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Sensitivity of Neoproterozoic Snowball-Earth inceptions to continental configuration, orbital geometry, and volcanism

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The Cryogenian period (720–635 million years ago) in the Neoproterozoic era featured two phases of global or near-global ice cover, termed 'Snowball Earth'. Climate models of all kinds indicate that the inception of these phases must have occurred in the course of a self-amplifying ice–albedo feedback that forced the climate from a partially ice-covered to a Snowball state within a few years or decades. The maximum concentration of atmospheric carbon dioxide (CO_2) allowing such a drastic shift is difficult to determine because it depends on the choice of model and the boundary conditions prescribed in the model. Many previous studies report values or ranges for this CO_2 threshold but typically test only very few different boundary conditions. Furthermore, most studies include some kind of variability internal to the climate system but exclude variability due to volcanism. Here we present a comprehensive sensitivity study considering different scenarios for the Cryogenian continental configuration, orbital geometry, and short-term volcanic cooling effects in a consistent model framework, using the climate model of intermediate complexity CLIMBER-3α. The continental configurations comprise palaeogeography reconstructions for both Snowball-Earth periods from two different sources, as well as two idealised configurations with either uniformly dispersed continents or a single polar supercontinent. Orbital geometries are sampled as multiple different combinations of the parameters obliquity, eccentricity, and argument of perihelion. For volcanic eruptions, we differentiate between single and globally homogeneous perturbations, single and zonally resolved perturbations, and random sequences of globally homogeneous perturbations with realistic statistics. The CO_2 threshold lies between 10 and 250 ppm for all simulations. While the idealized continental configurations span a difference of around 200 ppm for the threshold, the continental reconstructions differ by only 20–40 ppm. Changes in orbital geometry account for variations in the CO_2 threshold by up to 32 ppm. The effects of volcanic perturbations largely depend on the orbital geometry. A very large peak reduction of net solar radiation by around –20 W/m^2 can shift the CO_2 threshold by the same order of magnitude as the orbital geometry. Even larger eruptions of up to –40 W/m^2 may shift the threshold by up to 50 ppm. However, the smaller, more frequent eruptions mostly have much lower impacts than the changes in continental configuration and orbital geometry. Eruptions near the equator tend to, but do not always, cause larger shifts than eruptions at high latitudes. Realistic sequences of eruptions lower the long-term temperature and have a bigger effect on the CO_2 threshold than single large eruptions of comparable magnitude.