

Supplemental Information

MODEL AND METHODS

Late Paleozoic experiments were completed using the GENESIS atmospheric general circulation model (AGCM) version 3.0 coupled to a three-dimensional dynamic ice-sheet model. GENESIS consists of an AGCM coupled to a land-surface model with multi-layer models of vegetation, soil or land ice, and snow. The AGCM has a spectral resolution of T31 ($3.75^{\circ} \times 3.75^{\circ}$) and 18 vertical levels. The land-surface grid has a resolution of $2^{\circ} \times 2^{\circ}$. Sea-surface temperatures and sea ice are computed using a 50-m slab oceanic layer with diffusive heat flux (Pollard and Thompson, 1995; Thompson and Pollard, 1997). The thermo-mechanical ice-sheet model operates on a $1^{\circ} \times 2^{\circ}$ surface grid (Deconto and Pollard, 2003), and is based on the vertically integrated continuity equation for ice mass (Huybrechts, 1993; Ritz et al., 1997). The evolution of ice geometry is determined by surface mass balance, basal melting, and ice flow. Ice temperatures are predicted to account for their effect on rheology and basal sliding. The time step of the ice-sheet model is one year. The local bedrock response to ice load is a simple relaxation toward isostasy with a time constant of 5,000 years. Lithospheric flexure is modeled by linear elastic deformation. In this version of the model, ice shelves are not simulated.

For the purpose of this study, we have simplified the periods of each orbital parameter such that eccentricity, obliquity, and precessional periods occur every 80, 40, and 20 ka, respectively (Figure 1; Deconto and Pollard, 2003). To couple the climate and ice-sheet models, we use an asynchronous technique that consists of alternating AGCM

and ice-sheet integrations. To begin, GENESIS is integrated with specified orbital conditions (Fig.1) for 30 yrs to produce a steady-state climatology. Mean monthly meteorological fields (i.e. surface air temperature, evaporation, and precipitation) from the last ten years of the GENESIS run are then used to drive the ice-sheet model. Each ice-sheet model experiment is run for 5,000 yrs and predicts ice-sheet area, thickness, and isostatically adjusted continental topography. These new boundary conditions and updated orbital conditions are incorporated into the subsequent AGCM iteration. After the initial iteration, the AGCM is run in 15 yr segments and the meteorological fields from the last ten years are passed to the ice-sheet model. For each experiment, this scheme is repeated 48 times representing 320 ka and 4 eccentricity cycles.

Experiments were developed for four different atmospheric $p\text{CO}_2$ levels: 0.5 (140 ppm), 1 (280 ppm), 2 (560 ppm), and 4 (1120 ppm) \times PAL. The 4 \times PAL experiment was discontinued after \sim 240 ka due to the lack of significant continental ice volume. These CO_2 values were chosen to span the range of late Paleozoic $p\text{CO}_2$ reported by Montañez et al. (2007).

Besides $p\text{CO}_2$, all other boundary conditions are identical between experiments, and were chosen where possible to represent Sakmarian conditions. The paleogeography and paleotopography are based on the Paleogeographic Atlas Project's reconstruction for this time interval (Ziegler et al., 1997). Because our objective is to estimate continental ice, we modified the Sakmarian paleogeography by removing any prescribed continental ice. The ocean diffusive heat flux was set to a value that provides the best simulation for the modern climate. The late Paleozoic solar luminosity was specified as 1330.3 Wm^{-2} , 3% less than modern, in accordance with solar evolution models (Gough, 1981). The

range of orbital settings used in these experiments is based on the solar calculations of Berger and Loutre (1991) for the last ten million years. In the absence of proxy estimates for the late Paleozoic, trace gas concentrations of CH₄ (0.650 ppm) and N₂O (0.285 ppm) were set to pre-industrial levels. To estimate the sea-level change represented by our ice volume simulations, we employ the methods of Crowley and Baum (1991) and Patterson (1994). The simulated global ice volume in each experiment is converted to a water equivalent (WE) assuming an ice density of 0.917 g/mL. We then estimate an isostatically adjusted sea-level equivalent (IASLE) by:

$$\text{IASLE} = (1-k) \times \text{WE} / \text{ocean surface area}$$

where k has a value of 0.284 (the ratio of seawater density to oceanic lithosphere density). The isostatic adjustment approximates the response of the oceanic lithosphere to seawater loading/unloading. The Permian ocean surface area ($386.4 \times 10^6 \text{ km}^2$) was calculated from the Sakmarian paleogeographic reconstruction.

TABLE CAPTION

Table DR1. First order approximation of radiative forcing and temperature change. Radiative forcing (RF) describes the net change in incoming radiation versus out going radiation and is calculated from a reference pCO₂ level ($C_0=280 \text{ ppm}$) [$\text{RF} = 5.35 \times (\ln(C/C_0))$]. The temperature change is based on the equilibrium climate sensitivity ($\lambda = 0.8$), which refers to the equilibrium change in surface air temperature following a unit change in radiative forcing [$\delta T = \lambda \times \text{RF}$] (Myhre, 1998; IPCC, 2007).

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