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Key Points:
- The contribution of transient Antarctic ice sheet variations to Miocene δ^{18}O signals is smaller than indicated by equilibrium differences
- Transient ice volume variability is centered around a preferred small state and is dependent on the timescale of the forcing
- Enlarging the West Antarctic land surface increases the self-sustenance of the Miocene Antarctic ice sheet, decreasing the variability

Supporting Information:
- Supporting Information S1

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Transient Variability of the Miocene Antarctic Ice Sheet Smaller Than Equilibrium Differences

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Abstract During the early to mid-Miocene, benthic δ^{18}O records indicate large ice volume fluctuations of the Antarctic ice sheet (AIS) on multiple timescales. Hitherto, research has mainly focused on how CO_2 and insolation changes control an equilibrated AIS. However, transient AIS dynamics remain largely unexplored. Here, we study Miocene AIS variability, using an ice sheet-shelf model forced by climate model output with various CO_2 levels and orbital conditions. Besides equilibrium simulations, we conduct transient experiments, gradually changing the forcing climate state over time. We show that transient AIS variability is substantially smaller than equilibrium differences. This reduces the contribution of the AIS to δ^{18}O fluctuations by more than two thirds on a 40-kyr timescale, hence requiring a larger contribution by deep-sea-temperature variability. The growth rates are much slower than the decay rates, which ensures variability around a preferred small state. Finally, if the bedrock topography enlarges the West Antarctic land surface, AIS self-sustenance increases.

1. Introduction

During the early to mid-Miocene (23 to 14 Myr ago), benthic δ^{18}O records show lower values than during the Pleistocene, indicative of a warmer climate and smaller ice sheets (e.g., Cramer et al., 2009; Holbourn et al., 2013; Zachos et al., 2008). In particular, there was probably only limited ice cover on the Northern Hemisphere (Maslin et al., 1998). Moreover, benthic δ^{18}O records are fluctuating strongly during this time, most prominently on orbital timescales (Holbourn et al., 2013; Levy et al., 2019; Liebrand et al., 2011; Zachos et al., 2001). This prompts the possibility of large variability of the Antarctic ice sheet (AIS), which at times diminished to sizes considerably smaller than present-day. After the mid-Miocene Climatic Optimum (17 to 14.5 Myr ago), the AIS stabilizes around its present-day size, showing more modest variations (e.g., de Boer et al., 2015; Masson-Delmotte et al., 2010). Benthic δ^{18}O records are, however, not only influenced by the AIS volume but also by deep-sea temperatures, and the precise partitioning of the Miocene δ^{18}O variations remains under debate (e.g., Bijl et al., 2018; Billups & Schrag, 2002; Holbourn et al., 2013; Langebroek et al., 2010; Lear et al., 2010; Liebrand et al., 2011, 2017; Shevenell et al., 2008). Ice sheet models, particularly of the AIS, driven by Miocene climate forcing, can be used to elucidate this problem from an ice-physical point of view (Barker et al., 1999). To achieve continental-scale variability of the AIS, these models require large local temperature fluctuations of about 10 K, the absolute temperatures being dependent on the mass balance formulation (de Boer et al., 2010; Huybrechts, 1993; Stap et al., 2016). This temperature range has proven to be hard to simulate by climate models, because the associated CO_2 range is very large due to hysteresis in the relation between temperature and CO_2 (Pollard & DeConto, 2005). This hysteresis, which is mainly caused by the ice albedo and the surface-height-temperature feedbacks, results in substantially different CO_2 thresholds for waxing and waning of the AIS. Furthermore, orbital variations can mediate the hysteresis width and therefore affect AIS variability (e.g., Dolan et al., 2011; Langebroek et al., 2009; Pollard & DeConto, 2005; Stap et al., 2017). A recent attempt to model Miocene AIS variability used an isotope-enabled setup of a 3-D ice sheet model coupled to a regional climate model nested in a general circulation model (GCM; Gasson et al., 2016). They performed a set of steady state experiments with CO_2 levels ranging from 280 to 840 ppm and obtained significant variability of the AIS. However, the transiently evolving AIS is not necessarily in equilibrium with the climate. This is because the change in AIS volume over a given period of time is limited by the rates of accumulation and ablation. Furthermore, the hysteresis in the CO_2-temperature relation may result in different simulated ice volumes for warming and cooling