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Emplacement of Antarctic ice sheet mass affects circumpolar ocean flow

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ABSTRACT

During the Cenozoic the Antarctic continent experienced large fluctuations in ice-sheet volume. We investigate the effects of Glacial Isostatic Adjustment (GIA) on Southern Ocean circulation for the first continental scale glaciation of Antarctica (~34 Myr) by combining solid Earth and ocean dynamic modeling. A newly compiled global early Oligocene topography is used to run a solid Earth model forced by a growing Antarctic ice sheet. A regional Southern Ocean zonal isopycnal adiabatic ocean model is run under ice-free and fully glaciated (GIA) conditions. We find that GIA-induced deformations of the sea bottom on the order of 50 m are large enough to affect the pressure and density variations driving the ocean flow around Antarctica. Throughout the Southern Ocean, frontal patterns are shifted several degrees, velocity changes are regionally more than 100%, and the zonal transport decreases in mean and variability. The model analysis suggests that GIA induced ocean flow variations alone could impact local nutrient variability, erosion and sedimentation rates, or ocean heat transport. These effects may be large enough to require consideration when interpreting the results of Southern Ocean sediment cores.

1. Motivation

At the Eocene–Oligocene boundary ~33 million years ago (Myr), the Southern Hemispheric climate system experienced a rapid transition. The quasi ice-free Antarctic continent glaciated within less than $5 \cdot 10^5$ years, oscillated in orbitally paced glacial cycles between 40% and 140% of its present day volume for about ten million years, almost vanished at the Oligocene–Miocene boundary (23 Myr), but increased again in the mid to late Miocene (Hambrey et al., 1991; Zachos et al., 1997; DeConto et al., 2008; Gallagher et al., 2013). Simultaneously, in between the late Eocene and the early Miocene, the Southern Ocean circulation reorganized from basin wide gyres to an Antarctic Circumpolar Current (ACC). The development of the (proto) ACC was facilitated by the opening of two gateways: (1) the well-constrained deepening of the Tasmanian Gateway at 33.5 Myr (Stickley et al., 2004; Bijl et al., 2013), and (2) the Drake Passage, which opened/deepened sometime between 41 and 23 Myr (e.g. Barker and Burrell, 1977; Scher and Martin, 2006; Dalziel et al., 2013).

Two hypotheses have been proposed for the sudden glaciation of Antarctica at the end of the Eocene: ice sheet growth dominantly controlled by (1) the thermal isolation of the continent through the development of the ACC or (2) global cooling due to CO_2 changes (Kennett, 1977; Oglesby, 1989). Previous model studies have focused on either or both of these mechanisms, which involve ocean–atmosphere, atmosphere–ice sheet or ice sheet–bedrock interactions (e.g. Huber and Nof, 2006; DeConto et al., 2008; Sijp and England, 2011; Cristini et al., 2012; Lefebvre et al., 2012; Yang et al., 2013). Other mechanisms proposed to have influenced ice sheet growth are transitions of the Atlantic meridional overturning circulation (Tigchelaar et al., 2011) or the shallow opening of the Tasman Gateway, which might have cooled the Antarctic margins and waters of intermediate depth (Bijl et al., 2013).

The Antarctic ice sheet today stores approximately $25 \cdot 10^6$ km^3 of water, while the highest estimates for the early Oligocene are $36 \cdot 10^6$ km^3 (Wilson et al., 2013). The load exerted on the solid Earth surface and the gravitational pull exerted by the growing ice sheet on the oceans result in space- and time-dependent deformations of the crust and of the mean sea surface, the latter remaining an equipotential surface of gravity (Farrell and Clark, 1976). Known as Glacial Isostatic Adjustment, the combination of these processes are accounted for by solving the Sea Level Equation (SLE) for a prescribed ice sheet chronology and solid Earth rheological model (Spada and Stocchi, 2007). Since the equations of ocean motion are defined relative to an equipotential surface of gravity, only a deformation of the solid Earth and a change in the water column height have the potential to impact the modeled ocean flow.

In this paper, we address the question to what extent the sea bottom deformations – induced by the Antarctic ice sheet mass – could have impacted the ocean flow in an Eocene–Oligocene–Miocene world. We focus solely on the effect of the load and mass – which has not been studied before – and thereby isolate the problem from effects of ocean

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and atmospheric buoyancy and heat transport. Here, we combine for the first time a solid Earth model and an ocean model for deep-time paleo conditions. A global early Oligocene topography (described in Section 2.1) is used to run a solid Earth model (Section 2.2) forced by a growing Antarctic ice sheet. Subsequently, a zonal isopycnal adiabatic ocean model (Section 2.3) representing the Southern Ocean is forced with the ice free topography and the ice load adjusted topography. Results of the simulations are presented in Section 3. Analysis of ocean model output in terms of the vertically integrated vorticity equation is presented in Section 4. Before we conclude in Section 6, we discuss possible implications of our findings and their relation to proxy measures in Section 5.

2. Model setup and experimental design

2.1. Reconstruction of early Oligocene topography

We compiled a global early Oligocene topography from different datasets (Fig. 1). Markwick et al. (2000) is used for the continental shape and topography, Wilson et al. (2012) for the Antarctic topography, and Müller et al. (2008) for the deep sea bathymetry. The shelf and coast areas are interpolated between these datasets (Somme et al., 2009), dependent upon how much is known for a region (e.g., Close et al., 2009, for the continental margin along Wilkes Land). Poorly constrained regions were supplemented or adapted with data from: Meulenkamp and Sissingh (2003) for the Tethys region, van Hinsbergen et al. (2012) and Torsvik et al. (2012) for the Indian–South Asian region and the position of Africa and South America, McQuarrie and van Hinsbergen (2013) for the Arabian region, and Mix et al. (2011) for the elevation of Western North America. We used the program GPlates (http://www.gplates.org/) to assure the relative position of the continental plates; where they differ from the Markwick data set the GPlate position was prioritized. The reconstruction has a resolution of 1° and is available (together with a vegetation file not used here) in different configurations for the Southern Ocean gateways upon request from the authors. It is more realistic, detailed and has a higher resolution than those used in earlier modeling studies for the Eocene or Oligocene time periods (e.g. Huber and Nof, 2006; Sijp and England, 2011; Cristini et al., 2012).

For this study we interpolated the topography to 1/4° resolution and both Southern Ocean gateways are assumed to be open and deep. The timing of the Drake Passage opening and deepening is widely debated (Diester-Haass and Zahn, 1996; Latimer and Filippelli, 2002; Lawver and Gahagan, 2003; Barker and Thomas, 2004; Livermore et al., 2005; Pfuhl and McCave, 2005; Dalziel et al., 2013). Due to these considerable uncertainties, our configuration can be representative of the late Eocene, Oligocene, or possibly the Miocene. Thus, we use the Eocene–Oligocene transition as an *example* of a time slice where the Southern Ocean gateways were deep and the Antarctic ice volume changed substantially. We are concerned with the mechanism that connects changing ice load and changing ocean depth, and do not attempt to explain the temporal behavior of specific proxies. The choice of deep gateways is discussed further in Sections 2.3 and 5.

2.2. Solid Earth model and sea level equation

We use the code SELEN (Spada and Stocchi, 2007) to solve the SLE by means of the pseudo-spectral method (Mitrovica and Peltier, 1991) and retrieve the relative sea level changes on a global scale and in time. We assume that the Earth is spherically symmetric, self-gravitating, non-rotating, and radially stratified. Hence, the rheological parameters only depend upon the distance from the center of mass of the Earth and no lateral variations are accounted for. The outer shell is assumed to be perfectly elastic and mimics the lithosphere. The mantle is discretized into three Maxwell viscoelastic layers, the inner core is assumed to be inviscid. We adopt the normal mode technique to generate the response of the Earth to variations of surface ice- and water-loading (Peltier, 1974). We solve the SLE for the viscous and elastic components of the solid Earth deformation by simulating the ice-sheet chronology over 2.2 Myr. Fig. 2 shows the global relative sea level change (left column) and that of a sector around Antarctica (right column) at 1.5 (a,b), 1.55 (c,d), and 2.2 Myr (e,f).

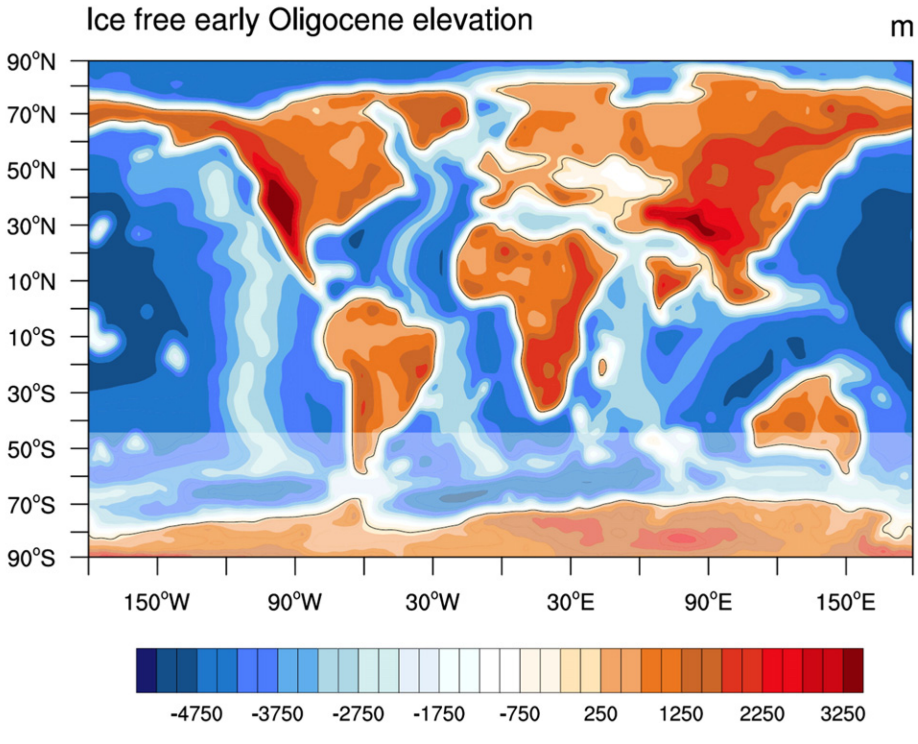

Fig. 1. Ice free global topography used to initiate the solid Earth model. The shaded part is the region used for the ocean model control run. The dataset is available upon request for different versions of Southern Ocean gateways.