanding the environmental conditions of the late Proterozoic?

2. Model Description and Experiments

This study also uses the GENESIS GCM with the same idealized super-continent as in *Jenkins and Frakes* [1998]. GENESIS has 12 vertical levels and a horizontal resolution of approximately 4.5° of latitude by 7.5° of longitude. In *Jenkins and Frakes* [1998], oceanic conditions and therefore sea-ice amounts were determined because of the prescribed SSTs. In this set of simulations this constraint is removed and SSTs are computed in a 50-meter slab ocean. This allows us to investigate the possibility of global glaciation. The slab ocean accounts for the thermal heat capacity of the upper ocean, but it does not account for wind-driven or thermal/salinity driven circulation of the deep or upper ocean. There is an annual implied flux of heat at each grid point to represent the poleward transport of heat by the ocean. The implied oceanic heat transport is symmetric about the Equator and based on present-day estimates of oceanic heat transport [*Jenkins and Frakes*, 1998; *Thompson and Pollard*, 1995]. Each simulation is initialized from "Cold-Start" conditions with equatorial temperatures of 303°K and polar temperatures of 267°K. From this initial

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Table 1. Simulations and Boundary Conditions

Simulation	Day-length (hours)	CO_2 mixing ratio	Solar forcing relative to present	Oceanic Heat Transport
24h100	24	100	0.94	present-day
18h100	18	100	0.94	present-day
18h340q	18	340	0.94	2 x present-day
18h1700	18	1700	0.94	present-day
18h3400	18	3400	0.94	present-day

SST configuration, 2 meters of sea-ice is assigned to latitudes poleward of 70° in each hemisphere.

The thermodynamic sea-ice model has six layers and the sea-ice albedo has a value of .8 and .5 in the visible and near infrared wavelengths, respectively, if the temperature is below -5°C . Snow has an albedo of .9 and .6 in the visible and near infrared wavelengths, respectively, if the temperature is below -15°C [*Thompson and Pollard*, 1995]. We have conducted 5 simulations with varied CO_2 concentrations, rotation rate and oceanic heat transport (Table 1). Each simulation has been integrated for 15-25 years with the last 3 years used as the time-averaging period.

3. Results

Figure 1a shows the time evolution of global mean temperatures for each experiment. The slopes increase with decreasing CO_2 concentrations for the five simulations. Sub-freezing global mean temperatures are found when CO_2 concentrations are less than 1700 ppmv. The global mean temperatures for the 100-ppmv CO_2 simulations (24h100, 18h100) fall below 273°K within five simulated model years,. The global mean 2-meter temperatures for the 100-ppmv CO_2 simulations come to near equilibrium after year 15. After 25 years of integration, the 24h100 simulation has an equilibrium global mean temperature of approximately 221°K. Increasing CO_2 concentrations to present-day values and doubling the poleward oceanic heat transport (18h340q) slows but does not prevent global glaciation. After 20 years of model integration, the global mean temperature in the 5 x CO_2 simulation is slowly drifting downward but there is no impending evidence of global glaciation. The global mean annual temperature averaged over the last three years of each simulations are 221.5°K(24h100), 220.9°K(18h100), 237.5°K(18h340q), 278.5°K(18h1700) and 287.5°K(18h3400).

In Figure 1b, the zonally averaged mid-summer (July) two-meter air temperatures are shown. Sub-freezing temperatures are found at all latitudes for the 100-ppmv CO_2 simulations. At slightly higher CO_2 concentrations (18h340q) subfreezing temperatures are found at all locations except those near the Equator. Sub-freezing temperatures are found poleward of 47°N in the 5 × CO_2 simulation (18h1700) and 65°N for the 10 × CO_2 simulation (18h3400) respectively. Further, the steepest meridional temperature gradient is found in low latitudes for the low CO_2 concentration cases, but mid- latitudes for the high CO_2 simulations.

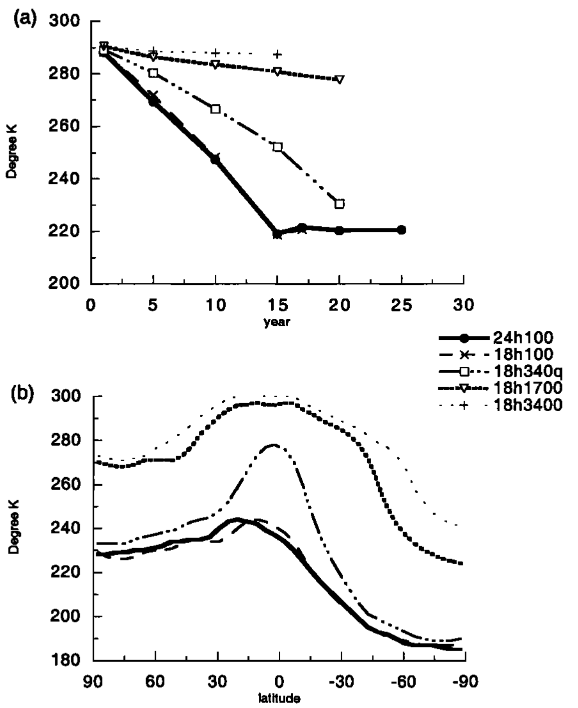

Figure 1. (a) Time evolution for mean annual globally averaged 2-meter air temperatures. (b) July zonally averaged 2-meter air temperatures time averaged over the last three years. Units are Degree K.

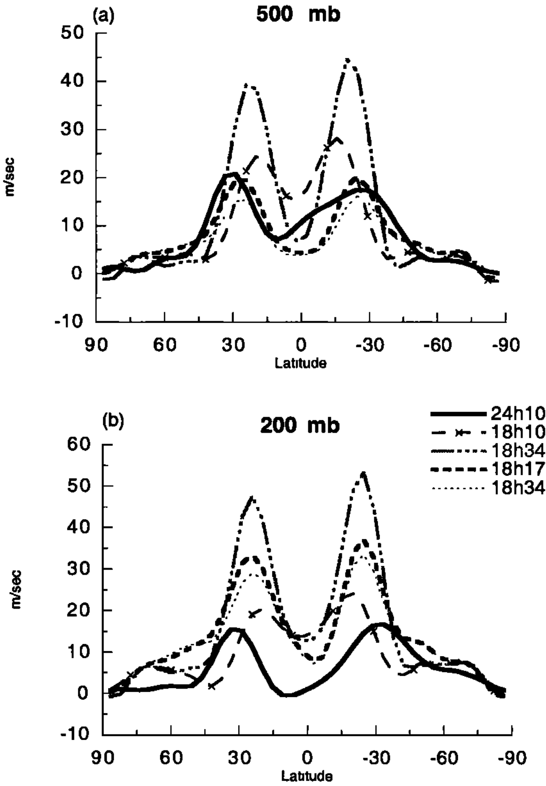

Figure 2. Mean annual zonal winds (U) for the five simulations. (a) 500 mb; (b) 200 mb. Units are m/sec.

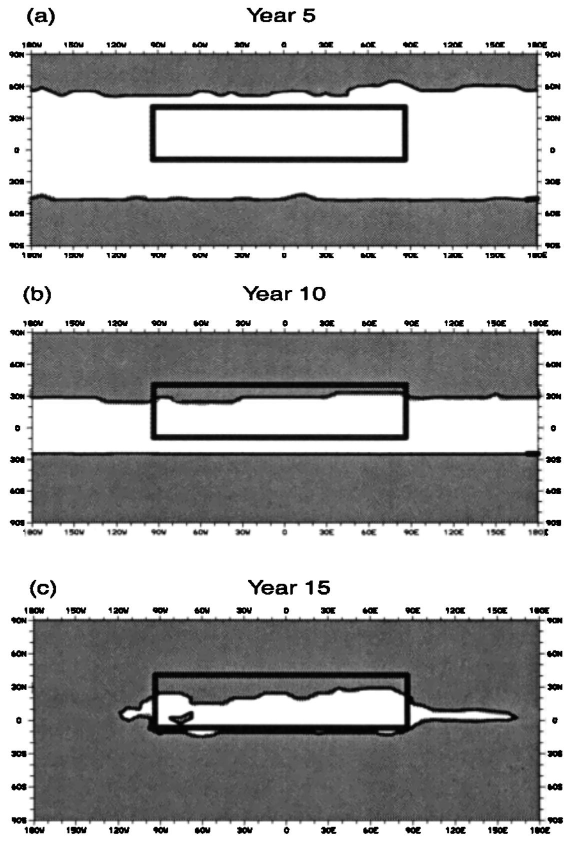

Figure 3. Time evolution of snow cover (shaded). A minimum snow depth of 15 cm is required to for shading.

The equatorial shift in the meridional temperature gradient is consistent with an equatorial shift of the Jet Stream to lower latitudes for the 24h100 and 18h100 simulations (Figure 2a, 2b). Furthermore, the tropopause and the Jet Streams in the Snowball Earth simulations (24h100, 18h100) are vertically displaced from approximately 200 mb to near 500 mb, consistent with the "White Earth Solution" of *Wetherald and Manabe* [1975]. Stronger zonal winds are found at 500 mb (Figure 2a) than at 200 mb (Figure 2b) for the 18h100 and 24h100 simulations in contrast to the other simulations. The strongest Jet Stream is found for the 18h340q simulation because of the large temperature contrast between the low and mid-latitudes. Finally, a faster rotation rate is the cause for the Jet Stream migration into lower latitudes in the other 18 hour day-length simulations [*Jenkins*, 1996].

In Figure 3, the time evolution of mid-summer (July) snow cover (minimum of 15 cm) for the 18h100 simulation is shown. By year 15, snow has covered the entire globe except for a small region over the southern interiors of the idealized super-continent. The small snow-free region is a result of the hydrologic cycle coming to a near complete shutdown at the end of the simulation. Figure 4 shows the zonal mean annual precipitation rates for the five simulations. There is virtually no precipitation falling in the 24h100 and 18h100 simulations, while any precipitation falling in the 18h340q simulation occurs equatorward of the subtropics. The asymmetry in the zonal mean precipitation is caused by the supercontinent where a strong monsoon circulation dominates the southern portions of the landmass. Global mean precipitation rates fall from 143 cm/year in 18h3400 simulation to 2.9 cm/year in 24h100 simulation. All precipitation in the 24h100 and 18h100 simulations fall in the form of snow with deepest snow pack found in the northern regions of the north-south mountain chain.

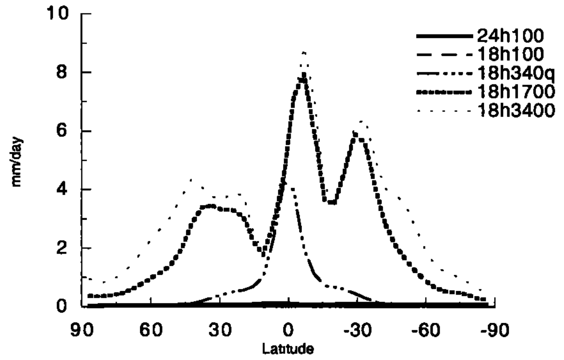

Figure 4. Mean annual zonally averaged precipitation rates for the five simulations. Units are mm/day.

4. Discussion and Conclusion

The results presented here confirm the possibility of a Snowball Earth as reported by *Hoffman et al.* [1998]. The Snowball Earth is initiated when the CO_2 concentrations fall below a critical value and the lower solar forcing of the late Proterozoic cools surface temperatures accelerating the growth of sea ice and snow. A critical value in the range of 5 to 10 × CO_2 (1700-3400 ppmv) to prevent Snowball Earth conditions is implied from the GCM results. These CO_2 values are within a factor of 2 of the estimates by *Berner* [1990] and *Kasting* [1993] at the end of the Proterozoic and the early Phanerozoic. As postulated by *Hoffman et al.* [1998], once Snowball conditions are present, greenhouse gases would have to be elevated by several orders of magnitude to ensure the return of relatively warm climatic conditions.

The critical threshold for atmospheric CO_2 concentrations to avoid global glaciation may, however, be lower than reported here as noted in *Jenkins and Scotese* [1998]. The simple ocean used in this study does not account for the wind-driven or Thermohaline circulation. Further, the slab-ocean does not account for seasonal variations in the mixed layer associated with heating and cooling at the ocean's surface [*Meehl*, 1984]. The results from this study and *Jenkins and Frakes* [1998] constrain climate conditions for a landmass in low latitudes with different solutions derived solely by the state of the ocean. If the ocean freezes over, year-round sub-freezing temperatures over land occur. Conversely if the ocean does not freeze, sub- freezing temperatures and snow cannot be maintained on the idealized super-continent.

The work of *Crowley and Baum* [1993] using a two-dimensional energy balance model (EBM) with a slab ocean produced different results than those reported here for a tropical continent that is parallel to the Equator. They show that Snowball Earth conditions do not occur with a 6% reduction in the solar forcing and CO_2 concentrations of 40 ppmv. There might be several reasons for the different results including the use of interactive clouds, a hydrologic cycle, a thermodynamic sea-ice model and the incorporation of atmospheric motions in the GENESIS GCM.

Because the simple slab-ocean is only a first order approximation to the real ocean it is quite possible that even under lower solar and CO_2 forcing the ocean would not freeze over. Hence it is possible that the global ocean did not freeze over but only the waters surrounding Rodinia. This type of scenario is similar to present-day Antarctica, but the continent is centered in low latitudes instead of high latitudes. In this case, the ice is confined mainly to the shallow seas and attached to a super-continent that has a lower heat capacity. There are several consequences that occur as a result of a partially frozen ocean. (a) Sea-life communities near the continental margins are brought to the brink of extinction, but those communities in ice-free ocean continue to evolve and even flourish. It should be noted that organisms in ice-free areas could be threatened because of a reduction in the amount of nutrients (phosphorus) supplied to the global ocean with a sharp reduction in runoff from the continents. (b) The atmosphere can transport water vapor from the open into land areas and allow for the build-up of ice-sheets, glaciers and snow over land. Further, a faster rotation rate brings the Jet Stream, storm tracks and weather systems into lower latitudes increasing precipitation over the supercontinent. (c) The Earth system can recover from glacial conditions without a massive build-up of atmospheric CO_2.

The hypothesis of *Hoffman et al.* [1998] suggests that the Proterozoic climate oscillated between warm and Snowball Earth conditions. The cause for the Snowball Earth conditions were due to a draw-down in atmospheric CO_2 initiated by the breakup of Rodinia in the Sturtian period or the collision of the Congo Craton with the southern half of Rodinia around 650 Ma [*Scotese*, 1998] which initiated the Vendian glacial events. This view also suggest that low latitude glaciation in the early Proterozoic [*Evans et al.*, 1997] was initiated by a reduction in atmospheric CO_2 or CH_4. However, this mechanism may not necessarily serve as a cause for the Lower Congo glaciation because it is possible that this event occurred before the breakup of Rodinia. There is still disagreement to the exact timing of the Lower Congo glacial events relative to the breakup of Rodinia [*Harland*, 1983; *Kennedy et al.*, 1998]. Moreover, geologic evidence of carbonates, evaporates [*Chumakov and Elston*, 1989] and various forms of life in shallow marine environments [*Seilacher et al.*, 1998] suggest large spatial and temporal differences in climatic state of Rodinia and the oceans in the late Proterozoic. There may have been times when the continent of Rodinia was warm and snow free even in the face of a lower solar constant, while at other times large parts of the super-continent were buried under snow.

The challenge for obtaining a better understanding of the late Proterozoic environment rests in three areas. (1) Paleogeographic reconstruction of Rodinia at various time periods of the late Proterozoic. Paleo-geographic reconstructions at a higher temporal resolution are necessary during the period of rapid change (breakup of Rodinia, Congo Craton collision). (2) Lithological maps of the late Proterozoic at 100 million year time intervals to determine the approximate locations and time periods of various geologic deposits (carbonates, evaporites and glacial deposits). These maps can serve as a proxy for the climate throughout various time-periods of the Neoproterozoic. (3) Climate model simulations using the reconstructed paleo-geography as boundary conditions. Preliminary climate simulations can use a simple slab ocean, however a coupled atmosphere-ocean model capturing the dynamic components of the ocean is necessary to fully understand the problem.

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