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Invited review article

Hydrological and associated biogeochemical consequences of rapid global warming during the Paleocene-Eocene Thermal Maximum

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ABSTRACT

The Paleocene-Eocene Thermal Maximum (PETM) hyperthermal, ~56 million years ago (Ma), is the most dramatic example of abrupt Cenozoic global warming. During the PETM surface temperatures increased between 5 and 9 °C and the onset likely took < 20 kyr. The PETM provides a case study of the impacts of rapid global warming on the Earth system, including both hydrological and associated biogeochemical feedbacks, and proxy data from the PETM can provide constraints on changes in warm climate hydrology simulated by general circulation models (GCMs). In this paper, we provide a critical review of biological and geochemical signatures interpreted as direct or indirect indicators of hydrological change at the PETM, explore the importance of adopting multi-proxy approaches, and present a preliminary model-data comparison. Hydrological records complement those of temperature and indicate that the climatic response at the PETM was complex, with significant regional and temporal variability. This is further illustrated by the biogeochemical consequences of inferred changes in hydrology and, in fact, changes in precipitation and the biogeochemical consequences are often conflated in geochemical signatures. There is also strong evidence in many regions for changes in the episodic and/or intra-annual distribution of precipitation that has not widely been considered when comparing proxy data to GCM output. Crucially, GCM simulations indicate that the response of the hydrological cycle to the PETM was heterogeneous – some regions are associated with increased precipitation – evaporation (P – E), whilst others are characterised by a decrease. Interestingly, the majority of proxy data come from the regions where GCMs predict an increase in PETM precipitation. We propose that comparison of hydrological proxies to GCM output can be an important test of model skill, but this will be enhanced by further data from regions of model-simulated aridity and simulation of extreme precipitation events.

1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) concluded that anthropogenic warming by 2100 is likely to exceed 2 °C above preindustrial temperatures for both stabilisation (RCP6.0) and high-emission (RCP8.5) greenhouse gas scenarios. Predicting the associated response of Earth's hydrological cycle is a fundamental endeavour, given the environmental and related socio-economic implications of such changes (e.g. Trenberth et al., 2003; Dai, 2006). Global warming is widely considered to cause an intensification of the hydrological cycle, with globally increased evaporative fluxes balanced by increased precipitation at around 2% K^{-1} (Allen and Ingram, 2002; Trenberth, 2011). Regionally, a 'wet-wetter dry-drier' style response is anticipated, with increased water vapour transport from moisture divergence zones into convergence zones (Held and Soden, 2006; Chou and Neelin, 2004). Beyond first-order predictions, regional variations in hydrological changes are more uncertain, with General Circulation Models (GCMs) exhibiting

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significant differences in their projected end-of-century climatology (Schaller et al., 2011; Knutti and Sedláček, 2013). Beyond predicting changes in mean annual or seasonal precipitation distributions, simulating variations in precipitation frequency, intensity and type are highly uncertain within numerical models (Dai, 2006; Sun et al., 2006), but potentially crucial to understanding localised hydrological responses.

The environmental impacts and feedbacks resulting from changes in the hydrological cycle are likely to be profound. Although current changes in runoff, erosion and coastal water quality are often dominated by direct human pressures such as land use change, water abstraction and increased fertiliser use (Fabricius, 2005; Walling, 2009), warming-induced hydrological changes will likely impart a significant impact on the hydrological cycle in coming decades (Jiménez Cisneros et al., 2014; Yang et al., 2003; Rabalais et al., 2009). Elevated global precipitation is predicted to result in increased soil erosion (Nearing et al., 2004; Zhang et al., 2012), although changes in seasonality of precipitation and the occurrence of high intensity events may increase erosion even in regions where total annual precipitation declines. On land, changes in precipitation and soil moisture will affect the vegetation distribution (Jiang et al., 2012; Yu et al., 2016), the extent of wetlands (Milzow et al., 2010; Acreman et al., 2009) and rates of organic matter decomposition (Jobbagy and Jackson, 2000; Conant et al., 2011), all with profound impacts on the carbon cycle. Moreover, changes in runoff will impact the delivery of freshwater, nutrients and terrigenous materials to continental shelves with associated impacts on biogeochemistry (Jiménez Cisneros et al., 2014), and intense storm activity could result in greater turbulent mixing (Meire et al., 2013).

Warmer-than-present intervals in Earth's history can serve as partial analogues for our future Earth (Lunt et al., 2013; Haywood et al., 2011), especially high atmospheric CO_2 end-of-century scenarios (White et al., 2001; Suarez et al., 2009). In particular, a coupled approach that integrates geologic proxy data with the results of modelling offers the possibility to evaluate whether GCMs are capable of adequately simulating the hydrological cycle of deep-time warm climates (Winguth et al., 2010; Speelman et al., 2010), with implications for understanding how best to utilise model projections for future prediction. Furthermore, the study of paleohydrology also has wide implications for understanding past changes in climate, biogeochemistry, and the carbon cycle.

In this paper, we explore changes in the hydrological cycle during the Paleocene-Eocene Thermal Maximum (PETM; Section 2), a greenhouse-gas induced hyperthermal warming event which occurred around 56 Ma (Westerhold et al., 2009). Despite extensive research on the environmental impacts of the PETM and several model-derived reconstructions of precipitation, a synthesis of proxy evidence is currently lacking. This is crucial, because much of the data reveal complex (Schmitz and Pujalte, 2003; Schmitz and Pujalte, 2007; Handley et al., 2012; Garel et al., 2013), or even contradictory interpretations (Bowen et al., 2004; Wing et al., 2005; Bowen and Bowen, 2008; Retallack et al., 2009). Furthermore, proxies are not direct indicators for changes in precipitation or evaporation, but rather more indirect evidence for how hydrological changes impacted sediments or biota. These proxies also respond to different temporal signals of hydrological change, but this process remains largely unconsidered (e.g. Foreman, 2014). In this paper, a compilation of proxy indicators that incorporate either direct or indirect signals of Eocene hydrological change is presented, focussing on the PETM but including some data for other transient hyperthermals and long-term changes associated with the Early Eocene Climatic Optimum (EECO). Crucially, by compiling results from different proxy approaches, a spatially distributed data set is generated, suitable for qualitative proxy-model comparison and for critical evaluation of the global hydrological cycle -and its consequences - during rapid global warming events.

2. Early Paleogene climate change

Early Paleogene (57–48 Ma) pCO_2 estimates are sparse and variable but generally indicate levels much higher than those of today (Royer et al., 2001; Fletcher et al., 2008; Doria et al., 2011; Yapp, 2004; Jagniecki et al., 2015; Anagnostou et al., 2016). As a consequence of putative pCO_2 increase, but also perhaps influenced by oceanographic change (e.g. Hollis et al., 2012), the early Eocene is characterised by gradual long-term warming. This culminated in the EECO (53–49 Ma), a long-term temperature maximum (Zachos et al., 2001; Littler et al., 2014). Sea surface temperature (SST) estimates inferred from inorganic and organic proxies for this interval indicate very high SSTs, including tropical temperatures warmer than today, $> 30\ ^\circ C$ (Pearson et al., 2001; Pearson et al., 2007; Inglis et al., 2015a), and markedly warmer SSTs at high latitudes, with estimates ranging between ~ 25 and $35\ ^\circ C$ (Bijl et al., 2009; Creech et al., 2010; Hollis et al., 2012; Frieling et al., 2014; Inglis et al., 2015a). As such, a reduced equator-pole temperature gradient has been suggested for the early Eocene (Bijl et al., 2009; Inglis et al., 2015a; Tierney and Tingley, 2014), with significant implications for the global hydrological cycle (Speelman et al., 2010).

The early Paleogene is also characterised by a series of hyperthermal events, including the PETM which occurred around ~ 56 Ma and is associated with $\sim 5\ ^\circ C$ of warming in the deep ocean (Zachos et al., 2001; Tripati and Elderfield, 2005) and up to $8\ ^\circ C$ of warming in the surface ocean (Sluijs et al., 2006; Zachos et al., 2006; Sluijs et al., 2007; Sluijs et al., 2011). The PETM is characterised by a ~ 3–6‰ negative carbon isotope excursion (CIE) which indicates the release of ^{13}C–depleted carbon into the ocean-atmosphere system (Dickens et al., 1995; Cramer, 2003; Lourens et al., 2005). The CIE occurs globally (McInerney and Wing, 2011) but differs in magnitude depending on both the archive and location (Schubert and Jahren, 2013; Section 3.4), leading to difficulties constraining the amount of carbon input. There is also little consensus over the source of carbon released during the PETM. Warming has been widely attributed to the dissociation of seafloor marine hydrates and the subsequent oxidation of methane to carbon dioxide (Dickens et al., 1995; Dunkley Jones et al., 2010), but this appears to be unable to explain the magnitude of the observed temperature rise (Zeebe et al., 2009). As such, additional carbon sources have been invoked, many of which represent biogeochemical feedbacks modulated by the hydroclimatic regime, including the decomposition of soil organic carbon in high-latitude permafrost (DeConto et al., 2012), enhanced terrestrial methane cycling in peat-forming environments (Pancost et al., 2007; Beerling et al., 2011) and/or increased carbon turnover in soils (Cotton et al., 2015). The drawdown of CO_2 that drove the PETM recovery is also thought to have been governed by biogeochemical feedbacks, including enhanced carbon storage in the terrestrial biosphere (Bowen and Zachos, 2010), increased efficiency in the biological pump (Bains et al., 2000) and/or enhanced marine carbonate preservation (Kelly et al., 2005).

3. Hydrological change during the PETM

Dramatic hydrological change during the PETM has been inferred from a range of sedimentological, geochemical and biological proxies. A compilation, and in some cases re-examination, of these proxies is essential for future data-model comparisons. Quantitative botanical proxies for precipitation are discussed first, followed by qualitative proxies for other hydrological changes.

3.1. Botanical proxies for change in precipitation

Fossilised plant remains provide two distinct methods for estimating ancient precipitation rates. Leaf Area Analysis (LAA) is a physiognomic approach whereby larger leaves predominate in climates with greater mean annual precipitation rates (Wilf et al., 1998). However, the LAA approach can underestimate precipitation (see Peppe et al., 2011 and