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Paleogeographic control on the Snowball Earth threshold through geologic time

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In the last two billion years of Earth's history, Snowball Earth glaciations appear restricted to the Neoproterozoic, raising the question of why comparable events appear absent from the earlier Proterozoic or later Phanerozoic record. A common hypothesis is that the Neoproterozoic continental configuration led to Snowball initiation by enhancing silicate weathering, but this effect has not been quantified consistently across Earth history. Here we use the intermediate-complexity general circulation model PlaSim to simulate the climate state and global weathering across a wide range of atmospheric pCO_2 and solar insolation values for multiple paleogeographies (2,200 total simulations). We quantify how insolation and continental configuration influence (1) the pCO_2 threshold for Snowball initiation and (2) the background CO_2 required for the carbon cycle to be in steady state, and use these to evaluate the proximity of Earth's climate state to the Snowball bifurcation under different boundary conditions.

Across all configurations tested, we find that insolation dominates the variability in both the Snowball threshold and steady-state pCO_2, with paleogeography exerting a comparatively minor influence (Fig. 1). Additionally, the background pCO_2 required to maintain steady state is more than an order of magnitude higher than the Snowball initiation threshold. This implies that although the Snowball threshold itself varies by orders of magnitude across parameters, the magnitude of CO_2 drawdown required to trigger a Snowball is generally set by the background state rather than shifts in the Snowball bifurcation alone. In our simulations, the Neoproterozoic background state is further from the Snowball threshold than modern or Carboniferous comparisons. These results suggest that either there was a destabilizing perturbation to the carbon cycle in the Neoproterozoic, additional stabilizing feedbacks in the carbon cycle during the Phanerozoic, or both.

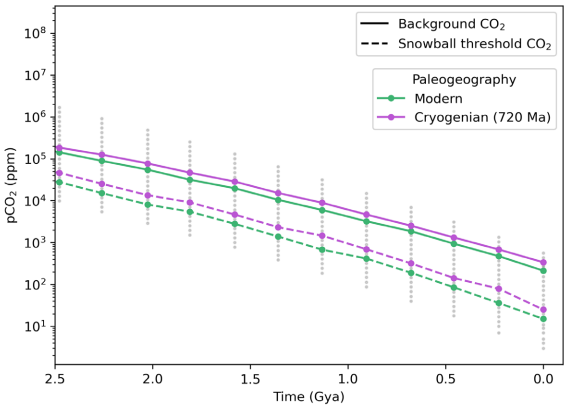

Figure 1. Background pCO_2 and Snowball threshold pCO_2 across geologic time for two paleogeographies. Grey dots represent each insolation-pCO_2 combination tested with the PlaSim general circulation model for both continental configurations. Solid lines show the background pCO_2 required for carbon cycle steady state, interpolated from the simulation grid for each paleogeography. Dashed lines indicate the maximum pCO_2 at which a Snowball can be maintained.