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The snowball Earth aftermath: Exploring the limits of continental weathering processes

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ABSTRACT

Carbonates capping Neoproterozoic glacial deposits contain peculiar sedimentological features and geochemical anomalies ascribed to extraordinary environmental conditions in the snowball Earth aftermath. It is commonly assumed that post-snowball climate dominated by CO_2 partial pressures several hundred times greater than modern levels, would be characterized by extreme temperatures, a vigorous hydrological cycle, and associated high continental weathering rates. However, the climate in the aftermath of a global glaciation has never been rigorously modelled. Here, we use a hierarchy of numerical models, from an atmospheric general circulation model to a mechanistic model describing continental weathering processes, to explore characteristics of the Earth system during the supergreenhouse climate following a snowball glaciation. These models suggest that the hydrological cycle intensifies only moderately in response to the elevated greenhouse. Indeed, constraints imposed by the surface energy budget sharply limit global mean evaporation once the temperature has warmed sufficiently that the evaporation approaches the total absorbed solar radiation. Even at 400 times the present day pressure of atmospheric CO_2, continental runoff is only 1.2 times the modern runoff. Under these conditions and accounting for the grinding of the continental surface by the ice sheet during the snowball event, the simulated maximum discharge of dissolved elements from continental weathering into the ocean is approximately 10 times greater than the modern flux. Consequently, it takes millions of years for the silicate weathering cycle to reduce post-snowball CO_2 levels to background Neoproterozoic levels. Regarding the origin of the cap dolostones, we show that continental weathering alone does not supply enough cations during the snowball melting phase to account for their observed volume.

1. Introduction

Geological evidence suggests the occurrence of two global glaciations during the Neoproterozoic. The older glaciation, the Sturtian event, is commonly inferred to have occurred at ca. 700–680 Ma, while the latter, end-Cryogenian glaciation ended at 635 Ma (Hoffman et al., 2004; Condon et al., 2005). The melting of these snowball Earth events requires very high atmospheric pCO_2, so that the greenhouse warming overcomes the freezing feedback induced by a high sea-ice albedo. The amount of CO_2 required to initiate melting of a snowball was first calculated to be 0.12 bar (400 PAL) using a simple energy balance model (Caldeira and Kasting, 1992) but more recent modelling suggests it was above 0.2 bar (660 PAL) (Pierrehumbert, 2004). Geochemical evidence seems to confirm exceptionally high pCO_2 following at least the 635 Ma snowball event (Kaseman et al., 2005; Bao et al., 2008), but the behavior of this supergreenhouse climate under very high CO_2 levels is still poorly understood. Was it just a short pulse, lasting a few hundreds of kyrs, or was it longer-lived, with environmental consequences enduring for millions of years? According to the classic snowball Earth hypothesis the supergreenhouse drove a hyper-active hydrological cycle inducing intense continental weathering, such that CO_2 levels would have been drawn down from very high levels to preglacial levels in about 200 kyrs (Higgins and Schrag, 2003).

Up to now, this timespan subsequent to the snowball glacial event has never been investigated with a comprehensive climate model. In this contribution, four numerical models (Fig. 1) are used to investigate the evolution of the post glacial climate: (1) a 3D-climate model to characterize the super hothouse climate, (2) a continental weathering model to investigate the behaviour of the CO_2 weathering sink, (3) a simple carbon-alkalinity cycle model to simulate the evolution of the atmospheric CO_2 levels in the immediate aftermath of the snowball Earth, and (4) a simple eustatic model to investigate the

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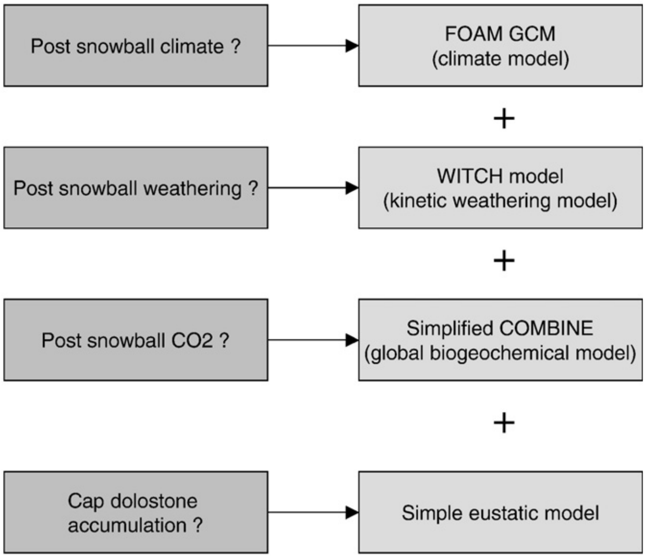

Fig. 1. General design of the simulations. At each level, a question is added and addressed using a specific model. When going down through the diagram, any new specific question requires the coupling of a hierarchy of models (specified by the sign '+').

consequences of post snowball continental weathering on cap dolostone accumulation. Our aim is to use numerical modelling to produce a first order reconstruction of the supergreenhouse climate and the timescale over which it is relaxed. Weathering processes are influenced by the air temperature controlling the dissolution rates of minerals, and by the continental runoff, which modulates dissolution through water-rock interactions and carries the weathering products to the oceans. We will first focus on climatic reconstructions of the supergreenhouse environment, after which the behaviour of the weathering sink under this climate will be discussed, and its consequences on the duration of the supergreenhouse will be investigated. Specifically, we will address the accumulation of cap dolostones which were deposited during the post glacial eustatic transgression and are a key element of the snowball hypothesis.

2. The climate of the snowball aftermath

2.1. Climate model description and simulation design

The climate of the post snowball is investigated with the general circulation climate model FOAM 1.5. 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 (Jacob, 1997). All simulations have been performed with an R15 spectral resolution (4.5°×7.5°) and 18 vertical levels. FOAM is used in mixed-layer mode, meaning the atmospheric model is linked to a 50-meter mixed-layer ocean with heat transport parameterized through diffusion. FOAM has been extensively applied to the study of ancient climate (Poulsen, 2003; Poulsen and Jacob, 2004; Donnadieu et al., 2006) and Pierrehumbert has demonstrated the validity of the FOAM radiative code in highly enriched CO_2 atmospheres such as the one hypothesized in the snowball Earth aftermath (Pierrehumbert, 2004). We have used a simplified paleogeographic model for the late Cryogenian (i.e. Marinoan) adapted from Macouin [pers.com] wherein the continental fragments of the former supercontinent Rodinia are clustered in low latitudes. An orography is assumed considering geological features (old orogenic belts and recent rifting) (Meert and Torsvik, 2003) [Macouin, pers. com.] (Fig. 2). We prescribe the presence of orogens and rifts (Meert and Torsvik, 2003) as elevated areas, between 500 and 1100 m (these relatively low altitudes are the consequence of the spectral smoothing implied by the model low surficial resolution), while the continental area outside uplifted surface has an elevation of 75 m. Solar luminosity is fixed at 94% of its present day value (1286 W/m^2) according to stellar evolution models (Gough, 1981). Orbital parameters are set at their present day values. Regarding continental runoff, a present day simulation of FOAM linked to the mixed-layer ocean predict a global value of 27 cm/yr, a value very close to the observed 25 cm/yr (Berner and Berner, 1987) or 22 cm/yr (Gaillardet et al., 1999).

The melting phase of the snowball Earth has never been investigated. Indeed, modelling the climate under several hundred times the present day CO_2 pressure and with the presence of melting icecaps but also of melting sea-ice glaciers remains an unsolved challenge in terms of numerical tools and of computational times. The aim of this paper is not to model in detail the deglaciation: rather the

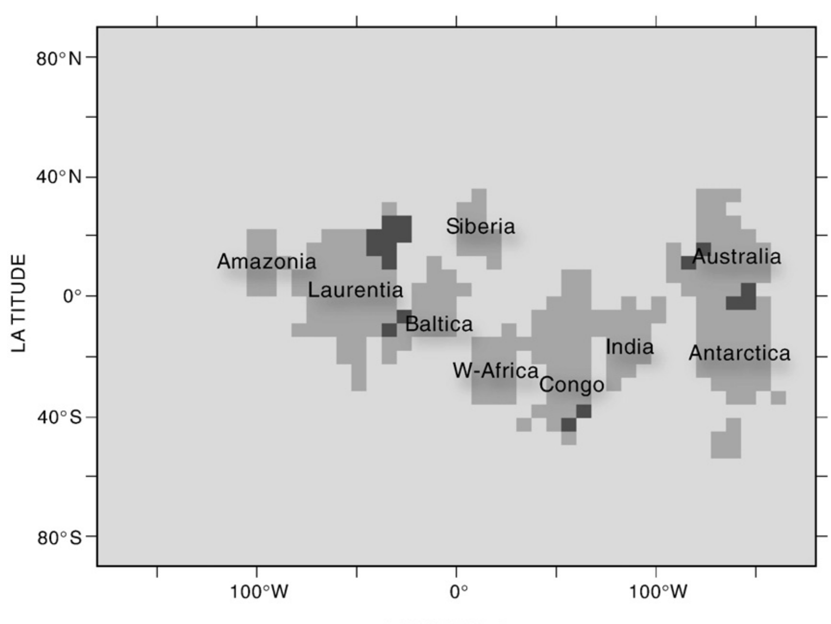

Fig. 2. End-Cryogenian (ca. 635 Ma) paleogeography used in the numerical modelling in this paper. Location of continental flood basalt provinces are shown in dark grey.