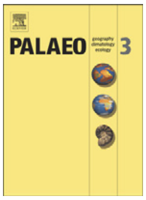
Palaeogeography, Palaeoclimatology, Palaeoecology 306 (2011) 82–94

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo



On the sensitivity of ocean circulation to arctic freshwater input during the Paleocene/Eocene Thermal Maximum

Jesse T. Cope, Arne Winguth *

University of Texas at Arlington, Arlington, Texas, United States

A R T I C L E I N F O

Article history:
Received 27 May 2010
Received in revised form 24 March 2011
Accepted 31 March 2011
Available online 12 April 2011

Keywords:
Paleocene/Eocene Thermal Maximum
Carbon isotope excursion
Methane hydrates
Arctic
Ocean circulation
Freshwater
Climate modeling

A B S T R A C T

The Paleocene/Eocene Thermal Maximum (PETM) ~55 Ma ago, corresponds to a time characterized by extreme global warming caused by a massive carbon input into the ocean and atmosphere. Climate proxies from sedimentary records suggest that fresh water flow from an ice-free Arctic into the remainder of the global ocean increased due to tectonic changes, enhanced runoff, and thermal expansion. In this study we use the Community Climate System Model version 3 (CCSM-3), including a carbon cycle model, to examine the sensitivity of the ocean circulation to freshwater outflow from the Arctic Ocean during the PETM, and whether these changes may have contributed to an additional warming during the PETM. Two experiments, the first with freshwater exchange between the Arctic and Pacific Oceans and the second between the Arctic and Atlantic Oceans, are compared with a reference experiment with exchange between the Arctic and Indian Oceans and with independent stratigraphic and geochemical records from the Ocean Drilling Program (ODP). As freshwater is transported from the Arctic into the North Pacific Ocean, stratification is enhanced in the North Pacific due to a significant reduction in surface salinity. As a consequence, intermediate to deep-water sources shift from both hemispheres in the Pacific Ocean to a dominant source in the South Pacific Ocean and an additional source in the northern Tethys Ocean. This simulated shift of deep-water sources during the PETM is in agreement with recent Nd isotope measurements. The circulation patterns in the Pacific are similar to those inferred from stable isotope reconstructions, but contradicting a strong North Atlantic deep-water source during the PETM. Freshwater input into the Pacific Ocean results in a warming of intermediate water masses of >2 °C in the North Pacific. When freshwater flow is routed from the Arctic into the Atlantic Ocean, surface density changes are too small to change vertical stratification substantially, contrary to a previous study. In summary, based upon circulation patterns and temperature increases due to freshwater flux through the Bering Strait, Arctic freshwater input into the North Pacific may have contributed to methane hydrate destabilization, an event suggested to have accelerated warming during the PETM.

1. Introduction

The Paleocene Eocene Thermal Maximum (PETM), ~55 Ma ago, was a transient global warming event of a relatively brief duration, characterized by a massive carbon release, and provides an ideal case to study interactions between climate and carbon cycle (e.g., Zachos et al., 2008). Significant changes in the global ocean involved sea surface temperature (SST), deep-sea temperature, calcite compensation depth (CCD), and patterns of global ocean circulation. Sea surface temperatures during this time rose by varying amounts around the globe; the mid-latitude regions were up to 8 °C warmer than background temperatures while the high latitudes were as much as 6 °C warmer (Kelly et al., 2005; Sluijs et al., 2006,2007a; Weijers et al., 2007; Zachos et al., 2003; Zachos et al., 2005). Records from ODP sites indicate deep-sea temperatures 4–5 °C warmer than background (Kennett and Stott, 1991; Thomas and Shackleton, 1996; Tripati and Elderfield, 2005; Zachos et al., 2001) and a CCD, though varying on local levels, that shoaled by up to ~2 km during this time (Kelly et al., 2005; Zachos et al., 2005).

Significant ecological changes occurred during the PETM due to warming and shoreline transgressions (Bowen et al., 2006; Bijl et al., 2009; Sluijs et al., 2007b; Weijers et al., 2007), forcing animals and plants to adapt, migrate and evolve (Woodburne et al., 2009). Examples range from size reduction and dispersion of terrestrial mammals in the northern hemisphere, to range extensions of mid-latitude flora, the increased occurrence of the dinoflagellate cyst Apectodinium (Sluijs et al., 2007a), rapid planktonic foraminifera diversification (Clyde and Gingerich, 1998; Gibbs et al., 2010; Kelly et al., 1998; Wing et al., 2005) and large-scale extinction of benthic foraminifera (Thomas and Shackleton, 1996; Thomas, 1998).

The likely cause of climate change was more than 2000 gigatons of carbon (GtC) entering the atmosphere and ocean over a period of no

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* Corresponding author at: Department of Earth and Environmental Sciences, University of Texas at Arlington, 500 Yates St., Arlington, Texas, 76019, United States.
E-mail address: awinguth@uta.edu (A. Winguth).

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doi:10.1016/j.palaeo.2011.03.032

more than 10,000 years (e.g. Bowen et al., 2004; Zachos et al., 2008). In response to the carbon emissions during the PETM, atmospheric CO_2 levels increased and were in the range of 2000–4000 ppm (Breecker et al., 2010; Zachos et al., 2008) as compared to present levels of ~385 ppm. This carbon release and increase in atmospheric CO_2 concentration is comparable to the amount of carbon to be emitted over the next few centuries due to human activities. Multiple hypotheses have been put forward as the initial trigger of the carbon release. For example, intensive volcanism liberating greenhouse gases could have initiated the warming (Dickens, 2004; Sluijs et al., 2007a; Storey et al., 2007; Svensen et al., 2004). This warming could then lead to a reorganization of the deep sea circulation with bottom water warming, as inferred from isotope ratios (e.g. Dickens et al., 1995; Zachos et al., 2008) and modeling (Bice and Marotzke, 2002; Lunt et al., 2010; Winguth et al., 2010), and could have triggered the injection of carbon through the dissociation of methane hydrates into the climate system.

Topography and bathymetry during the PETM differed significantly from today, with respect to the distribution of landmasses, changes in size of ocean basins and more or less restricted seaways (Fig. 1; Scotese, 2008). Sea levels are affected by tectonic activity (e.g. Larson et al., 2004; Long and Shennan, 1994; Schmitz and Pujalte, 2003; Watts and Thorne, 1984) as well as climatic variability (e.g. Miller et al., 1998; Gale et al., 2002; Antonov et al., 2005; Miller et al., 2005) and are thus difficult to precisely resolve, however, ostracode and dinoflagellate records suggest that sea levels during the PETM rose by approximately 20–30 m from previous levels (Sluijs et al., 2008; Speijer and Morsi, 2002). A connection between the Arctic Ocean and the Tethyan water masses via the Turgay Strait during this time of increased sea level has been inferred from dinoflagellate cysts (e.g. Iakovleva et al., 2001). Limited throughflow via the Fram and Bering Straits due to high sea levels and continued seafloor spreading, is also suggested for the PETM and is supported by Nd–Sr isotopes in fish fossils (Gleason et al., 2009; Roberts et al., 2009) as well as by previous model results and reconstructions (Heinemann et al., 2009; Scotese, 2008). However, the formation of a volcanic bridge between Europe and Greenland (Maclennan and Jones, 2006) would have favored a closed or very narrow and shallow Fram Strait.

Conditions in the Arctic during the PETM are represented by significant increases in sea surface temperature and sea level, and salinity decreases (Sluijs et al., 2006) due to increased runoff from ice melt (Pagani et al., 2006a; Sluijs et al., 2006,2008; Waddell and Moore, 2008) or from enhanced precipitation in high latitudes (Winguth et al., 2010). Fresh water pulses from the Arctic may have affected deep-water formation and the strength of the deep-sea circulation, such as north to south flow in the Atlantic basin. These changes would have influenced global temperature gradients and thus the climate.

The novel approach in this study is to use a fully comprehensive climate model including the marine carbon cycle to explore how changes in the throughflow in ocean passages could have affected the ocean circulation, deep sea temperatures, geochemical tracers and contributed to the global warming during the PETM. For this purpose, sensitivity experiments are carried out comparing a freshwater exchange between the Arctic and the Pacific (Bering Strait) and Atlantic

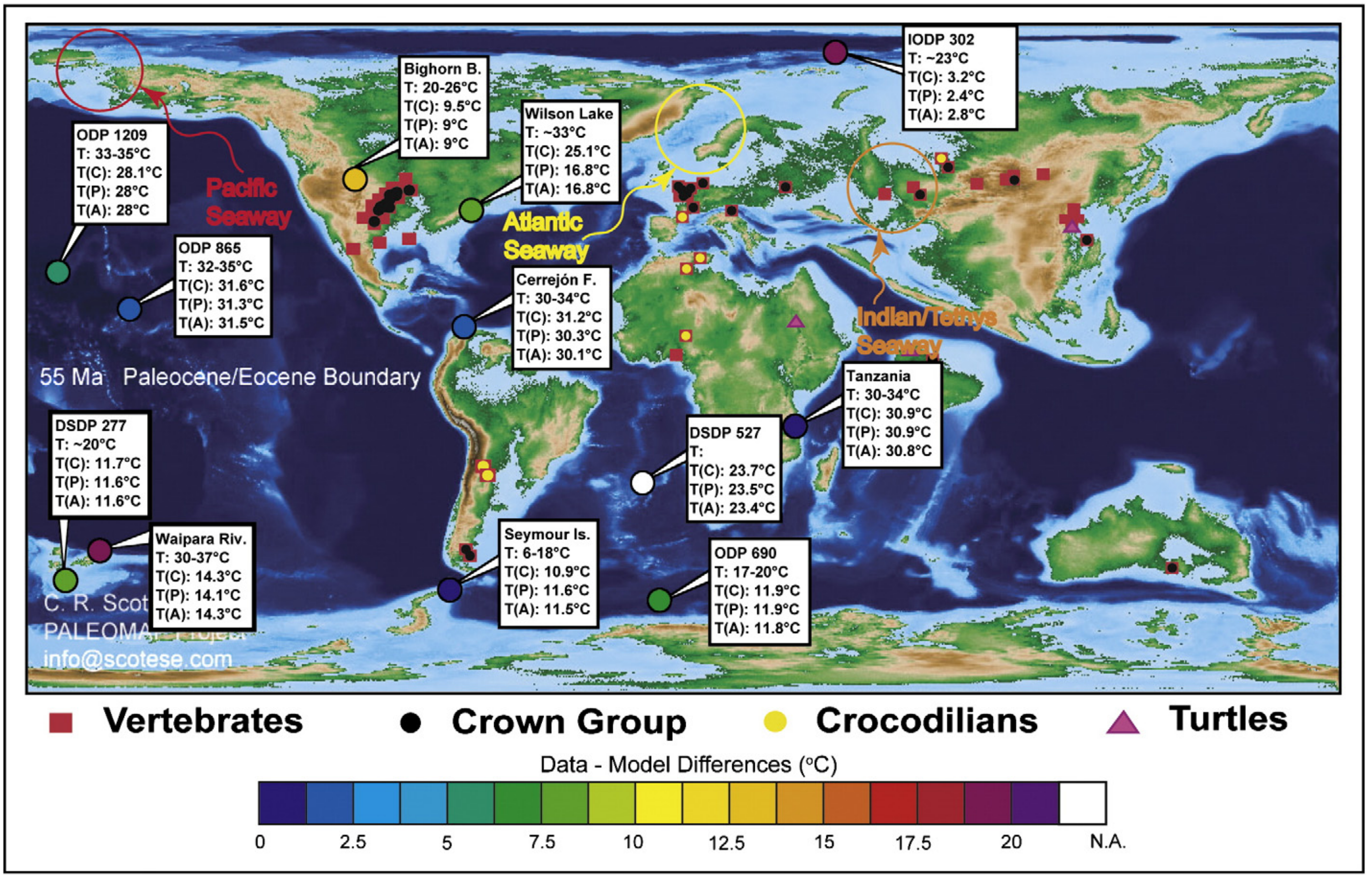

Fig. 1. Geographical reconstruction for the PETM with possible freshwater exchange locations between the Arctic and the remainder of the global ocean; from the PALEOMAP Project (www.scotese.com). The light blue color represents very shallow water (200–500 m), and dark blue are water depths >500 m. Boxes indicate reconstructed surface temperatures across the Paleocene–Eocene boundary for the Control, EOCPAC, and EOCATL experiments (Bralower et al., 2006; Hollis et al., 2009; Ivany et al., 2008; Pearson et al., 2007; Shackleton and Kennett, 1975; Sluijs et al., 2006, 2007b; Sluijs et al., 2008; Thomas et al., 1999; Tripati and Elderfield, 2005; Wing et al., 2005; Zachos et al., 2004; Zachos et al., 2006). Filled circles denote average temperature differences between data and the Control experiment. Fossil locations taken from Markwick (1997). Figure after Winguth et al. (2010).