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High latitude hydrological changes during the Eocene Thermal Maximum 2

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ABSTRACT

The Eocene hyperthermals, including the Paleocene–Eocene Thermal Maximum (PETM) and Eocene Thermal Maximum 2 (ETM2), represent extreme global warming events ~56 and 54 million years ago associated with rapid increases in atmospheric greenhouse gas concentrations. An initial study on PETM characteristics in the Arctic region argued for intensification of the hydrological cycle and a substantial increase in poleward moisture transport during global warming based on compound-specific carbon and hydrogen isotopic ($^2H/^1H$) records from sedimentary leaf-wax lipids. In this study, we apply this isotopic and hydrological approach on sediments deposited during ETM2 from the Lomonosov Ridge (Integrated Ocean Drilling Program Expedition 302). Our results show similar $^2H/^1H$ changes during ETM2 as during the PETM, with a period of ^2H-enrichment ($\sim 20‰$) relative to "pre-event" values just prior to the negative carbon isotope shift (CIE) that is often taken as the onset of the hyperthermal, and more negative lipid δ^2H values ($\sim -15‰$) during peak warming. Notably, lipid ^2H-enrichment at the base of the event is coeval with colder TEX_{86}^H temperatures.

If $^2H/^1H$ values of leaf waxes primarily reflect the hydrogen isotopic composition of precipitation, the observed local relationship between temperature and $^2H/^1H$ values for the body of ETM2 is precisely the opposite of what would be predicted using a simple Rayleigh isotope distillation model, assuming a meridional vapor trajectory and a reduction in equator-pole temperature gradients. Overall, a negative correlation exists between the average chain length of *n*-alkanes and $^2H/^1H$ suggesting that local changes in ecology could have impacted the hydrogen isotopic compositions of leaf waxes. The negative correlation falls across three separate intervals — the base of the event, the initial CIE, and during the H2 hyperthermal (of which the assignment is not fully certain). Three possible mechanisms potentially explain ^2H-enriched signals at the base of the event, including (1) intense local drying and cooling leading to evaporative ^2H-enrichment; (2) changes in frequency/intensity of storm events and its impact on high latitude amount effects; and (3) changes in low-latitude temperatures. Evidence for hydrological shifts at the base of both hyperthermals suggests that hydrological change or the factors promoting hydrological change played a role in triggering the release of greenhouse gases. Generation of similar high-resolution isotopic- and temperature records at other latitudes is crucial for understanding the causal links between temperature and hydrological changes and may help constrain the source and mechanism of carbon release that triggered the early Eocene hyperthermals.

1. Introduction

The impact of greenhouse-gas induced warming on the character of the global hydrological cycle has been a matter of widespread debate in the climate community (Allan and Soden, 2007; Allen and Ingram, 2002; Barron et al., 1989; Held and Soden, 2006; Huntington, 2006; Trenberth, 2011; Wentz et al., 2007). The general view is that warming intensifies the global hydrological cycle, but an intensified cycle does not simply imply a wetter world (Pierrehumbert, 2002). Rather, it refers to an increase in the intensity of evaporation in evaporative zones with a compensating increase in moisture delivery in regions that experience net precipitation. Held and Soden (2006), in their assessment of coupled

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climate simulations, find global enhancement of evaporation–precipitation (E-P) spatial patterns under future climate change scenarios. Outside of the tropics, they find that modern E-P zones are located in the mid to high latitudes and global warming is expected to result in midlatitude drying and increased poleward moisture transport. However, confidence in these projections is limited by the lack of long-term data required for validation. Modern day satellite measurements and documented historical observations (NRC, 2006) do not capture the magnitude of temperature changes predicted under future scenarios of CO_2 emission. As a consequence, ancient records of climate when global temperatures were substantially elevated above modern conditions need to be explored.

Several rapid and extreme transient global warming events, termed hyperthermals, occurred during the late Paleocene and early Eocene (Thomas and Zachos, 2000; Lourens et al., 2005; Cramer et al., 2003). Global average temperatures during hyperthermals rose by as much as 5 °C above pre-event temperatures (e.g., Dunkley Jones et al., 2013) that were already at least 10 °C warmer than today (Huber and Caballero, 2011; Lunt et al., 2012), and thus provide case studies of hydrological characteristics under a much warmer world. Hyperthermals are characterized by substantial carbonate dissolution associated with shoaling of the calcite compensation depth, and negative carbon isotopic excursions (CIE) (e.g., Bralower et al., 1997; Schmitz et al., 1996; Zachos et al., 2005; Stap et al., 2009) that implicate a massive and rapid increase in ocean–atmosphere CO_2 concentrations (Dickens et al., 1995, 1997; Lourens et al., 2005; Sluijs et al., 2009). Accordingly, these events are often referred to as extreme end-member scenarios of modern day greenhouse gas-induced global warming (Pagani et al., 2006; Zachos et al., 2004; Abels et al., 2012).

During the Paleocene–Eocene Thermal Maximum (PETM; ∼55 Ma), global average surface temperatures rose by 4–5 °C (Dunkley Jones et al., 2013), with some regional variations (Kennett and Stott, 1991; Thomas et al., 1999; Zachos et al., 2003, 2006; Wing et al., 2005; Sluijs et al., 2006, 2011). The magnitude of the negative CIE ranges from ∼ −2.5 to −6‰, in terrestrial and marine carbonates (e.g., Zachos et al., 2007; Bowen et al., 2004), paleosols (Koch et al., 1992), organic matter (Sluijs and Dickens, 2012), and biomarkers of higher-plants (Pagani et al., 2006; Schouten et al., 2007; Smith et al., 2007) and marine archaea (Schoon et al., 2013). ETM2 is more poorly studied, but records indicate several geochemical characteristics similar to the PETM, including a negative CIE approximately half the magnitude of PETM (Lourens et al., 2005; Sluijs et al., 2009; Stap et al., 2010; Schoon et al., 2011). Another warming event (termed H2) following ETM2 by approximately 100 kyrs, is also associated with deep ocean carbonate dissolution and a negative carbon isotope excursion (Cramer et al., 2003; Stap et al., 2010).

During ETM2, TEX_{86}-based sea surface temperatures, pollen data and dinoflagellate records from the Lomonosov Ridge, Arctic Ocean (∼85°N paleolatitude; Integrated Ocean Drilling Program Expedition 302; Arctic Coring Expedition; ACEX) suggest sea-surface temperatures (SST) increased ∼3–5 °C, with evidence for tropical vegetation on land and a decrease in sea surface salinity (Sluijs et al., 2009). Due to oceanographic changes and possible vertical water-column migration of archaea, the production depth of the lipids used in the TEX_{86} proxy, temperature estimates and peak warming are not well constrained (Sluijs et al., 2009). The current assessment argues that temperature and hydrographic responses to increased CO_2 during ETM2 in the Arctic region are similar to the changes observed for the PETM, but at a smaller scale.

A range of hypotheses have been proposed to explain the source of carbon driving early Eocene hyperthermals, including dis-association of methane hydrates (Dickens et al., 1995, 1997; Lunt et al., 2011), conflagration of peat deposits (Kurtz, 2003), intrusive-heating of organic-rich marine sediments (Svenson et al., 2004), drying of restricted seaways leading to oxidation of organic matter (Higgins and Schrag, 2006), bolide impact (Kent et al., 2003; Wright and Schaller, 2013), extreme tropical warmth resulting in death and oxidation of plant matter (Huber, 2009) and high latitude permafrost oxidation (DeConto et al., 2012). An early increase of global or regional temperatures prior to the release of $\delta^{13}C$-depleted carbon has been argued as the reason for initiation of the PETM (Sluijs et al., 2007; Eldrett et al., 2014), but at present, there is no evidence for warming leading the CIE during ETM2. Poor temporal resolution of temperature records with respect to carbon isotope records, as well as the accuracy of absolute temperature values, limits our capacity to constrain the timing of initial temperature shifts and to firmly establish lead–lag relationships (e.g., Sluijs et al., 2007). Improved linkages between carbon input, global temperature perturbations, runoff characteristics and the hydrological cycle, investigations of hydrological changes could provide an alternative path for assessing the character of climate change prior to- and during hyperthermals.

Hydrological perturbations during the PETM and other hyperthermals have been investigated using various methodologies. Leaf Margin Analysis and changes in macro-flora at the Cabin Fork section (Wyoming) shows an ∼40% decline in precipitation at the onset of the PETM followed by increased precipitation during the latter part of the event (Wing et al., 2005). Continental records in the Spanish Pyrenees across the Paleocene/Eocene boundary indicate a change from semiarid coastal plain deposits to conglomerate braid deposits (interpreted to be proximal parts of a mega-fan; Schmitz and Pujalte, 2007), suggesting increased seasonality, intensified intra-annual humidity gradients and more intense precipitation events. Bowen et al. (2004) used soil–carbon modeling to argue that the offset between the magnitude of the terrestrial and marine CIEs during the PETM in the northern midlatitudes could be explained by an increase in relative humidity (RH) and/or soil moisture. Many shelf sections show an increase in the supply of terrigenous material during several hyperthermals, suggesting more intense weathering (Hollis et al., 2005; Giusberti et al., 2007; Nicolo et al., 2007; Sluijs et al., 2008a; Slotnick et al., 2012; see overview in Sluijs et al., 2008b). Proliferations of fresh-water tolerant dinoflagellates and increases in the supply of terrestrial pollen and spores have been related to increased river runoff (Crouch et al., 2003; Sluijs et al., 2006; Sluijs and Brinkhuis, 2009; Harding et al., 2011). Finally, pollen assemblages have been used to assess hydrological changes and regionally found to lead the carbon isotope excursion across the onset of the PETM (Eldrett et al., 2014).

Hydrogen isotope compositions of higher-plant leaf wax lipids preserved in sedimentary deposits (Huang et al., 1995; Polissar et al., 2009; Wilkie et al., 2013) have been used to interpret hydrological conditions during periods of climate change (Pagani et al., 2006; Tierney et al., 2010; Feakins et al., 2012; Schefuß et al., 2011), changes in the rates of evaporation and precipitation (E-P) (Huang et al., 2000, 2002; Xie et al., 2000; Andersen et al., 2001), and source–water composition (Schouten et al., 2006). Leaf waxes during the PETM have been analyzed in a range of localities including the tropics (Jaramillo et al., 2010; Handley et al., 2008, 2012), midlatitudes (Big Horn Basin, North America: Smith et al., 2007 and Forada, Italy: Tipple et al., 2011), and the high latitude Arctic Ocean (Pagani et al., 2006). Low-latitude leaf-wax *n*-alkane records from Venezuela show an ∼ −40‰ δ^2H shift at the base of the CIE (Jaramillo et al., 2010) and interpreted as reflecting increased precipitation and forest diversification. *n*-Alkane δ^2H records from the Big Horn Basin (Wyoming, USA) show an initial positive shift (∼5‰) at the base of the CIE and more negative values (∼10‰) during the body of the event (Smith et al., 2007). The direction of changes at the Big Horn Basin is remarkably similar to the $^2H/^1H$