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The role of ocean gateways on cooling climate on long time scales

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ABSTRACT

We examine ocean changes in response to changes in paleogeography from the Cretaceous to present in an intermediate complexity model and in the fully coupled CCSM3 model. Greenhouse gas concentrations are kept constant to allow a focus on effects arising from changing continental configurations. We find consistent and significant geography-related Cenozoic cooling arising from the opening of Southern Ocean (SO) gateways. Both models show significant deep ocean cooling arising from tectonic evolution alone. Simulations employing continental configurations associated with greenhouse climates, namely the Turonian and the Eocene simulations, systematically exhibit warm deep ocean temperatures at elevated pCO_2 close to 10 °C. In contrast, continental configurations associated with (later) icehouse climates are associated with cooler deep ocean temperatures at identical pCO_2, arising from a progressive strengthening of the Antarctic Circumpolar Current. This suggests that a component of the Cenozoic benthic cooling trend recorded in oxygen isotopes could arise directly from changes in continental configuration, and so be partially decoupled from the Cenozoic greenhouse gas history. In this paper we will present our model results against the background of an extensive review of previous work on ocean gateways and additional modelling results from several other global climate models.

Contents

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1. Introduction

1.1. Equable climates and their deterioration

During the Cretaceous (142–65 Ma) and early Cenozoic era, Earth's surface was significantly warmer than today, most notably at high latitudes. Through the Cenozoic (65 Ma to present), Antarctica was located more or less in its present position, yet remained largely ice-free up to the earliest Oligocene (33.5 Ma Zachos et al., 1994, 2001a). The early Eocene epoch (about 55 to 48 Ma) saw the warmest global climates of the Cenozoic with much smaller equator to pole temperature gradients than today (Barron, 1987; Greenwood and Wing, 1995; Wolfe, 1995; Bijl et al., 2009). Pross et al. (2012) infer diverse near-tropical forests, including palm trees, in lowland regions along the Wilkes Land coast (at a paleolatitude around 70°S) from sedimentary pollen distributions. Early to mid Eocene deep water temperatures, and therefore winter temperatures at the deep water formation sites (Kim et al., 2008), were at least 10 °C warmer than today (Miller et al., 1987; Lear et al., 2000; Zachos et al., 2001a, 2008; Cramer et al., 2011), consistent with high-latitude presence of frost-intolerant flora and fauna (Hutchison, 1982; Spicer and Parrish, 1990; Wing and Greenwood, 1993; Greenwood and Wing, 1995; Markwick, 1998; Carpenter et al., 2012; Contreras et al., 2013, 2014). There is also evidence for cold-intolerant plant and animal species such as palms, cycads and crocodiles at subpolar latitudes during the early Eocene also in Greenland, with an estimated mean annual temperature of 14 ± 3 °C and coldest month temperatures in excess of 5 °C (Eldrett et al., 2009).

As the Eocene progressed, these warm climates were followed by a gradual shift towards cooler conditions, particularly in winter and high latitudes, and thus increasing latitudinal temperature gradients (Bijl et al., 2009; Eldrett et al., 2009). Tropical sea surface temperatures (SSTs) are now believed to be greater than 30 °C (much warmer than at present), and to have remained remarkably constant during the Eocene, implying that the Eocene cooling trend occurred mainly at the poles (Pearson et al., 2007).

SSTs can be inferred from $\delta^{18}O$ (Zachos et al., 1996; Pearson et al., 2001; Fricke and Wing, 2006; Pearson et al., 2007; Eldrett et al., 2009), Mg/Ca (e.g. Lear et al., 2010) on planktonic foraminifera or bivalves (e.g., Ivany et al., 2008), and recently with novel methods such as clumped isotopes on carbonate Δ_{47} (Ghosh et al., 2006). Unfortunately the carbonate-based proxies can often not be applied on high-latitude sections because of the general absence of carbonate-rich sediments in high-latitudes. Other proxies such as TEX_{86} (Schouten et al., 2002; Kim et al., 2010) and Uk37 (Brassell et al., 1986; Liu et al., 2009; Bijl et al., 2010) can be applied independently of latitude and therefore provide a useful toolbox for the reconstruction of latitudinal temperature gradients. The compilation of sea surface paleotemperature proxy data based on biomarker proxies provides a picture of extremely warm polar regions but only slightly warmer polar sea surfaces. The warmth of polar regions may be slightly overestimated by the biomarker proxies, potentially because of a bias in these proxies towards the warm season (Bijl et al., 2009) but temperatures above 20 °C for southern high latitudes were confirmed by terrestrial palynomorph data from the Antarctic Margin (Pross et al., 2012; Contreras et al., 2013), South Australia (Carpenter et al., 2012) and by carbonate paleotemperature proxies from New Zealand (Hollis et al., 2009, 2012). The middle Eocene is characterised by no or only mild cooling of tropical waters but quite substantial cooling of high latitude waters. For the Arctic the extreme cooling may be explained by the isolation of the Arctic Ocean leading to a disconnection with adjacent oceans (Sluijs et al., 2008). For the Southern Ocean however, such isolating barriers did not exist and therefore another explanation for the cooling was sought. Bijl et al. (2013) argued that a decline of atmospheric CO_2 through the middle Eocene (e.g. Beerling and Royer, 2011) can explain the high latitude cooling but that mechanism would also have caused a tropical cooling. Therefore, the Southern Ocean cooling must result from a regional cause in addition to a decline in atmospheric CO_2. Bijl et al. (2013) assign a role to the opening of southern Ocean gateways in cooling Southern Ocean surface waters during the Eocene.

Later, the long-term Cenozoic cooling culminated in the glaciated and low-pCO_2 "icehouse" conditions that persist today, with the rapid growth of the Antarctic ice sheets in a most profound climatic transition at the Eocene–Oligocene transition (EOT; ~34 Ma). This occurred in two abrupt shifts (Coxall et al., 2005; Houben et al., 2012), and eventually stabilised at a net $\delta^{18}O$ shift of ~1‰ (Zachos et al., 1996) after an overshoot. Tigchelaar et al. (2010) attempt to link this two step structure to changes in the ocean's meridional overturning polarity in their conceptual climate model, while ice sheet numerical model experiments of DeConto and Pollard (2003) seem to produce a two-step ice growth with simply a linear decrease of atmospheric CO_2 subimposed on a favourable orbital configuration.

Liu et al. (2009) found a 5 °C drop in high latitude temperature from a range of sites for the EOT and use a coupled climate model to simulate a 3–5 °C cooling under a drop in CO_2 from 1120 ppm (representing the late Eocene) to 560 ppm (the early Oligocene). Benthic foraminiferal Mg/Ca ratios, serving as a proxy for temperature, aid in deconvolving bottom water temperature and ice volume effects on the $\delta^{18}O$ record (Lear et al., 2000; Martin et al., 2002; Billups and Schrag, 2003; Lear et al., 2004; Shevenell et al., 2008; Lear et al., 2010). Estimates of global ice volume suggested little Northern Hemisphere (NH) glaciation (Lear et al., 2000, 2004, 2008), in agreement with model simulations by DeConto et al. (2008). The Cenozoic trend (to the present day) can be inferred from a ~4‰ increase in benthic foraminiferal $\delta^{18}O$ over the past 50 million years (Shackleton and Kennett, 1975; Miller et al., 1987; Zachos et al., 2001a), reflecting both a 12 °C deep ocean cooling based on $\delta^{18}O$–Mg/Ca comparisons (Lear et al., 2010) and increasing ice volume (Oerlemans, 2004; Coxall and Pearson, 2007; Boer et al., 2010).

In conclusion, the decline in atmospheric CO_2 seems to be an important driver of Paleogene–Neogene climate changes in the Southern Ocean, but the opening of gateways and subsequent migration of continents also had a profound effect on regional climate change and oceanography.