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An open ocean region in Neoproterozoic glaciations would have to be narrow to allow equatorial ice sheets

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[1] A major goal of understanding Neoproterozoic glaciations and determining their effect on the evolution of life and Earth's atmosphere is establishing whether and how much open ocean there was during them. Geological evidence tells us that continental ice sheets had to flow into the ocean near the equator during these glaciations. Here we drive the Parallel Ice Sheet Model with output from four simulations of the ECHAM5/Max Planck Institute Ocean Model atmosphere-ocean general circulation model with successively narrower open ocean regions. We find that extensive equatorial ice sheets form on marine margins if sea ice extends to within about 20° latitude of the equator or less (Jormungand-like and hard snowball states), but do not form if there is more open ocean than this. Given uncertainty in topographical reconstruction and ice sheet ablation parameterizations, we perform extensive sensitivity tests to confirm the robustness of our main conclusions. **Citation:** Rodehacke, C. B., A. Voigt, F. Ziemen, and D. S. Abbot (2013), An open ocean region in Neoproterozoic glaciations would have to be narrow to allow equatorial ice sheets, *Geophys. Res. Lett.*, *40*, 5503–5507, doi:10.1002/2013GL057582.

1. Introduction

[2] Among the most fundamental and undisputed evidence that Neoproterozoic glaciations (snowball Earth events) differ dramatically from Pleistocene glaciations is the occurrence of glacial deposits in sediments, indicating thick glaciers flowing from land into ocean, at locations that paleomagnetic evidence suggests were very near the equator [*Kirschvink*, 1992; *Hoffman et al.*, 1998; *Evans and Raub*, 2011]. Based on energy balance model (EBM) results [*Budyko*, 1969; *Sellers*, 1969], early thinking was that it was unlikely global ocean ice coverage could exceed ≈50% (sea-ice latitude of ≈30°) without global glaciation occurring (hard snowball Earth), which would appear to require global glaciation to explain equatorial ice sheets [*Hoffman et al.*, 1998]. Simulations with an ice sheet model coupled to an EBM, however, implied that equatorial continental ice sheets could grow at a global ocean ice coverage of ≈50% [*Hyde et al.*, 2000] or even less [*Crowley et al.*, 2001; *Liu and Peltier*, 2010]. In contrast, atmosphere-ocean general circulation model (AOGCM) simulations suggested that surface temperatures on tropical continents would be well above freezing with global ocean ice coverage ≈50% [*Voigt and Marotzke*, 2010; *Voigt et al.*, 2011], which would prevent the growth of tropical ice sheets. Nonetheless, the proposal of some open ocean during Neoproterozoic glaciations by *Hyde et al.* [2000] is appealing, if physically realistic, because it would easily allow the survival of complex marine organisms through snowball Earth events, for which there is some evidence [e.g., *Love et al.*, 2009; *Bosak et al.*, 2011], although oases [e.g., *Campbell et al.*, 2011; *Tziperman et al.*, 2012] or thin tropical ice [*McKay*, 2000; *Pollard and Kasting*, 2005] might also permit survival of these organisms.

[3] *Abbot et al.* [2011] proposed that if sea ice extended into the dry descent region of the Hadley cell, where modern deserts occur, it would become bare (not covered with snow), so that stable climate solutions are possible with sea ice extending to within ≈10–20° of the equator if the bare sea-ice albedo is low enough (the "Jormungand Mechanism"). Solutions with a sea-ice latitude this low were later found in the AOGCMs Community Climate System Model Version 3 [*Yang et al.*, 2012a, 2012b] and ECHAM5/Max Planck Institute Ocean Model (MPI-OM) [*Voigt and Abbot*, 2012] when the models used a low bare sea-ice albedo. These studies also found low-latitude continental surface temperatures well below freezing, which opens the possibility that a snowball climate state with a sea-ice latitude of ≈10–20° might allow ice sheets on equatorial continents.

[4] The goal of this paper is to determine how large an open ocean region can be during Neoproterozoic glaciations while still allowing ice sheets that flow from continents into the ocean at the equator. We use the Parallel Ice Sheet Model (PISM) forced by four equilibrated climate states from ECHAM5/MPI-OM (Table 1). Only two previous Neoproterozoic studies [*Donnadieu et al.*, 2003; *Pollard and Kasting*, 2004] have forced an ice sheet model with GCM results, as opposed to with EBMs [e.g., *Hyde et al.*, 2000; *Crowley et al.*, 2001; *Liu and Peltier*, 2010], which are unable to calculate atmospheric heat and moisture transport in a dynamically consistent way. *Pollard and Kasting* [2004] considered glaciation in some states with open ocean and found mixed results. Here we systematically force the ice sheet model with climate states of decreasing sea-ice latitude and vary uncertain parameters of the ice sheet model. We find that large equatorial ice sheets robustly grow in states with a narrow region of open ocean supported by the Jormungand mechanism, but robustly do not grow if the entire tropical ocean is open (free of sea ice).

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Table 1. Climate States Based on Output From the ECHAM5/MPI-OM GCM Used to Force the Ice Sheet Model (PISM)[a]

Simulation	Global Sea-Ice Coverage	Sea-Ice Latitude	Notes
SNOW (Snowball Earth)	100%	0°	High bare sea-ice albedo
JORM1 (Narrow Jormungand-like)	85%	≈10°	Low bare sea-ice albedo No sea-ice dynamics
JORM2 (Wide Jormungand-like)	70%	≈20°	Low bare sea-ice albedo
OPEN (Open Tropics)	55%	≈30°	High bare sea-ice albedo

[a]OPEN and SNOW are described in full by *Voigt et al.* [2011]. JORM1 and JORM2 are described in full by *Voigt and Abbot* [2012].

2. Modeling Framework

[5] The comprehensive atmosphere-ocean general circulation model ECHAM5/MPI-OM calculates the dynamics of the atmosphere, including interactive clouds, the ocean, and sea ice. The model was used to study snowball initiation using modern continents [*Voigt and Marotzke*, 2010] as well as an end-Cryogenian period plate reconstruction [*Voigt et al.*, 2011; *Voigt and Abbot*, 2012]. The simulations presented here use an end-Cryogenian period plate reconstruction with two supercontinents located close to the equator (M. Macouin, personal communication, 2009) and a uniform elevation of 100 m. Total solar irradiance is set to 94% of modern (1285 W m^{-2}). To simulate the four different climate states, *Voigt and Abbot* [2012] varied the sea-ice albedo and the treatment of sea-ice dynamics (Table 1). The first state, OPEN, has the lowest sea-ice latitude possible in the standard configuration of ECHAM5/MPI-OM (≈30°, or ≈55% global ocean ice coverage) [*Voigt and Abbot*, 2012], which has a high bare sea-ice albedo. In the next two states, JORM1 and JORM2, the bare sea-ice albedo is decreased so that the Jormungand mechanism can allow smaller open ocean regions [*Abbot et al.*, 2011]. The sea-ice latitude is ≈20° in JORM2 and ≈10° in JORM1 [*Voigt and Abbot*, 2012], and the difference between the simulations is that sea-ice dynamics are disabled in JORM1. The final state, SNOW, represents hard snowball Earth conditions and is described in *Voigt et al.* [2011].

[6] We use the ice sheet model PISM (version 0.3) [*Bueler and Brown*, 2009] with a simplified Earth lithosphere relaxation model and a positive degree day (PDD) ablation scheme [*Ziemen*, 2013]. PISM exploits the shallow shelf approximation and the shallow ice approximation for grounded ice in a hybrid mode permitting the representation of ice shelves and ice streams. The sliding conditions at the ice base are described as plastic till for which the yield stress is given by a Mohr-Coulomb formula [*Bueler and Brown*, 2009]. These conditions are dictated by bedrock topography, bedrock composition, and ice conditions at the ice base. The pressure of a thick ice column shifts the pressure-dependent melting point and can cause a wet base, allowing fast-flowing ice and purging ice streams. The smooth bedrock topography we use allows a coarse resolution of 80 km.

[7] We drive PISM with 2 m air temperatures and precipitation derived from ECHAM5/MPI-OM. PISM requires monthly mean and standard deviation air temperature, which we calculate from 50 years of 6-hourly ECHAM5/MPI-OM output. Melting and ice surface temperature are parameterized by the PDD scheme. Since appropriate PDD factors are uncertain, we varied them simultaneously from 2 to 12 mm d^{-1} K^{-1} for snow and from 5 to 22 mm d^{-1} K^{-1} for ice (Table 2). For reference, values of roughly 4 mm d^{-1} K^{-1} for snow and 10 mm d^{-1} K^{-1} for ice are commonly used for large-scale ice sheet simulation [e.g., *Ritz et al.*, 1997], and our range covers the extremes for high- to low-latitude ice sheets [*Hock*, 2005]. We apply a constant geothermal heat flux of 60 mW m^{-2}. The simulations of *Zweck and Huybrechts* [2005] indicate that $\mathcal{O}(1)$ geothermal heat flux variations have little influence on the areal extent of an ice sheet.

[8] Given the uncertainty in Neoproterozoic topography, we perform one set of simulations with a constant continental topography of 100 m, which is what was used in the ECHAM5/MPI-OM simulations (*flat*), and another set with three idealized mountains of height 1100 m (*mountains*) chosen to seed ice growth near the equator and at the highest southern latitude (see Figure 1). We adjust the ECHAM5/MPI-OM temperature and precipitation output to account for height changes due to mountain and/or ice topography by applying a lapse rate correction to the temperature and a height-desertification correction to the precipitation [*Budd and Smith*, 1981]. Starting from ice-free conditions, PISM generally reaches statistical steady state in less than 30 kyr, and all our cases are run for at least 56 kyr.

[9] Our methodology is designed to consider a large range of uncertain parameters but neglects climate-ice sheet interactions. Growth of tropical ice sheets is necessary for consistency with geological data, but not sufficient, and the current work intends only to evaluate this necessary condition. Nevertheless, the Jormungand-like climate states, particularly JORM1, exist over large ranges in radiative forcing [*Voigt and Abbot*, 2012, Figure 12], which indicates that global climate could remain stably in them as a large tropical ice sheet grew. This issue can only be fully assessed by future calculations with an ice sheet model asynchronously coupled to a GCM.

Table 2. Parameters of the Ice Sheet Model PISM That We Varied and the Ranges We Applied[a]

Parameter	Applied Values			
PPD snow (mm d^{-1} K^{-1})	2.0	4.0	6.0	12.0
PPD ice (mm d^{-1} K^{-1})	5.0	10.0	18.0	22.0
AOGCM forcing (Table 1)	SNOW	JORM1	JORM2	OPEN
Lapse rate (K km^{-1})	–4.5		–6.5	
Topography	flat		fountains	

[a]The PDD values for snow and ice are changed simultaneously. For flat topography, the land elevation is 100 m everywhere, while for mountains topography, three continental mountain ranges with a maximum elevation of 1100 m are introduced (see Figure 1). When considering the applied lapse rates, note that lapse rates on mountains and ice sheets are generally significantly smaller than those in the surrounding atmosphere due to shortwave absorption by land or ice. See Table 1 for further description of the AOGCM forcings.

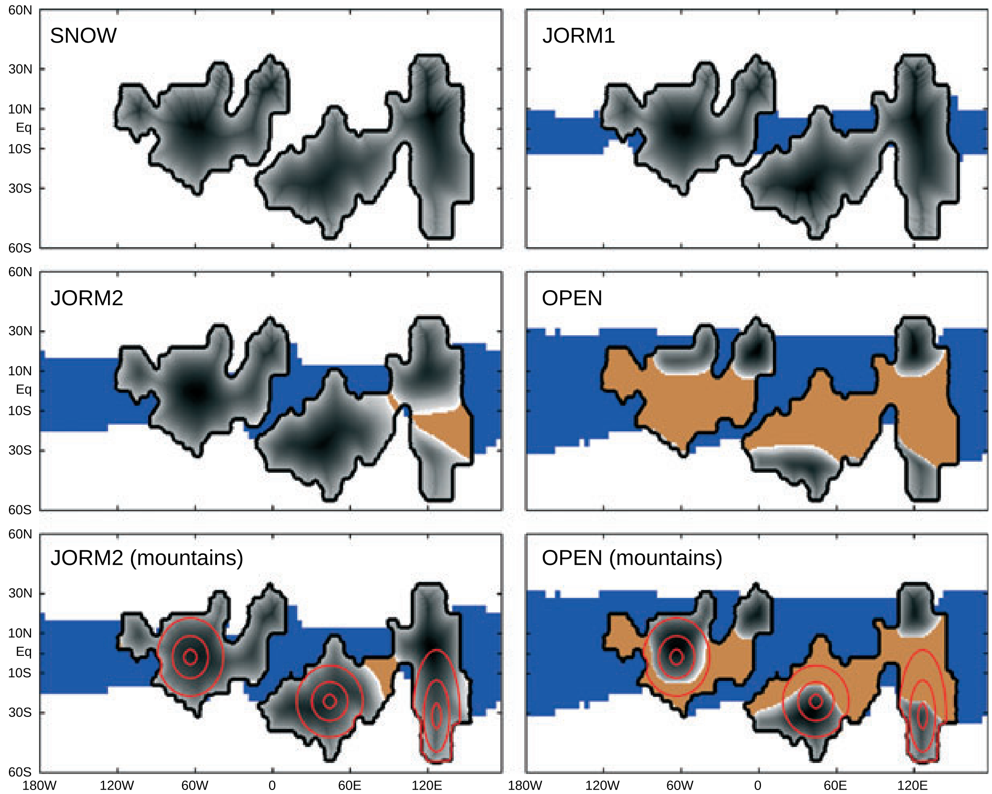

Figure 1. Regions covered by glaciers (gray), open ocean (blue), bare land (brown), and sea ice (white, sea-ice concentration of at least 15%) with best-guess PDD factors of 4 mm d^{-1} K^{-1} (snow) and 10 mm d^{-1} K^{-1} (ice) and a lapse rate of 6.5 K km^{-1}. Glacial thickness is depicted by color, with the lightest gray corresponding to a thickness of 100 m and black corresponding to a thickness of 7000 m. Mountain elevation is depicted by red contours with level spacing of 400 m, starting at an elevation of 200 m. Black contours indicate continental boundaries. Results from (top and middle rows) the flat case are shown for all climate states, and results from (bottom row) the mountains case are shown for JORM2 and OPEN.

3. Results

[10] For "best-guess" parameter choices, ice sheets grow easily in the hard snowball Earth climate state SNOW (Figure 1). Our modeling framework may be biased toward ice sheet formation in a hard snowball because of small patches of seasonally open ocean in the SNOW simulation, which may lead to an overestimate of precipitation, and because the PDD parameterization may underestimate ablation in cold, hard snowball conditions [*Pollard and Kasting*, 2005]. Nevertheless, these limitations are likely quantitative, rather than qualitative, since both *Donnadieu et al.* [2003] and *Pollard and Kasting* [2005] also found large equatorial ice sheets in a hard snowball.

[11] In both Jormungand-like climates, JORM1 and JORM2, large ice sheets that flow into the ocean at the equator cover the tropical continents. This shows that a climate state with a narrow region of open equatorial ocean can produce ice sheets capable of explaining the basic geological evidence of equatorial glacial deposits during Neoproterozoic glaciations. In contrast, ice sheets are limited to relatively high latitudes and/or elevations in OPEN.

[12] Figure 1 also shows that mountains have a fairly minor effect on ice sheets. In SNOW, JORM1, and JORM2, surface temperatures are low enough to allow ice sheet formation with or without mountains. Similarly, in OPEN surface temperatures are so high that low-latitude, low-elevation ice sheets cannot form regardless of mountain topography. Localized ice sheets tend to form on the mountains themselves in OPEN due to decreased temperature at higher altitudes (lapse-rate effect); however, these mountain ice sheets cannot penetrate far into the surrounding, warmer, low-latitude regions. In particular, these localized mountain ice sheets do not reach equatorial coastal regions and hence cannot explain the observed Neoproterozoic glacial deposits.

[13] The results of Figure 1 are generally robust to changes in parameters (Figure 2). Both the topographic forcing and lapse rate have only a small effect (Figure 2). The most important varied parameter is the PDD factor, which controls ice sheet ablation. Lower PDD factors are appropriate for pristine snow and ice, for which melting should be low, whereas larger values are appropriate if impurities such as dust [*Abbot and Pierrehumbert*, 2010; *Le Hir et al.*, 2010] reduce albedo [*Dadic et al.*, 2013] and increase melting. The PDD factors used to generate Figure 1 (4.0 mm d^{-1} K^{-1} for snow and 10.0 mm d^{-1} K^{-1} for ice) are standard and correspond to relatively clean ice. When these values are varied, ice sheets remain small, localized, and do not generally reach the equatorial coastal regions in OPEN (Figure 2), except for the lowest PDD factor, for which ice sheets reach the equatorial coast in a few small, isolated areas near mountains for mountains topography. Ice sheet behavior is insensitive to PDD factor in SNOW and JORM1. For JORM2, the PDD factor has a small, but not decisive, effect: For the highest PDD factor, tropical glacial coverage drops to around

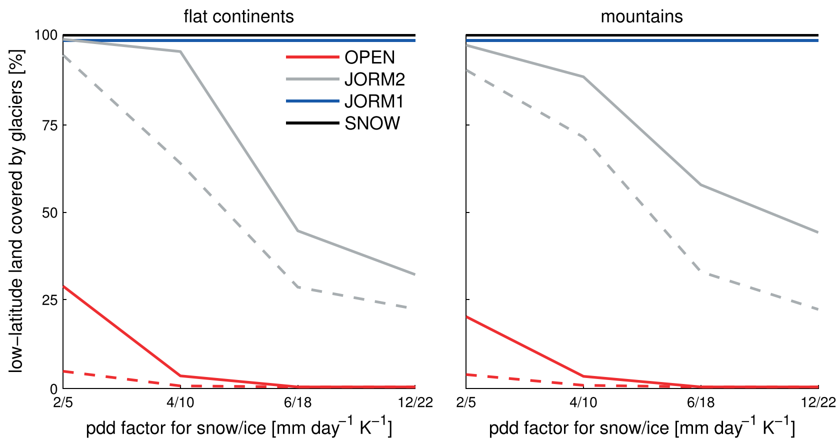

Figure 2. Fraction of low-latitude land (within 10° latitude of the equator) covered by glaciers of a minimum thickness of 100 m for different values of the PDD factor for snow/ice (x axis), atmospheric lapse rates (solid: 6.5 K km^{-1}, dashed 4.5 K km^{-1}), and assuming (left) flat and (right) mountains topography. For mountains topography, only land of elevation less than 200 m is included in the glacial coverage fraction. SNOW and JORM1 both result in 100% glacial coverage for all parameter values and have been slightly displaced vertically for better visibility.

25–50%. However, this is not necessarily inconsistent with geological data from Neoproterozoic glaciations because ice sheets still flow into the ocean near the equator in numerous areas in these simulations.

4. Conclusion

[14] The question of whether there was open ocean during the Neoproterozoic glaciations, and how large the open ocean region was, is fundamental to our understanding of these glaciations and their effect on the evolution of life. The geological evidence requires grounded ice sheets on equatorial marine margins. We have driven an ice sheet model (PISM) with output from a coupled atmosphere-ocean general circulation model (ECHAM5/MPI-OM) and find that this is only possible if the sea-ice latitude is 20° or less. The Jormungand mechanism (exposure of low-albedo bare sea ice in the Hadley cell descent region) can allow such low sea-ice latitude states to exist. Although climate states with very narrow (sea-ice latitude ≈10°) open ocean regions require weak sea-ice dynamics [*Voigt and Abbot*, 2012; *Yang et al.*, 2012a, 2012b], a sea-ice latitude of ≈20° is possible if the Jormungand mechanism is operating even with strong sea-ice dynamics [*Voigt and Abbot*, 2012]. Our work rules out a climate state with a large open ocean region as a model for Neoproterozoic glaciations; however, it is possible that some glaciations were hard snowballs and others were Jormungand-like. Distinguishing between the two will require other geological, geochemical, and paleontological data.

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