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Initiation of a Marinoan Snowball Earth in a state-of-the-art atmosphere-ocean general circulation model

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The apparent existence of low-latitude land glaciers at sea level during at least two episodes of the Neoproterozoic era, the Sturtian (∼710 million years before present, Ma) and the Marinoan (∼635 Ma), has led to the proposal that these glaciations were accompanied by completely ice-covered oceans. These states have become popular under the term "Snowball Earth." In this contribution, we study the initiation of a Marinoan Snowball Earth with the most sophisticated model ever used for this purpose, the atmosphere-ocean general circulation model ECHAM5/MPI-OM. In particular, we focus on the total solar irradiance and atmospheric concentration of carbon dioxide needed to trigger a Marinoan Snowball Earth.

Comparing the Marinoan control climate with a pre-industrial control climate, we find that the change of surface boundary conditions from present-day to Marinoan, including a shift of continents to low latitudes, induces a global mean cooling of 4.6 K. Two thirds of this cooling can be attributed to increased planetary albedo, the remaining one third to a weaker greenhouse effect. The Marinoan Snowball Earth bifurcation point for pre-industrial atmospheric carbon dioxide is between 95.5 and 96% of the present-day total solar irradiance (TSI), whereas a previous study with the same model found that it was between 91 and 94% for present-day surface boundary conditions. Our study hence supports the notion that low-latitude continents facilitate Snowball Earth initiation. A Snowball Earth for TSI set to its Marinoan value (94% of the present-day TSI) is prevented by doubling carbon dioxide with respect to its pre-industrial level. A zero-dimensional energy balance model is used to predict the Snowball Earth bifurcation point from only the equilibrium global mean ocean potential temperature for present-day TSI. We do not find stable states with sea-ice cover above 55%, and land conditions are such that glaciers could not grow with sea-ice cover of 55%. Therefore, none of our simulations qualifies as a "slushball" solution, with the caveat that mountains are not included in our study.

While uncertainties in important processes and parameters such as clouds and sea-ice albedo suggest that the Snowball Earth bifurcation point differs between climate models, our results contradict previous findings that Snowball Earth initiation would require much stronger forcings. In particular, we show that models that calculate ocean heat transport dynamically are not necessarily more resistant to Snowball initiation than models that do not incorporate ocean dynamics but use a specified ocean heat transport.