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Testing paleogeographic controls on a Neoproterozoic snowball Earth

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[1] The distribution of continents during the Neoproterozoic has been hypothesized to play an important role in the initiation of an ice-covered Earth. In this study, the influence of paleogeography on the Neoproterozoic climate is evaluated using a fully coupled ocean-atmosphere general circulation model (FOAM). Three simulations were completed with different continental distributions. Each simulation included a reduced solar luminosity (93% of present-day) and low atmospheric CO_2 (140 ppmv). Model results indicate that a low-latitude concentration of continents leads to lower tropical temperatures, through reduced receipt of shortwave radiation and a smaller tropical greenhouse effect, but does not significantly affect high-latitude temperatures or sea-ice extent. In contrast, the presence of snow-covered, mid- and high-latitude continents increases the sensible heat transport over the ocean, giving rise to sea-surface cooling, deep-water formation, and an advanced sea-ice margin. Nonetheless, an ice-covered Earth is not simulated in these experiments. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 9619 Information Related to Geologic Time: Precambrian

1. Introduction

[2] *Kirschvink* [1992] first proposed the concept of a snowball Earth to explain widespread Neoproterozoic glaciogenic sequences. In its original conception, the snowball Earth described a snowball Earth with extensive continental glaciation and pack ice over most the middle and high latitudes [*Kirschvink*, 1992]. More recently, the snowball Earth hypothesis has been revived and "hardened" by *Hoffman et al.* [1998] on the basis of $\delta^{13}C$ data from carbonate rocks capping low-latitude Neoproterozoic glacial deposits, which are interpreted to reflect a drastic decline in marine productivity. In its reincarnation, the snowball Earth describes a completely ice-covered world.

[3] One of the major challenges facing the snowball Earth hypothesis is understanding the conditions that led to its initiation. A reduction of atmospheric CO_2 through silicate weathering of tropical continents has been cited as a potential trigger for the development of low-latitude glaciation [*Worsley and Kidder*, 1991; *Kirschvink*, 1992; *Hoffman and Schrag*, 2000]. Low-latitude, high-albedo continents are also an attractive component of the snowball Earth hypothesis, because they would reflect tropical shortwave radiation back to space [*Kirschvink*, 1992]. While Neoproterozoic reconstructions position most of the continents in the mid- and high-latitudes of the Southern Hemisphere [*Dalziel*, 1997; *Chandler and Sohl*, 2000], paleomagnetic data place few constraints on the paleogeography. Most of the paleogeographic constraints are based on stratigraphic relationships between tectonic plates [*Chandler and Sohl*, 2000].

[4] The extent to which paleogeography promoted a snowball Earth remains an unresolved question. Climate model studies of the Neoproterozoic have used a variety of paleogeographies, including idealized supercontinents [*Crowley and Baum*, 1993; *Jenkins and Frakes*, 1998; *Jenkins and Smith*, 1999; *Poulsen et al.*, 2001], present-day configurations [*Oglesby and Ogg*, 1998], and Late Neoproterozoic reconstructions [*Chandler and Sohl*, 2000; *Hyde et al.*, 2000; *Baum and Crowley*, 2001]. Yet, it is difficult to discern the climatic differences due to paleogeography, because these studies employed climate models of varying complexity and incorporated an array of boundary conditions.

[5] In this study, the influence of paleogeography on the Neoproterozoic climate is systematically investigated using the Fast Ocean-Atmosphere model (FOAM), a coupled ocean-atmosphere model. *Poulsen et al.* [2001] previously used FOAM to demonstrate that ocean dynamics play a critical role in halting the seasonal advance of the sea-ice line, but noted that the numerical results may have been sensitive to the idealized paleogeography that was used. This study attempts to address whether the land/ocean configuration, and particularly a tropical concentration of continents, could have been a sufficient forcing to induce a snowball Earth. To this end, three paleogeographic reconstructions were used (Figure 1). The first reconstruction consists of a single, idealized supercontinent centered on the equator and is similiar to the paleogeographies used by *Jenkins and Frakes* [1998], *Jenkins and Smith* [1999], *Crowley and Baum* [2001], and *Poulsen et al.* [2001]. The second reconstructions includes three tropical continents that cover 75% of the tropical region. The final paleogeography is based on the 545 Ma reconstruction by *Dalziel* [1997], in which the continents extend from high to low latitudes in the Southern Hemisphere. The total land fraction in these reconstructions is 21, 36, and 33%, respectively.

2. Model Description and Numerical Experiments

[6] The model experiments were completed using the Fast Ocean-Atmosphere Model (FOAM), a fully coupled ocean-atmosphere GCM. The atmospheric component of FOAM is a parallelized version of NCAR's Community Climate Model 2 (CCM2) with the upgraded radiative and hydrologic physics

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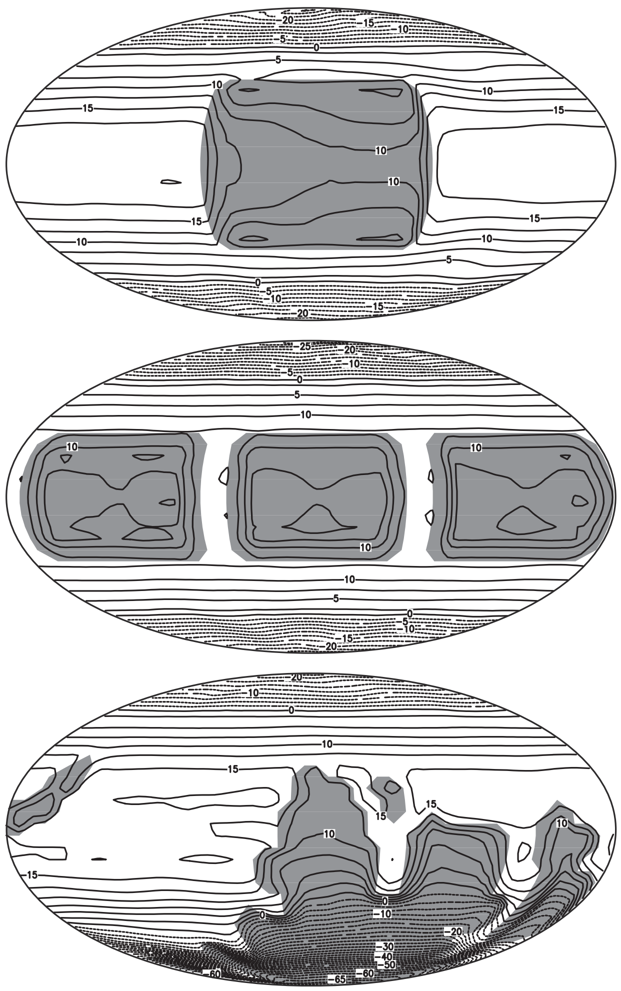

Figure 1. Mean-annual surface temperature for the (a) supercontinent, (b) three-continent, and (c) 545 Ma experiments averaged over the final 5 years (i.e., years 51–55) of the experiments. The contour interval is 2.5°C. Dashed lines represent negative temperatures.

incorporated in CCM3 version 3.2 (described in *Kiehl et al.* [1996]). The atmospheric model contains 18 vertical levels and a horizontal resolution of R15 (4.5° × 7.5°). The ocean component (OM3), is dynamically similar to the GFDL Modular Ocean Model (MOM) and has been optimized for performance and scalability on massively parallel processing computers. OM3 contains 16 vertical layers and uses a 128 × 128 point grid (1.4° × 2.8°). The ocean and atmospheric models are linked by a coupler, [*Jacob*, 1997]. In this version of FOAM, sea-ice forms when an ocean grid cell is cooler than −1.88°C. Sea ice has a constant thickness and albedos of .70 and .50 in the visual and near-infrared wavelengths. FOAM does not yet include sea-ice dynamics.

[7] To investigate the influence of paleogeography on the Neoproterozoic climate, three numerical experiments were completed with different paleogeographic reconstructions as described in the *Introduction*. Hereafter, these experiments will be referred to as the supercontinent, three-continent, and 545 Ma runs. The supercontinent and three-continent runs include N-S mountain ranges on their western and eastern margins with elevations of 500 m. Elsewhere, the relief is 50 m. The 545 Ma experiment has a uniform elevation of 50 m.

[8] All other boundary conditions were identical between the experiments. The ocean has a uniform depth of 5000 m. Since land plants had yet to evolve by the Neoproterozoic, the land surface in the model has the radiative characteristics of a desert (albedo of .35 and .51 in the visible and near-infrared wavelengths, respectively). At 600 Ma, the solar luminosity was between 4.7 and 6.3% lower than present [*Crowley and Baum*, 1993]. To facilitate snowball conditions, a 7% reduction in the solar constant and a CO_2 value of 140 ppmv was used in our experiments. The CH_4 concentration was set to the modern value (1714 ppbv). The model eccentricity, obliquity, precession, rotation rate, and ozone concentrations were defined as modern values. To further facilitate snowball conditions, the ocean was intialized with a cold temperature profile specified as follows: 10° (10 m), 5° (30 m), 2° (75 m), 1° (125 m), 0° (200 m), −1° (300 m), and −1.5° C (500 to 5000 m). The ocean was initialized with a uniform salinity of 34.9 psu.

[9] Each Neoproterozoic experiment was run in fully coupled mode for at least 55 years. After 55 years, globally average temperatures in the ocean and atmosphere are increasing and the sea-ice line has stabilized. Although 55 years is not enough time for the deep ocean to completely equilibrate, it is sufficient for the development of the major oceanic circulation features. To test this point, the supercontinent experiment was run for over 200 years. In year 201, the oceanic circulation is qualitatively similar to that of year 55 (see Results). With further integration, the main change is a gradual warming of the deep and intermediate ocean. The global average ocean temperature increased from −1.11° C in year 55 to −0.78° C in year 201.

3. Results

[10] The model results do not support the snowball Earth hypothesis as currently formulated. None of the experiments exhibits an ice-covered solution. The maximum equatorward extent of the sea-ice margin is ~42° S in the 545 Ma experiment and ~51° in the box-continent runs. In comparison to the box-continent experiments, the sea ice in the 545 Ma run displays a dampened seasonal oscillation in the Southern Hemisphere (not shown). The sea-ice margin in the Northern Hemisphere varies little between experiments. In all three experiments, sea ice is nearly always covered with snow, which has a significantly higher albedo (0.9 and 0.6 in the visual and near-infrared wavelengths) than sea ice at cold temperatures.

[11] After a rapid initial decline through model year 10, globally averaged mean-annual surface temperatures in all three experiments experience a gradual ascent through year 55 (Figure 2). At year 55, the supercontinent, three-continent, and 545 Ma experiments have globally average surface temperatures of 5.69°, 3.84°, and −0.58° C, respectively. Mean-annual surface temperature distributions vary considerably between the experiments (Figure 1). In general, the 545 Ma experiment is characterized by colder mid- and high-latitude surface temperatures in the Southern Hemisphere (Figure 1c). The three-continent experiment exhibits tropical sea-surface temperatures

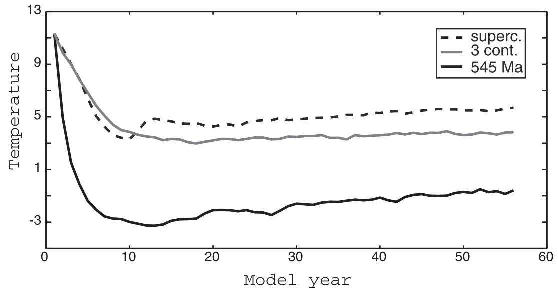

Figure 2. The globally-averaged, monthly surface temperature (in °C) through the 55 years of model integration. After an initial fall, surface temperatures rise steadily through year 55.

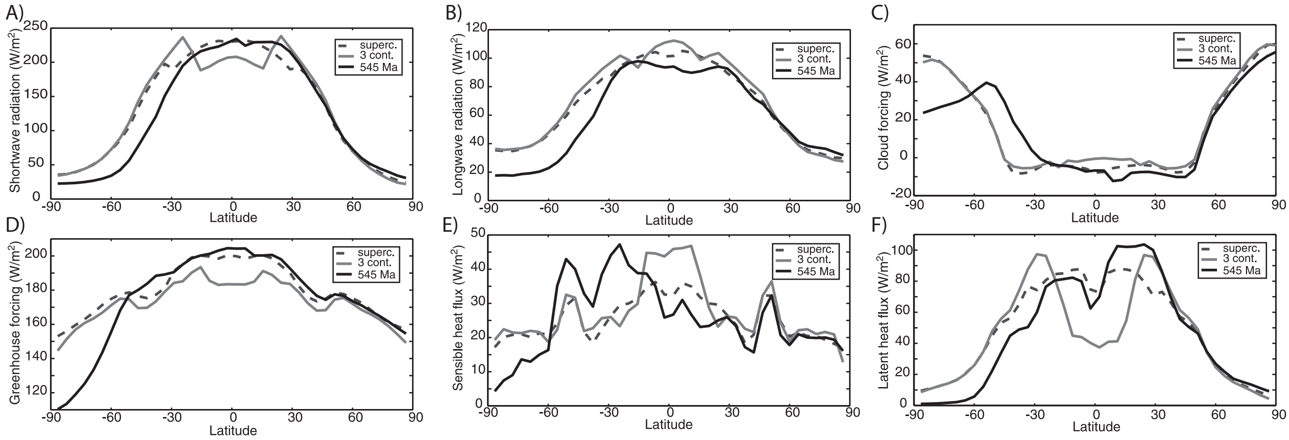

Figure 3. Mean-annual zonally-averaged (a) surface shortwave radiation, (b) surface longwave radiation, (c) surface cloud forcing, (d) greenhouse forcing, (e) sensible heat flux, and (f) latent heat flux. These values were averaged over the final 5 years (i.e., years 51–55) of the experiments. Units are Wm^{-2}.

that are several degrees cooler than the other experiments (Figure 1b).

[12] In the 545 Ma run, the cold high-latitude continental surface temperatures in the Southern Hemisphere result mainly from a reduction in shortwave radiation receipt over the continents (Figure 3a). This effect is enhanced by annual continental snow coverage that extends equatorward to 46° S. During winter, continental snow cover reaches as far north as 19° S. In contrast, continental snow coverage in the supercontinent and three-continent experiments is limited to less than 0.5 cm on the poleward margins of the continents during the winter months. In addition to snow coverage, high-latitude low cloud coverage serves as a positive feedback to the cold continental temperatures in the 545 Ma experiment. The cloud ice fraction predicted by the model is temperature dependant between −10 and −30°C [*Kiehl et al.*, 1996]. In the 545 Ma experiment, not only are atmospheric temperatures in the high-latitude southern hemisphere colder, annual low cloud coverage is higher than in the other experiments. The fraction of low clouds ranges from 78 to 95% between 50° and 90° S, nearly 20% higher than the high-latitude low cloud coverage in the other experiments. As a result, cloud forcing is lower over this region (Figure 3c).

[13] The cold continental temperatures in the 545 Ma run have a significant impact on the sea-ice extent in the Southern Hemisphere. The advection of cold continental air over the ocean surface lowers the mid- and high-latitude sea-surface temperatures and promotes the equatorward expansion of the sea-ice line. This result is demonstrated by the sensible heat fluxes over the Southern Hemisphere (Figure 3e). Over the mid-latitude oceans, the sensible heat flux is nearly twice as large in the 545 Ma experiment as in the other experiments (not shown).

[14] In the three-continent experiment, the cool tropical sea-surface temperatures are a consequence of both a reduction in shortwave radiation (Figure 3a) over the continents and a relatively small tropical greenhouse effect (Figure 3d). With little tropical surface ocean area, the source of atmospheric water vapor is limited, as demonstrated by the relatively low tropical latent heat flux (Figure 3f). Notably, a comparison of sea-surface temperatures between the supercontinent and three-continent experiments reveals that the tropical climate has little effect on high- and mid-latitude surface temperatures (Figures 1a and 1b).

[15] It is worth noting that the warmest tropical sea-surface temperatures occur in the supercontinent experiment (Figure 1), though the tropical greenhouse forcing is somewhat greater in the 545 Ma experiment (Figure 3c). The lower tropical temperatures in the 545 Ma experiments result from a greater ocean heat transport in the Southern Hemisphere (not shown). In fact, there are significant differences in the ocean circulation between the 545 Ma experiment and the box-continent experiments. In the idealized experiments, relatively warm, saline waters from the subtropics underpin fresh, high-latitude surface waters (Figures 4a and 4b). In the 545 Ma experiment, the deepest waters form mainly in high-latitude source regions of the Southern Hemisphere. These waters are colder and more saline than the deep-penetrating waters in the idealized experiments (Figure 4c).

[16] *Poulsen et al.* [2001] demonstrate that convective mixing in the ocean halts the seasonal sea-ice advance by warming the region in front of the ice margin during the winter months. The same process acts to halt the winter sea-ice advance in the experiments described here. The zonally average heating contribution by convective mixing ranges from 6–8° C per month between experiments.

4. Discussion and Conclusions

[17] The coupled ocean-atmosphere GCM experiments do not support the hypothesis that a world dominated by tropical continents would have promoted a Neoproterozoic snowball Earth. In the extreme case with 75% of the tropical area designated as land, the reduction in tropical shortwave radiation receipt and greenhouse forcing results in relatively cool tropical sea-surface temperatures, but has little effect on mid- and high-latitude climate. In contrast, the presence of mid- and high-latitude continents in the 545 Ma experiment promotes snow coverage over much of the continent, high-latitude sensible heat loss over the ocean, sea-surface cooling, and sea-ice formation. *Poulsen et al.* [2001] report that the sea-ice margin reached ~55° latitude in a simulation with a tropical supercontinent and a 5% reduction of the solar constant. In this study, the sea-ice lines in the supercontinent and 545 Ma experiments advanced to ~51° and ~42°, respectively. Thus, the position of the sea-ice line is more sensitive to the paleogeographic differences explored here than the 2% decrease in the solar constant from 95% to 93%.

[18] A number of studies have explored the parameter space within GCMs to identify the region susceptible to the initiation of a snowball Earth [e.g., *Jenkins and Frakes*, 1998; *Jenkins and Smith*, 1999; *Chandler and Sohl*, 2000; *Hyde et al.*, 2000; *Baum and Crowley*, 2001]. Several of these studies have identified $p\mathrm{CO}_2$ thresholds, below which a climate instability leads to a snowball Earth. In comparison to these uncoupled atmospheric GCM studies, FOAM exhibits a reduced climatic sensitivity to reductions in solar luminosity and $p\mathrm{CO}_2$, largely as a result of ocean dynamics

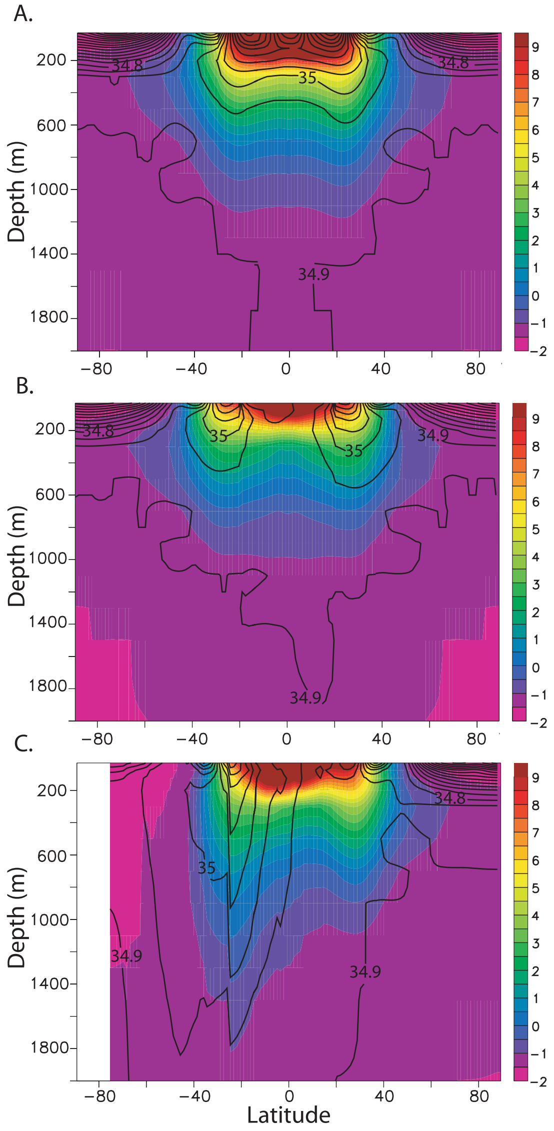

Figure 4. Mean-annual zonally-averaged ocean temperatures (shaded) and salinity (contoured) for the upper 2000 m. Results are illustrated for the (a) supercontinent, (b) three-continent, and (c) 545 Ma experiments. Temperature and salinity were time-averaged over the final 5 years of the experiments (i.e., years 51–55). The contour intervals are 0.5°C and 0.05 psu.

[*Poulsen et al.*, 2001]. It is unlikely that a further reduction of pCO_2 in the FOAM Neoproterozoic experiments will result in an ice-covered Earth, since radiative forcing has a logarithmic dependence on CO_2. This raises the possibility that alternative triggers are required to initiate a snowball Earth.

[19] There is no question that the snowball Earth hypothesis presents unprecedented challenges to our understanding of the climate system and our ability to predict such extreme climate using GCMs. In its prediction of middle and high latitude sea ice, the Neoproterozoic experiment with the 545 Ma geography is consistent with *Kirshivink*'s [2001] original concept of a "soft" snowball Earth. Nonetheless, the simulation of a "hard" snowball Earth using reasonable Neoproterozoic boundary conditions remains an elusive goal, mainly due to the thermal inertia of the oceans. Model inadequacies may also contribute to this failure. In particular, the absence of dynamic ice-sheet and sea-ice models in FOAM may prove to be important to the simulation of a snowball Earth. Additionally, the coarse resolution of the model and the absence of significant mountain ranges may prevent the initiation of glaciers on tropical continents.

[20] At the same time, the snowball Earth hypothesis is evolving as additional observations are gathered and is likely to undergo further refinement. For instance, methane has been implicated as the source of isotopically depleted carbon, possibly explaining the $\delta^{13}C$ excursion associated with the glaciogenic sequences [*Kennedy et al. 2001*]. Additional refinements of the snowball Earth hypothesis may also bring the model predictions and data interpretations into closer agreement.

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