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Climate simulations of Neoproterozoic snowball Earth events: Similar critical carbon dioxide levels for the Sturtian and Marinoan glaciations

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A B S T R A C T

The Sturtian and Marinoan snowball Earth episodes initiated 720 and 650 million years ago, respectively, are among the most dramatic events in Earth's history. The ultimate causes of these events remain obscure, however, and there is still uncertainty about the critical levels of greenhouse gas concentrations at which the snowball transition occurs. Furthermore, earlier modelling results (with incomplete representations of important boundary conditions) provided conflicting indications for differences between the critical carbon dioxide concentrations for the Marinoan and the Sturtian, reporting either the earlier or the later epoch to be more susceptible to global glaciation. Both the absolute values of and possible differences between these glaciation thresholds have profound implications for scenarios of snowball initiations during the Neoproterozoic. Here, we present coupled climate simulations (using an ocean general circulation model with dynamic/thermodynamic sea ice coupled to a fast atmosphere) focusing on the differences between the Neoproterozoic glaciations. For the first time, our simulations use realistic boundary conditions in terms of changes in solar luminosity between the two epochs and the most recent continental reconstructions. In agreement with previous studies with models including ocean and sea-ice dynamics, we report low values for the critical carbon dioxide concentration during the Neoproterozoic. But in contrast to hints from earlier studies we find very similar values of 100–130 ppm for the snowball bifurcation point during the Sturtian and Marinoan. This highlights the importance of realistic boundary conditions for climate simulations of the Neoproterozoic glaciations.

1. Introduction

Episodes of global glaciation are certainly among the most dramatic events in Earth's climate history. The geologic record shows evidence for several periods of time with continental ice sheets in the tropics (Hoffman and Schrag, 2002), possibly implying oceans completely covered by ice.

The two most recent of these 'snowball Earth' events (Kirschvink, 1992) happened during the Neoproterozoic era (1000–541 Ma, 1 Ma = 1 million years ago) in a geologic period aptly called the Cryogenian (850–635 Ma). They are commonly referred to as the Sturtian and Marinoan glaciations and occurred about 720–700 Ma and 650–635 Ma, respectively (Macdonald et al., 2010).

From the point of view of Earth's energy balance, climate states with a completely frozen ocean surface appear to be a consequence of a fundamental instability caused by the positive ice-albedo feedback: increasing ice cover in a colder world results in a higher albedo and hence more solar radiation being reflected back into space, thus leading to further cooling. At some critical point, termed the snowball Earth bifurcation, the climate system rapidly moves into a stable state characterised by global ice cover. While the ice-albedo feedback has been discussed for a long time (Croll, 1867), the snowball instability is known since the time of the first energy balance model studies of glaciations (Öpik, 1965; Eriksson, 1968; Budyko, 1969; Sellers, 1969). It is tempting to regard the geological evidence for low-latitude glaciations as manifestations of this fundamental climate instability, and the questions arise whether snowball Earth states can be simulated in climate models more sophisticated than the simple energy balance models, and, if yes, at which point they occur.

The study of these fascinating snowball Earth events has attracted considerable attention during the last two decades, and climate models spanning a wide range in complexity have been used to investigate this problem (e.g. Crowley, 1983; Jenkins, 1999; Chandler and Sohl, 2000; Hyde et al., 2000; Lewis et al., 2003; Donnadieu et al., 2004; Abbot et al., 2011; Pierrehumbert et al., 2011; Voigt et al., 2011; Liu et al., 2013). Three key questions arising from climate model studies of the Neoproterozoic are the focus of ongoing debates. First, at which critical greenhouse gas concentration (for a given Neoproterozoic solar constant) does the climate system enter a snowball state, and is this concentration higher

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than reasonably expected for that time period as some models indicate? Second, what is the difference between the critical CO_2 levels for the Sturtian and the Marinoan? And third, is there an additional stable state with a narrow belt of open water around the equator (sometimes called 'soft snowball' or 'slushball') rather than the global ice cover of a 'hard snowball'? These issues are of obvious relevance for the most fundamental of all questions: What triggered the Neoproterozoic glaciations in the first place?

Concerning the critical CO_2 concentration, a recent model intercomparison exercise shows that atmospheric general circulation models (AGCMs) coupled to a mixed-layer ocean with zero heat transport enter a snowball state between 1000 and 6000 ppm of CO_2 for a present-day continental configuration and a solar constant of 1285 W/m^2, while a coupled atmosphere–ocean general circulation model (AOGCM) yields a considerably lower value between 286 ppm and 572 ppm of CO_2 (Pierrehumbert et al., 2011; Voigt et al., 2011). The authors reasonably attribute this difference to the lack of ocean heat transport in the AGCM simulations. The generally lower values in models with ocean dynamics are confirmed by a recent study by Liu et al. (2013) who report critical CO_2 values even lower than Voigt et al. (2011), most likely due to the more realistic lower albedo values used in Liu et al. (2013).

Possible differences between the Sturtian and Marinoan snowball bifurcation points could shed some light on the ultimate causes of global glaciations. This is particularly relevant for hypotheses depending on continental configuration such as those suggesting enhanced drawdown of atmospheric CO_2 by weathering of tropical continents (Hoffman and Schrag, 2002) or flood basalts (Goddéris et al., 2003). Few studies, however, investigate (or touch upon) potential differences between the Sturtian and the Marinoan. Lewis et al. (2003) use an ocean general circulation model coupled to an energy–moisture balance atmosphere to study the influence of idealised continental configurations, finding that an equatorial supercontinent is more susceptible to global glaciation than supercontinents at higher latitudes. Voigt et al. (2011) report a cooling when moving from present-day conditions to the predominantly low-latitude continents in their AOGCM simulations for a Marinoan configuration. These two studies would thus indicate higher critical CO_2 levels for the Sturtian because of its low-latitude continents. Other studies with comparatively simple models, however, find that states with higher-latitude continents (Crowley, 1983) or more dispersed continental configurations (Donnadieu et al., 2004) are characterised by higher critical CO_2 concentrations than those with an equatorial supercontinent. This seems to be confirmed by a recent AOGCM study (Liu et al., 2013) which indicates that a 570 Ma continental configuration (taken to represent the Marinoan in that paper) is more susceptible to glaciation than a Sturtian configuration. However, most of these studies are based on idealised continental configurations, and none of them takes into account the non-negligible changes in solar luminosity between the Sturtian and the Marinoan.

Soft snowball states with comparatively narrow belts of open water around the equator appear attractive because they can easily explain the survival of photosynthetic life through extended snowball periods. To be consistent with the geologic record, low-latitude continental ice would have to exist in such states. Soft snowball states are reported in a number of modelling studies (Hyde et al., 2000; Liu and Peltier, 2010; Abbot et al., 2011). Most models which include ocean and sea-ice dynamics show no evidence for soft snowball states (Lewis et al., 2003; Voigt and Abbot, 2012) – with the exception of Yang et al. (2012), indicating that these effect tend to destabilise soft snowball states. However, the small number of such modelling studies, the considerable variations between different models and the lack of AOGCM studies with a coupled continental ice-sheet model preclude a final verdict on the existence of soft snowball states.

Here we explore the Neoproterozoic snowball Earth episodes using an ocean general circulation model including a dynamic/thermodynamic sea-ice model coupled to a fast atmosphere model. We investigate the critical carbon dioxide concentration and relate it to earlier results obtained with AGCMs coupled to a mixed-layer ocean and full AOGCMs, with a particular focus on possible differences between the Sturtian and Marinoan glaciations. Our work is based on the first coupled climate model simulations using appropriate boundary conditions in terms of the most recent reconstruction of Neoproterozoic continental configurations and taking into account the change in solar constant between the two events which had previously been neglected.

This paper is organised as follows. In Section 2, we describe the model as well as the boundary conditions used for our simulations. Section 3 discusses the critical carbon dioxide concentrations for the Sturtian and the Marinoan glaciations. Finally, Section 4 summarises our results.

2. Model setup and experiments

2.1. Model description

For our simulations we use an ocean general circulation model including sea ice coupled to a fast atmosphere model (Montoya et al., 2006). The ocean model (the Modular Ocean Model MOM3, Pacanowski and Griffies, 1999) is operated at a relatively low horizontal resolution of 3.75° × 3.75° with 24 vertical layers. The sea-ice model (Fichefet and Morales Maqueda, 1997) captures both the thermodynamics and the dynamics of sea ice. The fast atmosphere model does not solve the primitive equations, but statistically describes the large-scale circulation patterns and their dynamical response to climate changes (Petoukhov et al., 2000). It is employed at a horizontal resolution of 22.5° in longitude and 7.5° in latitude with 16 vertical layers.

It is important to note that the model realistically simulates ocean heat transport (which is suspected to explain the differences between atmospheric and coupled models of the Neoproterozoic, Pierrehumbert et al., 2011) and sea-ice dynamics (which has been shown to be important for studying the snowball bifurcation, Voigt and Abbot, 2012) while being sufficiently fast computationally to allow for a relatively large number of ensemble simulations.

The model has previously been used in a large number of studies including several model intercomparison projects (Gregory et al., 2005; Stouffer et al., 2006; Jansen et al., 2007; Eby et al., 2013; Zickfeld et al., 2013). Here, in contrast to the simulations of the faint young Sun paradox (Feulner, 2012) presented in Kienert et al. (2012, 2013), we use a model version with an improved parameterisation of the atmospheric lapse rate (see Appendix A) and lower clear-sky albedo values of 0.50 and 0.40 for freezing and melting sea-ice, and 0.75 and 0.65 for cold and warm snow, respectively. The model distinguishes between visible and near-infrared albedos by assuming partitions of 60% and 40% for these bands and assigning 0.30 larger values for the optical albedos. The effects of snow cover on sea-ice are taken into account.

2.2. Neoproterozoic boundary conditions

2.2.1. Continental configuration

While there is still considerable uncertainty about the distribution of continents during the Neoproterozoic, the fundamental characteristics agree between different reconstructions. In general, the Neoproterozoic continental distribution reflects the breakup of the supercontinent Rodinia after about 750 Ma. The continental configurations for the Sturtian and Marinoan time periods used in our model experiments are shown in Fig. 1. They are based on the most recent reconstructions from Li et al. (2013) for the 720 Ma