Is high obliquity a plausible cause for Neoproterozoic glaciations?

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[1] The main features of the low-latitude Neoproterozoic glaciations remain the subject of controversial debates concerning possible triggers. Here we use an AGCM coupled with a slab ocean to test one of the earliest and simplest explanation for tropical glaciations: a higher obliquity of the Earth's rotation axis. We show that high obliquity may result in an extensive glaciation during the Sturtian episode (750 Ma), due to the location of continental masses in the tropical areas, but cannot produce a large glaciation in the case of mid to high latitude paleogeographies such as those thought to typify the Varangian-Vendian episodes (620–580 Ma). *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 9619 Information Related to Geologic Time: Precambrian; 5416 Planetology: Solid Surface Planets: Glaciation. **Citation:** Donnadieu, Y., G. Ramstein, F. Fluteau, J. Besse, and J. Meert, Is high obliquity a plausible cause for Neoproterozoic glaciations?, *Geophys. Res. Lett.*, *29*(23), 2127, doi:10.1029/2002GL015902, 2002.

1. Introduction

[2] One of the most striking episodes in the Earth's climatic history occurred during the last 250 million years of the Proterozoic era (800–550 Myr). At least two phases of glaciation with low latitude deposits (equatorward of 10°) have been recognized, thanks to recent paleomagnetic studies from South Australia [*Sohl et al.*, 1999] and Northwest Canada [*Park*, 1997]. These are referred to as the "Sturtian" (near 750 Ma) and the "Vendian or Varangian" glaciations (between 620–580 Ma). In 1975, G. Williams [*Williams*, 1975] explained these low-latitude glaciations by using an obliquity of the rotation axis of the Earth higher than 54°, a threshold value for which the equatorial latitudes receive less annual solar insolation than the poles (Figure 1a). Moreover, he collected paleoclimatic indicators (sand wedge structures) that point to a high seasonal temperature contrast close to the equator, a feature that is most readily accounted for by a high obliquity. Conversely, based on large negative carbon isotope anomalies observed in carbonate rocks, [*Hoffman et al.*, 1998] gave new support to the controversial Snowball Earth theory. According to [*Hoffman et al.*, 1998], the carbon isotopic data indicate a collapse of oceanic photosynthesis for millions of years as a result of global glaciation until volcanogenic CO_2 buildup produced a sufficiently large greenhouse effect to melt the ice. The subsequent sudden warming caused a rapid precipitation of calcium carbonate, producing the cap carbonate rocks in sharp conformable contact with the underlying glacial deposits [*Hoffman et al.*, 1998].

[3] Previous simulations with atmospheric general circulation models (i.e. AGCM) showed that a near snowball state could occur with an obliquity of 70° and changes in solar insolation [*Jenkins*, 2000]. That study utilized an idealized rectangular supercontinent straddling the equator to mimic the Sturtian glacial interval (750 Ma). Although paleoreconstructions for that time period are extremely fluid, there is a general consensus favoring a low to mid latitude supercontinent named 'Rodinia' [*Dalziel*, 1997; *Meert*, 2001; *Weil et al.*, 1998]. Other modeling studies have simulated a soft snowball event using the present-day obliquity [*Hyde et al.*, 2000]. Those models relied on a 545 Ma reconstruction where the majority of continents extended across a wide range of latitudes [*Dalziel*, 1997; *Meert*, 2001]. We have thus performed AGCM simulations to investigate the impact of high obliquity when using a more realistic plate configuration for both time periods (Sturtian and Varangian-Vendian).

[4] Laskar et al. [*Laskar et al.*, 1993] showed that if the obliquity became greater than 60°, then the Earth would have experienced large, chaotic variations in obliquity between 60° and 90°. Therefore, we choose to test the high-obliquity hypothesis using the endpoint values, 60° and 90°, since all values in between are allowed and because obliquity may remain unchanged at one of these values over a 10 Ma period.

2. Model and Experiments

[5] We used the Laboratoire de Météorologie Dynamique (LMD) AGCM to perform numerical experiments. This 3D atmospheric model is extensively used to investigate future and past climates, especially during the last glacial/interglacial cycle [*Khodri et al.*, 2001], but it is also used for pre-Quaternary times [*Ramstein et al.*, 1997]. The version used (LMDz) has a horizontal resolution of 4° latitude by 5° longitude and 19 vertical levels. Since land plants had yet to evolve, the land surface has the radiative characteristics of a desert. A 50 m slab ocean that accounts for the storage of heat in the mixed layer is used. As there is absolutely no evidence for the ocean dynamics in a world with a poleward energy excess undergoing severe seasonality, we use a 'swamp' ocean (no heat transport). This hypothesis seems

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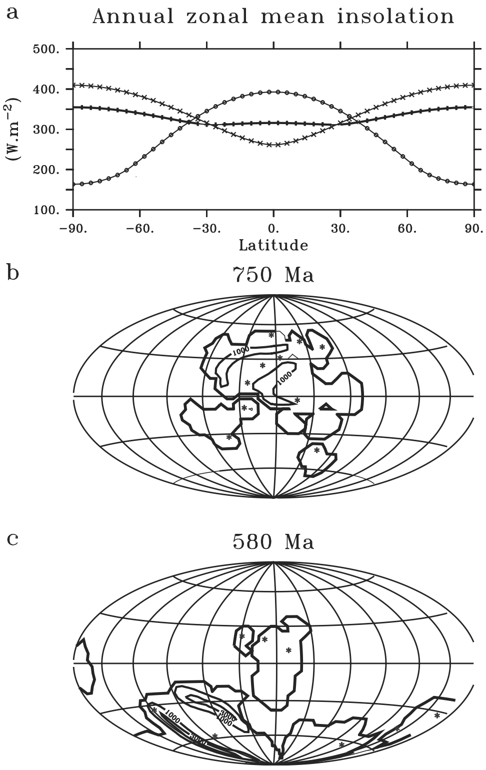

Figure 1. Boundary conditions (a) Insolation forcing at the top of the atmosphere in W m^{-2}. The solid circles are for the present-day obliquity (23.5°) whereas the plus (+) and the crosses (x) are for values of 60° and 90°, respectively. (b) Reconstruction of the supercontinent Rodinia. The relief of 1000 meters are the relic of the 'Greenvillian' -aged (1300–900 Ma) belts. (c) Reconstruction of the 580 Ma paleogeography based on paleomagnetic data described elsewhere. East Africa orogen and Brasiliano-Trans-saharan orogen are represented. The locations of glacial deposits [*Evans*, 2000] are marked by stars.

to us the most reasonable (see below for a discussion of this limitation). Sea-ice is simulated by a change in albedo from 0.1 to 0.6 and a change in heat capacity equivalent to a 10 meters sea-ice layer if the temperature is below −2°C. The LMDz AGCM has been run with four sets of boundary conditions combining two of the widely accepted paleogeographies (Figure 1b and 1c) and two obliquity values. At 600 Ma, the solar luminosity was between 4.7 and 6.3% lower than present-day leading us to use 94% of the modern values in our experiments. The CO_2 value is kept at its modern level of 330 ppm as little is known concerning the CO_2 evolution of the atmosphere prior to the Phanerozoic.

3. Results

[6] The annual mean global surface temperature is very cold for all simulations, with the lowest values for runs at 60° (from −27°C to −34°C, see Table 1). In such a cold climate, the precipitation over the continents is strongly damped by a factor of 10 in comparison with the control simulation (Table 1). The annual insolation at high latitudes is the greatest in the 90° obliquity configuration (Figure 1a) which explains the largest surface of ice-free water in the 90° runs (Figure 2) and also the greatest precipitation in these runs due to the

Table 1. Global Mean Climate Variables

Simulation	Surface Temperature (°C)	Precipitation Over Land (mm/day)	Snow Cover Over Land (%)
CTRL	15.8	2.22	24.1
Sturt90	−27.8	0.37	90.1
Sturt60	−34.0	0.15	98.1
Var90	−27.7	0.24	40.4
Var60	−32.1	0.16	39.1

The last equilibrated five year average 16–20 are used in the table. The CTRL run represents the present-day climate simulated by the model. Sturt and Var are abbreviations for Sturtian and Varangian-Vendian and are used in the Figures 2, 3 and 4. The numbers following indicate the value of the obliquity used. For all runs, the precession and eccentricity are kept to their present-day values.

possibility of large evaporation from the ice-free water (Table 1). The smaller surface of sea-ice found in the 90° runs compared to the 60° runs is at the root of the difference in temperature (via the ice-albedo feedback).

[7] Given the incoming solar radiation distribution (Figure 1a), all continents located between 40°S and 40°N are covered by perennial snow in all runs (Figures 3b, 3c, and 3d) - in general agreement with the available data [*Evans*, 2000]. Our models indicate that snow first accumulates between 20°S and 20°N (Figure 3c) thereby enhancing low temperatures via the albedo effect over continents and favoring the spreading of sea-ice (Figure 2). The poleward

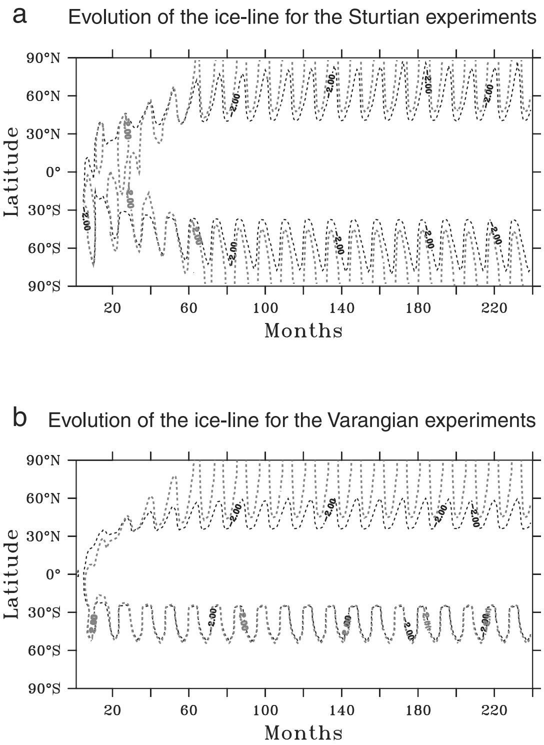

Figure 2. Latitudinal evolution of the monthly-mean sea-ice margin versus model integration time for the Neoproterozoic simulations. (a) Results from the 60° and 90° obliquity experiments for the Sturtian period. (b) Results from the 60° and 90° obliquity experiments for the Varangian-Vendian period. Dashed black and grey lines are for a 60° and 90° obliquity respectively. The sea-ice margin represents the highest latitude with circumglobal sea-ice coverage.

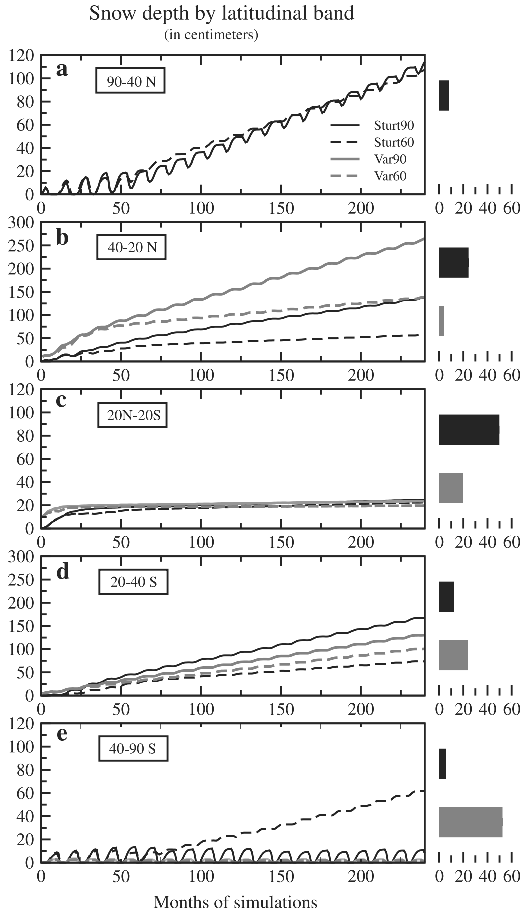

Figure 3. Time evolution of the meridional monthly-mean snow depth on land areas. (a) between 90°N and 40°N; (b) between 40°N and 20°N; (c) between 20°N and 20°S; (d) between 20°S and 40°S; and (e) between 40°S and 90°S. On the right of the picture, the percentage of continents by latitudinal band is shown using black (grey) rectangle for the Sturtian (Varangian-Vendian) paleogeography. From these curves, we see if boundary conditions are sufficient to produce perennial snow cover. For example, in (e), the Sturt90 run does not retain snow in summer, whereas the Sturt60 run shows an increase of snow depth associated with perennial snow cover beginning at year 5 and lasting until the end of the run.

progression of sea-ice and snow (Figures 2 and 3) reduces the source of moisture in the equatorial band. The snow depth thus increases very slowly after a few years of simulation (Figure 3c). We notice that runs with a 90°-obliquity have the largest snow accumulation at latitudes between 20° and 40° (Figures 3b and 3d) due to their weak but relatively active hydrologic cycle compared to the 60°-obliquity runs (Table 1).

[8] For both Sturtian runs and latitudes greater than 40°N, the presence of sea-ice results in a sufficient cooling of summer temperatures (Figure 4) to allow perennial accumulation of snow regardless of the high obliquity value (Figure 3a). On the other hand, the continents poleward of 40°S are candidates for an ice-sheet inception only with a 60°-obliquity (Figure 3e and Figure 4) because of their higher latitudinal position (i.e. see the isolated continent that goes across the latitude 60°S on the Figure 1b). This is evident by the relative importance of continental snow cover between the Sturt60 and Sturt90 runs (Table 1).

[9] For the Varangian-Vendian runs, polar continents experience a spectacular variation in temperatures, going from −70 °C in August to 80°C in January (Figure 4). In fact, all continents poleward of 40°S experience summer temperatures greater than 0°C. Therefore, the balance between accumulation and melting is such that no snow accumulation occurs on more than 50% of continents (Figure 3e). Continental snow cover on our Varangian-Vendian reconstruction reveals values closer to the present-day situation than to a snowball Earth (Table 1).

4. Discussion

[10] Regardless of the paleogeography used, our GCM experiments show that a high obliquity associated with a solar constant decrease is sufficient to produce nucleation sites for the build-up of ice-sheets between 40°N and 40°S. Moreover, the annual variation of equatorial monthly temperatures for the 90°-obliquity runs spans 40°C - a required value for the formation of sand-wedges [*Williams*, 1986]. Previously proposed climatic characteristics under high obliquity are confirmed for this latitudinal range by our study; however, the introduction of two paleogeographies and two obliquities is unique and offers new insights into possible triggers for the Neoproterozoic glacial epochs. Our experiments demonstrate that the ice-sheet latitudinal distribution, previously thought to be limited to latitudes equatorward of 40° [*Evans*, 2000], can spread to higher latitudes depending on both the geographic configuration and the value of the Earth's obliquity. We also note that the high obliquity allows a relatively active hydrological cycle to be maintained (other modeling studies [*Chandler and*

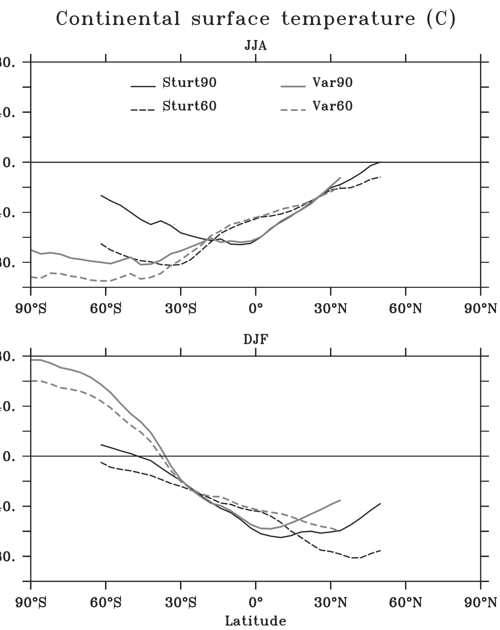

Figure 4. Zonally averaged surface temperature over continents. (a) Northern hemisphere summer; (b) Northern hemisphere winter.

Sohl, 2000; *Hyde et al.*, 2000] show a reduction in atmospheric water content by a factor of 100). This is due to the fact that none of our simulations reached a "hard snowball solution". Rather the sea-ice line oscillates seasonally (Figure 2) allowing a relatively active equatorward transport of moisture to be maintained by the atmosphere.

[11] However, the main strength of our simulations is that they illustrate the role of the latitudinal land-sea distribution as a limiting factor in the triggering and extent of glaciations on a high obliquity Earth. During the Sturtian period, given the insolation forcing, the low to mid-latitude settings of most of the continents and the polar oceans allow the source of moisture and the cold temperatures over the supercontinent to be maintained year round. This in turn provides optimal conditions for generating perennial snow (Figures 3 and 4 and Table 1). Conversely, because 50% of the continents are located in the 40°S–90°S latitudinal band during the Varangian-Vendian period (Figure 3e), the paleogeography, combined with the high obliquity insolation forcing, does not succeed in generating perennial snow on all continents. This result rules out high obliquity as a possible trigger for the Varangian-Vendian glacial period.

[12] Our GCM results, while clear and straightforward, are nonetheless subject to some uncertainties. (1) The exact latitudinal extent of the sea-ice and of the perennial snow cover are dependant on the absence of oceanic heat transport (the oceanic heat transport would slow the sea-ice migration towards the mid-latitudes). However, other modeling studies with two different climate models (the CCM1 with oceanic heat transport [*Oglesby and Ogg*, 1999] and the GENESIS with no oceanic heat transport [*Jenkins*, 2000]) have shown that tropical glaciations are achieved when using high obliquity values and reduced solar constant, reinforcing our model results. We expect that the basic nature of our results will hold even with the addition of an oceanic heat transport. In fact, regardless of the heat transport model used, it would not alter our conclusion that a high obliquity can not explain the extensive glaciations for the Varangian-Vendian period (to the contrary, it would reinforce our results as it may tighten the latitudinal band where glaciations occurs). (2) More importantly, it should be cautioned that some Varangian-Vendian glacial deposits lack radiometric age determinations [*Evans*, 2000] and there are no consensus paleogeographic reconstructions for the 580–700 Ma time period [*Meert and Powell*, 2001]. Nevertheless, recent geochronologic studies [*Gorokhov et al.*, 2001; *Thompson and Bowring*, 2000] help constrain the age of at least two of these glacial deposits. *Gorokhov et al.* [2001] estimate the age of the Vendian-Varangian glaciations in Norway falls between 630–560 Ma. *Thompson and Bowring* [2000] provide maximum age constraints on the Squantum tillite of the Boston Basin of 596 Ma. Thus, we feel that our Varangian-Vendian reconstruction is more applicable to our model than the 545 Ma reconstruction used in earlier climate models [*Hyde et al.*, 2000].

[13] However, if one chooses to accept the high obliquity as a possible trigger for the Sturtian glaciation, a new mechanism to recover from the high obliquity must be found. The only valid mechanism, climate friction [*Williams et al.*, 1998], requires the presence of an extended ice cap on the South polar supercontinent which is at odds with the models presented in this paper.

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