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Impact of ocean dynamics on the simulation of the Neoproterozoic "snowball Earth"

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Abstract. A fully coupled ocean-atmosphere general circulation model (the Fast Ocean-Atmosphere Model) is used to simulate the Neoproterozoic climate with a reduced solar luminosity (95% of present-day), low atmospheric CO_2 (140 ppmv), and an idealized tropical supercontinent. Two coupled simulations were completed with present-day and cold initial ocean temperatures. These experiments are compared with uncoupled (i.e., mixed-layer) model experiments to determine the impact of a dynamical ocean on the Neoproterozoic simulations. In contrast to global sea-ice coverage in the uncoupled experiments, the sea-ice margin seasonally advances to 46 and 55° latitude in the coupled experiments. The coupled simulations demonstrate that dynamic ocean processes can prevent a snowball solution and suggest that a reduced solar luminosity and low atmospheric CO_2 are not by themselves sufficient conditions for a snowball solution. Heat exchange through vertical mixing in the mid-latitudes, caused by static instability, is identified as the primary process halting the advance of the sea-ice margin.

Introduction

Neoproterozoic glaciations represent the most extreme climate events in Earth history [*Harland,* 1964]. Although the original paleomagnetic data used to infer low-latitude Neoproterozoic glaciations were called into question [*Meert and van der Voo,* 1994], new paleomagnetic evidence from South Australia and Northwest Canada confirmed their low-latitude setting (equatorward of 10°) [*Schmidt and Williams,* 1995; *Park,* 1997; *Sohl et al.,* 1999]. To explain these low-latitude glacial deposits and the presence of glaciogenic iron deposits, *Kirschvink* [1992] proposed a snowball Earth with nearly global sea-ice coverage and thin continental ice cover. The snowball Earth hypothesis gained considerable support from carbon isotope data from carbonate rocks capping Neoproterozoic glacial deposits [*Hoffman et al.,* 1998]. *Hoffman et al.* [1998] interpreted the large negative carbon isotope anomalies in these carbonates to indicate that the biological productivity in the surface ocean collapsed for millions of years as a result of global glaciation. Snowball Earth conditions were supposed to have been instigated by the transfer of atmospheric CO_2 to marine sediments through continental weathering of tropical continents [*Hoffman et al.,* 1998]. Cap carbonates are also consistent with the hypothesized mechanism for escape from a snowball condition- the onset of extreme greenhouse conditions brought on by millions of years of volcanic outgassing [*Hoffman and Schrag,* 2000].

The possibility of a snowball Earth raises fundamental questions about the Earth's climate. Central to this debate is understanding the conditions that gave way to a snowball Earth. Climate models of the Neoproterozoic have produced conflicting results. *Budyko* [1969] and *Sellers* [1969] first demonstrated that a reduction of the solar constant by a few percent could produce an ice covered Earth in energy balance models (EBMs). Since then, paleogeography [*Crowley and Baum,* 1993], dynamic ice sheets, [*Hyde et al.,* 2000], pCO_2 [*Ikeda and Tajika,* 1999], and the efficiency of latitudinal heat transport [*Held and Suarez,* 1974; *Ikeda and Tajika,* 1999] have been identified as important factors that influence glacial growth in EBMs. Snowball conditions have been simulated in the GENESIS version 1.02 atmospheric general circulation model (GCM) [*Jenkins and Frakes,* 1998; *Jenkins and Smith,* 1999]. These GCM studies have demonstrated that a snowball solution requires very specific boundary conditions including a reduced solar luminosity and low pCO_2. In contrast, snowball conditions were not simulated in either the GENESIS version 2.0 GCM [*Hyde et al.,* 2000] or the GISS GCM [*Chandler and Sohl,* 2000].

The treatment of the ocean varies considerably between these modeling studies. However, a common feature is their simplified, nondynamical nature. In the modern climate, the ocean plays an important role in the global heat budget through the seasonal storage and transport of heat. Here, we investigate how ocean dynamics influence the simulation of the Neoproterozoic Earth. Neoproterozoic climates simulated using an atmospheric GCM linked to (a) a mixed-layer ocean model with no heat transport, (b) a mixed-layer ocean model with diffusive heat transport, (c) an ocean GCM initialized with present-day ocean temperatures, and (d) an ocean GCM initialized with cold ocean temperatures are compared. Our model results indicate that the ocean plays a fundamental role in the prevention of snowball conditions.

Model Description and Experiments

The 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 incorporated in CCM3 v. 3.2.

The atmospheric model contains 18 vertical levels and a horizontal resolution of R15 (4.5° x 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 parallel processing computers. OM3 contains 16 vertical layers and uses a 128 x 128 point

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Mercator grid (1.4° x 2.8°). The ocean and atmospheric models are linked by a coupler, which implements the land and sea ice models and calculates and interpolates the fluxes of heat and momentum between the atmosphere and ocean models [*Jacob,* 1997]. In FOAM, sea-ice forms when an ocean grid cell is cooler than -1.90°C and has albedos of .70 and .50 in the visual and near-infrared wavelengths.

FOAM successfully simulates many aspects of the present-day climate and compares well with other contemporary medium-resolution climate models [*Jacob,* 1997]. Important modern climatic features, such as North Atlantic Deep Water and Antarctic Bottom Water, are simulated [*Jacob,* 1997]. In general, the simulated, present-day ice margin compares favorably with the observed ice margin, though there is too much ice growth in the North Atlantic during the winter and too much melting in the Arctic during the summer.

Neoproterozoic model experiments were completed using FOAM in fully coupled and mixed-layer modes. In the mixed-layer experiments, the atmospheric model was linked to a 50-meter mixed-layer ocean model, which parameterizes heat transport through diffusion. The meridional diffusion coefficient in the mixed-layer model is identical to that used in OM3 (4000 m^2 s^{-1}). This value was selected to elucidate the effect of diffusion on the evolution of the sea-ice margin and not because it produces a particularly good present-day climate. (In fact, in a present-day mixed-layer experiment with this diffusive coefficient, the sea-ice margin extends too far equatorward.) The horizontal diffusive coefficients were set to zero in the experiment with no ocean heat transport. Since the deep ocean relaxation time requires prohibitively long model integrations, two coupled simulations were completed with different initial ocean temperature prescriptions (present-day and cold). The cold initial temperature profile was 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).

Identical boundary conditions were implemented in each of the Neoproterozoic experiments and include a rectangular supercontinent centered on the equator, similar to those of *Crowley and Baum* [1993], *Jenkins and Frakes* [1998], and *Jenkins and Smith* [1999], with two 500-m N-S mountain ranges on its western and eastern margins. Elsewhere, the relief is 50 m. The ocean has a uniform depth of 5000 m. Since land plants had yet to evolve, 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). At 600 Ma, the solar luminosity was between 4.7 and 6.3% lower than present [*Crowley and Baum,* 1993]. A solar luminosity of 95% of the modern was used in our experiments. To facilitate snowball conditions, a CO_2 value of 140 ppmv was specified. The CH_4 concentration was set to a modern value (1714 ppbv). The model eccentricity, obliquity, precession, rotation rate, and ozone concentrations were defined as modern values.

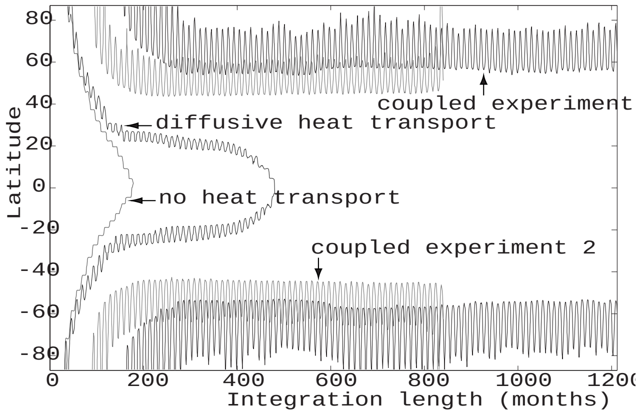

Figure 1. Monthly-mean sea-ice margin versus model integration time for the mixed-layer and coupled Neoproterozoic simulations. The sea-ice margin represents the lowest latitude with circumglobal sea-ice coverage. The maximum equatorward extent of sea-ice is usually within 5° latitude of the sea-ice margin.

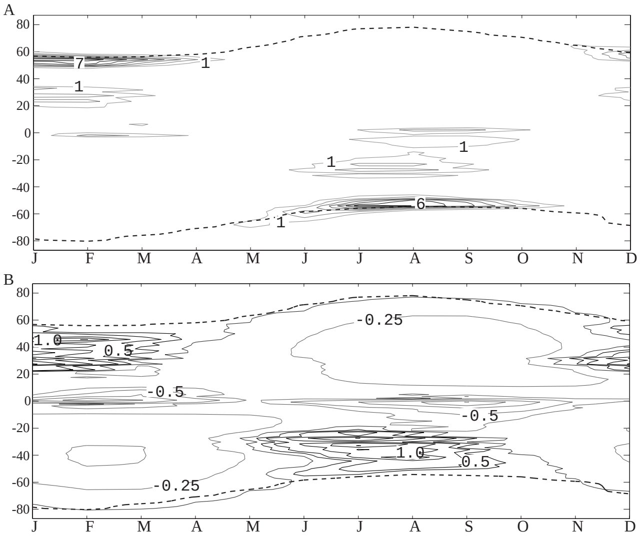

Figure 2. The zonally-averaged, monthly temperature (in °C) contribution to the sea-surface layer from (a) convective mixing and (b) vertical mixing by mechanical stirring. Results are from year 100 of the coupled Neoproterozoic simulation. The zonally-averaged, monthly-mean sea-ice margin is overlain as a thick, dotted line. The contour interval is (a) 1°C and (b) 0.25°C.

Results

Figure 1 illustrates the evolution of the sea-ice extent over the model integrations. In the mixed-layer experiments, the ocean surface is completely ice-covered within 18 and 43 model years. In the absence of any heat transports, the seasonal sea-ice advance is only slowed by the summer insolation and does not exhibit a summer retreat. The addition of meridional diffusion in the mixed-layer model slows the advance of sea ice into the tropics and provides for summer retreat of the sea-ice line. In contrast, the coupled Neoproterozoic experiments do not have a snowball solution. Rather, the sea-ice line seasonally oscillates between approximately 55 and 80°, and 46 and 64° latitude under present-day and cold initial conditions. The sea-ice line is characterized by considerable variability in both simulations. The abrupt summer retreat of the sea-ice line in year 67 and increasing global-average ocean temperatures (not shown) indicate that the the "cold" simulation is still equilibrating as subtropical waters move poleward (see below). These results demonstrate that ocean dynamics play a critical role in halting the seasonal advance of sea ice in the Neoproterozoic climate. In all experiments, only a trace of snow accumulates on the supercontinent.

OM3 accounts for a number of physical processes that are missing from the mixed-layer models including the mean ocean currents, transient eddies, and vertical mixing by mechanical stirring and static instability. These processes are represented in the model by horizontal and vertical advection, horizontal diffusion, the *Pacanowski and Philander* [1981] parameterization of vertical mixing, and convective adjustment. To determine which processes are responsible for halting the seasonal sea-ice advance, the monthly temperature contribution from each of these processes has been calculated for each grid cell in the shallowest model level. The zonally-averaged, monthly temperature contribution from convective mixing and vertical mixing are shown in Figure 2.

Convective mixing of the two shallowest model levels provides the largest contribution of heat to the sea-ice margin. In fact, convective mixing warms the region adjacent to the ice margin by up to 7°C (6°C in the "cold" simulation) during the winter months (Figure 2a). In addition to convective mixing, vertical mixing due to mechanical stirring also warms the mid-latitude ocean by as much as 2°C during the winter months (Figure 2b). However, most of this warming occurs nearly 5° equatorward of the ice margin. Meridional advection through ocean currents adds no more than 0.25°C to the sea-ice margin during the winter months and has a more significant impact on summer melting. Horizontal diffusion and vertical advection are essentially unimportant to the seasonal evolution of the sea-ice margin.

In the coupled experiments, convective mixing in front of the sea-ice margin results from radiative cooling during the winter. As the temperature of the surface ocean declines and the density increases, the upper layers of the ocean become statically unstable, triggering mixing between the upper model levels and surface warming. Surface heating through convective mixing requires that subsurface waters are warmer than those at the surface. In the Neoproterozoic experiments, warm intermediate water, as well as deeper water, forms at the poleward edge of the subtropics where the combination of high salinity and relatively low temperature produce the densest waters. As a result, the sea-ice margin is underlain by 5°C water (-0.9°C in the "cold" simulation) at 500 m. In addition to convective mixing during the winter, the first subsurface level also gains heat through mechanical mixing with the surface level (Figure 2b) and horizontal diffusion during the summer.

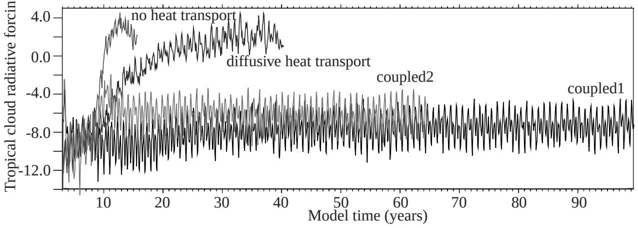

Figure 3. (a) Zonally-averaged, monthly-mean cloud radiative forcing (in Wm^{-2}) for year 100 of the coupled Neoproterozoic simulation. The mid- and high-latitude cloud forcing deters seasonal sea-ice growth and retreat. (b) Evolution of tropical (averaged between 28°S and 28°N) cloud radiative forcing (in Wm^{-2}) in the coupled and mixed-layer experiments.

Some comments about the role of clouds in the Neoproterozoic runs are appropriate, since dissipation of clouds has been cited as an important negative feedback on tropical sea-ice growth [*Hyde et al.,* 2000]. Under Neoproterozoic conditions there is a 35% reduction in global cloudiness in the GENESIS v. 2.0 GCM. By reducing equatorial albedo, this feedback partly compensates for the low solar luminosity, allowing open ocean to exist in the tropics [*Hyde et al.,* 2000]. Our model results also indicate that clouds play an important role in the Neoproterozoic climate. In the mid and high latitudes, clouds represent a negative feedback on seasonal ice growth and retreat (Figure 3a). This is to be expected as clouds over a high-albedo surface have a limited effect on planetary albedo, but continue to exert their full cloud greenhouse effect. However, our runs do not exhibit a reduction in global cloudiness. Globally-averaged total cloudiness is higher (72.2% and 69.6% versus 66.8%) in the Neoproterozoic coupled runs than in a present-day FOAM simulation. This underscores that cloudiness is not a simple function of temperature or atmospheric humidity. Low clouds, in particular, are more strongly affected by boundary layer dynamics and thermal structure than by temperature [*Miller,* 1997].

Moreover, through the course of the model integration, the mixed-layer experiments show little change in total cloudiness as the sea-ice margin advances and cloudiness does not decrease until the tropical ocean is nearly covered with sea ice. The partitioning between low, middle and high clouds likewise changes little, but as the planet cools a change in the cloud optical properties does result in an increase in the net tropical cloud radiative forcing (Figure 3b). Although this serves as a negative feedback on tropical sea-ice growth, it is not sufficient to halt the ice advance. It is difficult to say which cloud parameterization (CCM3 vs GENESIS v. 2.0) is more "correct," but in view of the substantial differences in cloud feedbacks amongst the extant GCMs, one must expect extreme model-to-model differences in the conditions admitting global glaciation.

Discussion

The impact of ocean dynamics on the simulation of a snowball Earth has important implications for previous studies performed with mixed-layer ocean models. These models generally include a parameterization to account for heat transported through wind-driven and thermohaline circulation. This parameterization varies in complexity between models, ranging from a heat flux specification with regional heterogeneity and seasonally varying mixed layer depth in the GISS model to a diffusive mixed-layer ocean in GENESIS v. 2.0. In both cases, the ocean heat fluxes are tuned to generate a reasonable present-day climate. However, as noted in *Chandler and Sohl* [2000], the magnitude of ocean heat transports still vary significantly between GCMs. Consequently, the simulation of global versus partial sea-ice coverage in various GCMs may result largely from differing ocean heat transport parameterizations. This point is illustrated by the mixed-layer ocean experiments, which indicate that very modest diffusion can significantly slow the sea-ice evolution in the tropics.

Moreover, an ocean heat transport parameterization based on the present-day climate may be inadequate for simulating very different past climates, particulary in the absence of a parameterization for vertical mixing. Results from the coupled Neoproterozoic simulations show that sea-surface warming by vertical mixing is crucial to halting the sea-ice margin in the mid-latitudes. However, the vertical mixing is localized at the sea-ice margin and dependant on rather specific oceanographic conditions, making it difficult to parameterize in a mixed-layer ocean model.

The coupled simulations suggest that a reduced solar constant and low pCO_2 are not sufficient to produce a snowball Earth. Under these conditions, a snowball solution may be possible with specialized oceanographic conditions that do not promote warming in the mid-latitudes through convective mixing. It is conceivable that a realistic paleogeographic reconstruction may promote intermediate water formation at higher latitudes or prevent ocean transport between the subtropics and high latitudes, thereby decreasing the sea-surface warming by convective mixing. Alternatively, an event (e.g., severe volcanic episode or meteor impact) causing subtropical cooling may possibly initiate a snowball Earth. On the other hand, as the sea-ice margin advances, other ocean processes such as heat transport through the subtropical gyres and transient eddies may stop the equatorward march of sea-ice.

To our knowledge, this is the first time a coupled ocean-atmosphere GCM has been used to simulate the Neoproterozoic climate. While ocean dynamics clearly influence the Neoproterozoic climate, it should be emphasized that coupled GCMs are still in an early stage of development. Moreover, these experiments do not incorporate either a dynamic sea-ice model or an ice-sheet model. Given the uncertainties in ocean modelling, our results should not be construed as ruling out the initiation of a Neo-Proterozoic global glaciation. The results do, however, show that there are dynamically consistent ocean heat transport mechanisms which powerfully inhibit the ice advance, and which must be taken into account in any theory of initiation of Snowball Earth.

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