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Multiple states in the late Eocene ocean circulation

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ABSTRACT

The Eocene-Oligocene Transition (EOT) marks a major step within the Cenozoic climate in going from a greenhouse into an icehouse state, with the formation of a continental-scale Antarctic ice sheet. The roles of steadily decreasing CO_2 concentrations versus changes in ocean circulation at the EOT are still debated and the threshold for Antarctic glaciation is obscured by uncertainties in global geometry. Here, a detailed study of the late Eocene ocean circulation is carried out using an ocean general circulation model under two slightly different geography reconstructions of the middle-to-late Eocene (38 Ma). Using the same atmospheric forcing, both geographies give a profoundly different equilibrium ocean circulation state. The underlying reason for this sensitivity is the presence of multiple equilibria characterised by either North or South Pacific deep water formation. A possible shift from a southern towards a northern overturning circulation would result in significant changes in the global heat distribution and consequently make the Southern Hemisphere climate more susceptible for significant cooling and ice sheet formation on Antarctica.

1. Introduction

The climate during the Cenozoic era (last 65 million years, Myr) has changed dramatically from a warm, basically ice-free world to the present-day climate with large ice sheets in both polar regions. This long-term transition has not been smooth though: between slow trends of gradual warming or cooling several relatively rapid transitions have occurred, sometimes associated with a change in (quasi-periodic) variability on orbital time scales (Zachos et al., 2001a; Cramer et al., 2009).

Often the opening or closing of oceanic gateways is used in explanations of the sometimes rather dramatic climate shifts observed in the proxy record. For example, it has been suggested that the Northern Hemisphere glaciation in the Pliocene may have resulted from the establishment of the present-day Atlantic Ocean meridional overturning circulation after the closure of the Central American Seaway (Haug and Tiedemann, 1998). Similarly, the closure of the Indian-Atlantic Ocean connection through the Tethys seaway has been proposed to have had profound impacts on the Miocene climate (Harzhauser et al., 2007). However, the most widely discussed example of a gateway-related cause for climate change is the hypothesis that the establishment of the Antarctic Circumpolar Current due to opening of the Southern Ocean gateways has thermally isolated Antarctica such that a large ice sheet could appear at the Eocene-Oligocene boundary (Kennett, 1977). While all of these hypotheses are being debated for various reasons (e.g. Antarctic glaciation forced by declining CO_2 levels (Gasson et al., 2014) rather than ocean gateways), often it is the uncertainty in timing and precise occurrence of the gateway closure/opening that makes a direct causal relationship with a climate transition problematic.

Uncertainty in paleobathymetry arises because of the complicated structure of plate boundaries and continents meeting each other. However, there are also more subtle uncertainties in geographical boundary conditions such as the positioning of plates (and continents) with respect to each other, which is only at the beginning of being quantified (Torsvik et al., 2012; van Hinsbergen et al., 2015). Plate-tectonic models rely on a specific frame of reference to determine how the plates are positioned with respect to the Earth's mantle (Dupont-Nivet et al., 2008). Currently, two such frameworks are used, one referred to as HotSpot (HS, Seton et al. (2012)) and the other as PaleoMag (PM, Torsvik et al. (2012)). Global middle-to-late Eocene reconstructions were made in these two different frames of reference (Baatsen et al., 2016) for use as boundary conditions for ocean-climate models. While the gateway regions are exactly the same in both versions, the rotation of the poles in the PM frame of reference results in continents shifted or rotated by as much as 5–6° with respect to the HS one.

As more and more time slices of paleogeography become available and are being used for ocean and climate model studies (von der Heydt and Dijkstra, 2006; Haywood et al., 2011; Herold et al., 2014; Lunt

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et al., 2016), we consider it important to determine how the modelled global ocean circulation is dependent on the chosen boundary conditions. In this paper, we study the sensitivity of the ocean circulation to relatively moderate changes in continental geography (Baatsen et al., 2016) using a global ocean-only model for the middle-to-late Eocene. We find an unexpected sensitivity of the Eocene global ocean flow to paleobathymetry and explain this by the occurrence of multiple equilibria.

2. Methods

2.1. Ocean model

The global version of the Parallel Ocean Program (POP v2.1) model (Smith et al., 2010) is used for computing the circulation in both (HS and PM) paleobathymetries. Horizontal viscosity is anisotropic (Smith and Mcwilliams, 2003) and horizontal tracer diffusion follows the parameterisation of Gent and Mcwilliams (1990). The model uses the KPP-scheme for vertical mixing coefficients (Large et al., 1994). The model is set up with a nominal 1° horizontal resolution (320 × 384 grid points) and 60 vertical (non-equidistant) layers using a curvilinear projection. We use the bipolar grid version of POP with the southern pole situated at 90°S in the Antarctic continent, and the northern pole is relocated to Greenland (at 68°N, 20°W). A simple sea ice module is enabled that introduces sea ice whenever the sea surface temperature drops below −1.8° C.

A global geography reconstruction made for 38 Ma, using the method described in Baatsen et al. (2016), is shown in Fig. 1 in a curvilinear projection as used by the ocean model here. This reconstruction uses the Torsvik et al. (2012) PaleoMag reference frame, the Müller et al. (2008) ocean bathymetry and the Wilson et al. (2012) Antarctic topography. White contour lines in Fig. 1 indicate the changes in the positions of the continents with respect to the PM reconstruction, when using a HS reference frame as in Seton et al. (2012).

2.2. Model forcing

The atmospheric forcing is taken from a lower resolution (T42; ~ 2.5°) Eocene coupled climate model (CCSM3) simulation under 4 × pre-industrial CO_2 (i.e. 1120 ppm) (Huber and Caballero, 2011). Surface fields of wind stress, freshwater flux, heat flux and sea surface temperature from CCSM3 are adjusted to the new model grid as shown in Fig. 2. Monthly climatologies (using a 50-year average) are considered, from which original land masses are removed using natural neighbour interpolation. Next, surface forcing fields are adjusted to the new land-ocean mask and interpolated onto the curvilinear grid. Localised extremes from river runoff in surface fresh water fluxes (Fig. 2a) are removed and global fields are bias corrected to conserve the global salt budget. Larger scale effects from run-off, precipitation and evaporation are still present in the adjusted forcing as seen in Fig. 2b. Similarly, a bias correction is applied to the surface heat fluxes to conserve the global heat budget at the atmosphere-ocean interface. The ocean model is then forced by the adjusted surface fresh water flux, wind stress (shown in Fig. 9) and heat flux, where the latter is combined with restoring conditions to sea surface temperatures.

Three different simulations are carried out; the first using a PaleoMag geography (referred to as ‘ PM’), the second using a HotSpot geography (‘ HS’) and the third starting from the Paleomag configuration but using adjusted surface fresh water fluxes (PM Adjusted). The PM Adjusted case serves to test the stability of the overturning regime by perturbing the system for a limited amount of time through adding 1Sv of integrated fresh water flux to the South Pacific and doing the opposite in the North Pacific (blue and red boxes in Fig. 2a, respectively).

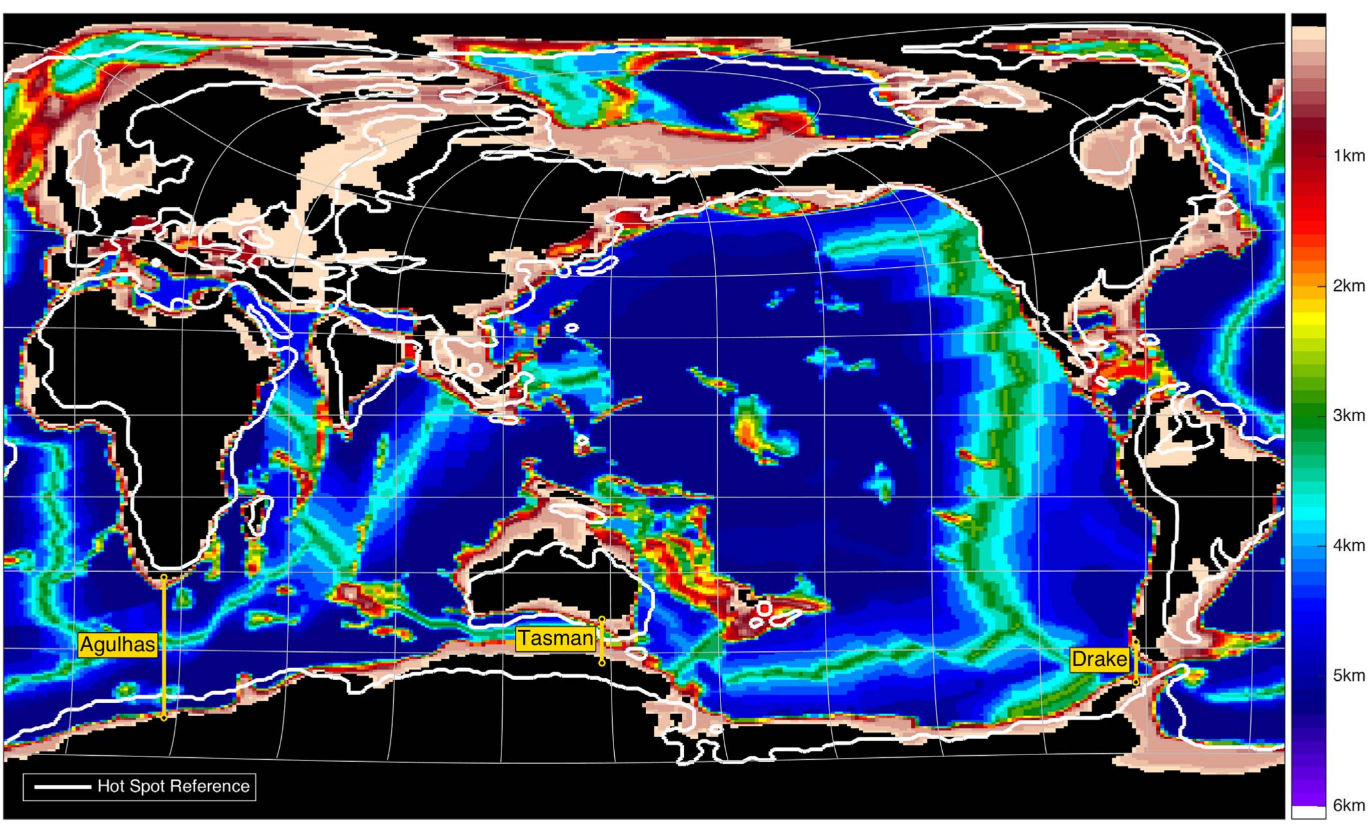

Fig. 1. Global bathymetry grid in curvilinear projection as used by the model; black shading shows the land mask and colours indicate depth. The model grid is based on a PaleoMag (PM) referenced 38 Ma reconstruction, while the white contour line indicates the shorelines using a HotSpot (HS) framework. A rectangular projection grid is added in grey, featuring 30° intervals in longitude and 20° in latitude. Thick yellow lines denote the positions of three Southern Ocean transects with their respective names, which will be used in the text below.