Earth and Planetary Science Letters 415 (2015) 100–110

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Evaluating key parameters for the initiation of a Neoproterozoic Snowball Earth with a single Earth System Model of intermediate complexity

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ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 22 January 2015
Accepted 26 January 2015
Available online 13 February 2015
Editor: J. Lynch-Stieglitz

Keywords:
paleoclimatology
Snowball Earth
Neoproterozoic
Earth system modelling

ABSTRACT

Even after more than two decades of intense research the main drivers for a potential Neoproterozoic Snowball Earth continue to be discussed controversially. In this study we present results from 37 sensitivity experiments that were performed with the Planet Simulator (PlaSim), an Earth System Model of intermediate complexity. In contrast to previous studies, in which only a limited number of potential climate-controlling parameters were assessed with different climate models, we tested our presumed key parameters within one single model. This approach makes it easier to compare the influence of the various parameters on extreme climate change as postulated for the Neoproterozoic Era. Furthermore we compare the results obtained to most recent high complexity state-of-the-art approaches. This comparison helps to estimate, which internal model interactions and physics are crucial for a Snowball Earth simulation and hence should be included into a model that is capable of realistically simulating a Neoproterozoic climate. To this effect we carried out simulations that involved reduced solar irradiation, land–sea distributions, atmospheric CO_2 concentrations, relief of the land surface and length of day. In addition, we focus on different land surface albedo values, which were most likely exceptionally low and similar to the Martian albedo, and obliquity changes between 23.5° and 80°. Our findings suggest that changes in land surface albedo are a strong climate driver that can compensate a much lower Neoproterozoic total solar irradiance if it is combined with shifts in obliquity or atmospheric CO_2 levels. We also obtained a critical threshold for increased obliquities beyond which a Snowball Earth situation turns into an extreme greenhouse climate with almost absent cryosphere, and furthermore, obliquity values that lead to a tropical ice age with sea ice spreading from the equator to high latitudes.

1. Introduction

Since the first investigations of late Precambrian glacial rocks on the British Isles (Thomson, 1871), which are intercalated between fossiliferous sedimentary rocks without discernible hiatus, these and similar occurrences all over the world have led to an intense debate on their possible origin. After Harland and Bidgood (1959) had reconstructed paleolatitudes between 4.5° S and 11° N for Norwegian and Greenlandic tillites by analyzing geomagnetic data, a Neoproterozoic glaciation within low latitudes has been postulated for some time (Harland, 1964). Following Budyko's (1969) early energy balance studies, Kirschvink (1992) proposed the term "Snowball Earth Event" (SEE), to explain the observed Neoproterozoic sediment successions. According to the SEE hypothesis, the whole Earth was covered by a thick layer of ice spreading from the poles to the equator. Kirschvink (1992) further argued that as soon as the sea ice borders expand to a latitude of 30° N/S, an SEE would become inevitable. Neither the triggers for an SEE nor the time span required for recovery from an SEE are well constrained. According to Kirschvink (1992) and Hoffman and Schrag (2002), Neoproterozoic SEEs were most likely triggered by concentrating large tracts of bright (vegetation-free) land masses within tropical regions. Such a global land distribution would lead to an increase in shortwave reflection in just those areas of maximum insolation. Furthermore, silicate weathering might have been enhanced because of high temperatures and precipitation at low latitudes, thus permitting the storage of greater amounts of atmospheric CO_2 in contemporaneous sedimentary rocks. Due to

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http://dx.doi.org/10.1016/j.epsl.2015.01.035

the combination of these effects, a positive feedback set in and global temperatures started to decrease (moderately in the beginning) and glaciers as well as sea ice started to spread. According to Hoffman and Schrag (2002), an SEE would be inevitable when sea ice borders reached latitude 30° N/S because at that point planetary albedo would be sufficiently high to reflect more shortwave radiation than the amount that is necessary to keep the climate system stable. After having passed this threshold, Earth would freeze within a short period of time ("Runaway Freeze") and global temperature would drop to hypothetical −50 °C. In addition to all these uncertainties, no agreement exists on the actual number of Neoproterozoic SEEs and the global stratigraphic correlation of the various glaciogenic deposits. Consensus has emerged, however, that intense glaciations, irrespective of whether they affected the entire planet or just large parts of it, with subsequent warm intervals occurred repeatedly from at least 750 Ma to the Precambrian/Cambrian boundary. As the geological record is seemingly not able to resolve the forces that dictated Neoproterozoic climate change, climate modelling provides a promising tool to test various driving factors of climate variations and to improve our understanding of paleoclimatological processes. The spectrum of models that have been used in the past ranges from simple energy balance models (EBMs) over Earth system models of intermediate complexity (EMICs) to state-of-the-art ocean–atmosphere general circulation models (OAGCM). Apart from a reduced Neoproterozoic solar radiation, the effect of obliquities >54° (Jenkins and Smith, 1999; Jenkins, 2000; Donnadieu et al., 2002), different Neoproterozoic continent configurations (Baum and Crowley, 2001; Poulsen et al., 2002; Donnadieu et al., 2004; Liu and Peltier, 2010; Voigt et al., 2011; Fiorella and Poulsen, 2013; Liu et al., 2013), topography (Romanova et al., 2006; Fiorella and Poulsen, 2013), varying atmospheric CO_2 levels (Romanova et al., 2006; Voigt et al., 2011; Yang et al., 2012; Fiorella and Poulsen, 2013; Russell et al., 2013), a reduced length of day (Jenkins and Smith, 1999; Jenkins, 2000), and various surface albedos (Romanova et al., 2006; Fiorella and Poulsen, 2013; Liu et al., 2013; Feulner and Kienert, 2014) have been tested. A major drawback of these studies has been that the various parameters were tested by different models, which makes the comparison of the results achieved rather difficult. To overcome this obstacle, we examined all these potential key factors with one single EMIC.

2. Model description

As the main goal of this study is to investigate a significant number of SEE-controlling parameters with one single model, we choose to use an intermediate model like PlaSim which makes it possible to run a large number of sensitivity experiments within an outstanding real time. The model has a modular structure which facilitates the integration and analysis of the different climate subsystems, such as the atmosphere, oceans, sea ice, vegetation or land-surface processes. PlaSim can be run in horizontal resolutions from T21 to T63 (i.e. 600 to 200 km grid box spacing) and consists of 10 vertical levels. PlaSim's atmospheric part was derived from the general circulation models (GCM) ECHAM-3 (Roeckner et al., 1992) and the Portable University Model of the Atmosphere (PUMA) (Fraedrich et al., 2005). The dynamic core is based on the primitive equations. In addition, parameterizations for subscale processes are integrated to achieve a set of closed model equations which are solved numerically in σ-coordinates and incorporate prognostic equations for vorticity, divergence, humidity processes and hydrostatic approximation. For reasons of simplicity PlaSim's radiation scheme only incorporates CO_2 as well-known climate driver and neglects the effects of other greenhouse gases as well as aerosol particles. The radiation scheme for the short wave part of the solar spectrum was adopted from Lacis and Hansen (1974) and incorporates Rayleigh scattering, ozone and water vapour absorption for clear sky processes in which ozone concentrations are prescribed in terms of an idealized annual cycle (Green, 1964). Parameterizations for high-, middle- and low-level clouds are taken from Stephens et al. (1984). Land surface and soil processes are parameterized and consider soil hydrology as well as a river transport scheme (Sausen et al., 1994). Other surface properties, like the albedo, roughness length, orography and land–sea distribution, are provided externally. In addition, the SimBA vegetation model (Kleidon, 2006) can be coupled to PlaSim. As our simulations were for the Neoproterozoic Era, SimBA was switched off. Ocean temperature, sea ice cover and thickness can be derived from climatological values, or computed (as in this study) by a thermodynamic mixed layer ocean with a uniform depth of 50 m. The sea ice model allows maximum values for snow-free and snow-covered sea ice of 0.7 (cold sea ice; if temperature drops below −1 °C) and 0.8 (for fresh snow).

3. Experimental design

A total of 37 simulations were conducted. An overview of the various input parameters used for these runs is given in Table 2. Each simulation was initialized under present day climate conditions and run over 250 yr. Usually climate models that are coupled to a slab ocean use flux correction to simulate heat exchange between the atmospheric and oceanic part of the model. However, it is difficult to obtain a good estimate for flux corrections for past climates (Steppuhn et al., 2006), or even impossible if the paleogeography differs from the current configuration. On that account we choose not to use an explicit flux correction for the Neoproterozoic situation (like e.g. Micheels and Montenari, 2008 or Fiorella and Poulsen, 2013) and the present day control run.

3.1. Reduced solar luminosity

For the Neoproterozoic Era a reduced total solar luminosity (TSI) of 94% is assumed. For our simulations we reduced TSI from a modern mean value of 1365 W/m^2 to 1283.1 W/m^2 according to the calculations of Gough (1981) and Bahcall et al. (2001). Even though solar luminosity might slightly be increased at 530 Ma, we choose to use the same TSI value for both scenarios to maintain comparability between both land sea masks used and most other studies.

3.2. Land–sea distribution

To assess the effect of different land–sea distributions, two different scenarios that might approximate the Neoproterozoic paleogeographic situation at around 630 Ma and 530 Ma were tested, corresponding to the Marinoan and Gaskiers glaciations, respectively. The design of the land–sea masks (Fig. 1(a), (b)) follows the paleogeographic reconstructions of Li et al. (2008). In addition, an experiment with a high mountain range was designed for the 530 Ma scenario (Fig. 1(c)). For a more detailed description of the land–sea distributions used see Table 1.

3.3. Land surface albedo

The reconstruction of Earth's land surface albedo over geological time is subject to considerable uncertainty because it is a complex function that depends on vegetation level and type, ice coverage, soil and rock type, soil moisture and weathering intensity. Plants began to colonize the land only in the course of the Early Paleozoic. Consequently, a vegetation-free land surface with little soil formation has to be assumed for Neoproterozoic land surfaces. These surfaces most likely looked like hostile wastelands that were