Earth and Planetary Science Letters 501 (2018) 24–36

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Changes in the occurrence of extreme precipitation events at the Paleocene–Eocene thermal maximum

Matthew J. Carmichael [a,b,c,*], Richard D. Pancost [b,c], Daniel J. Lunt [a,c]

[a] BRIDGE, School of Geographical Sciences, University of Bristol, UK
[b] Organic Geochemistry Unit, School of Chemistry and School of Earth Sciences, University of Bristol, UK
[c] The Cabot Institute for the Environment, University of Bristol, UK

ARTICLE INFO

Article history:
Received 11 November 2017
Received in revised form 25 July 2018
Accepted 3 August 2018
Available online xxxx
Editor: M. Frank

Keywords:
extreme precipitation
proxy-model comparisons
General Circulation Model
Eocene
PETM
paleoclimate

ABSTRACT

Future global warming is widely anticipated to increase the occurrence of extreme precipitation events, but such hydrological changes have received limited attention within paleoclimate studies. Several proxy studies of the hydrological response to the Paleocene–Eocene Thermal Maximum hyperthermal, ∼56 Ma, have recently invoked changes in the occurrence of extreme precipitation events to explain observations, but these changes have not been studied for the geologic past using climate models. Here, we use a coupled atmosphere–ocean general circulation model, HadCM3L, to study regional changes in metrics for extreme precipitation across the onset of the PETM by comparing simulations performed with possible PETM and pre-PETM greenhouse gas forcings. Our simulations show a shift in the frequency–intensity relationship of precipitation, with extreme events increasing in importance over tropical regions including equatorial Africa and southern America. The incidence of some extreme events increases by up to 70% across the PETM in some regions. While the most extreme precipitation rates tend to relate to increases in convective precipitation, in some regions dynamic changes in atmospheric circulation are also of importance. Although shortcomings in the ability of general circulation models to represent the daily cycle of precipitation and the full range of extreme events precludes a direct comparison of absolute precipitation rates, our simulations provide a useful spatial framework for interpreting hydrological proxies from this time period. Our results indicate that changes in extreme precipitation behaviour may be decoupled from those in mean annual precipitation, including, for example in east Africa, where the change in mean annual precipitation is small but a large increase in the size and frequency of extreme events occurs. This has important implications for the interpretation of the hydrological proxy record and our understanding of climatic, as well as biogeochemical, responses to global warming events.

1. Introduction

Projections of how Earth's hydrological cycle will operate on a future warmer Earth indicate changes to the sub-annual character of precipitation including the frequency and intensity of extreme events (Emori and Brown, 2005; O'Gorman, 2015). Observational data indicate that in some mid-latitude regions, there has already been a disproportionate increase in heavy precipitation events relative to mean annual changes (Donat et al., 2013; Dittus et al., 2015). Changes in the occurrence of extreme precipitation are expected from thermodynamical effects of warming which increases the saturation vapour pressure of the atmosphere on the order of 7% K^{-1}, according to the Clausius–Clapeyron relation. In regions that are not moisture limited, there is subsequently an exponential increase in precipitable water, assuming that relative humidity remains constant. While the global precipitation rate is energetically constrained to ∼2% K^{-1} (Allen and Ingram, 2002), extreme events are predicted to scale with Clausius–Clapeyron, occurring where most atmospheric moisture is converted to precipitation (Dai and Trenberth, 2004). However, regional variations in the occurrence of extremes are more uncertain: dynamical changes in atmospheric circulation can lead to variations in moisture convergence, and observational studies have shown increases in extremes which exceed Clausius–Clapeyron scaling (Lenderink and van Meijgaard, 2008).

The instrumental record provides only a limited constraint on the behaviour of extreme precipitation in a warm world (e.g. Asadieh and Krakauer, 2015). As such, the response of the hydrological cycle to intervals of global warmth in the geologic record is receiving increased attention in paleoclimate studies (e.g. Pierrehumbert, 2002; Speelman et al., 2010). The environmental

* Corresponding author at: BRIDGE, School of Geographical Sciences, University of Bristol, UK.
E-mail address: Matt.Carmichael@bristol.ac.uk (M.J. Carmichael).

https://doi.org/10.1016/j.epsl.2018.08.005

impacts of the Paleocene–Eocene Thermal Maximum (PETM) hyperthermal at ∼56 Ma have received particular attention given the global nature of the 5–9 °C warming, and the event's rapid onset and transient nature (e.g. Dunkley-Jones et al., 2013). A range of proxies indicate that the warming was accompanied by a major hydrological perturbation, with evidence for increased continental runoff (John et al., 2008), excursions in oxygen and deuterium isotopes indicative of changes in precipitation amount and airmass history (Pagani et al., 2006) and changes in paleosol characteristics suggestive of variations in soil moisture (Kraus and Riggins, 2007).

Changes in the occurrence of hydrological extremes have previously been invoked to explain the results of a number of PETM proxy studies. In the Spanish Pyrenees, paleosol properties such as colouration, calcite content and presence of soil nodules indicate a semi-arid early Eocene climate with little soil moisture. Despite this, a 1–4 m thick conglomerate with clasts >65 cm marks the onset of the PETM (Schmitz and Pujalte, 2007) and is correlated with elevated coarse-grained sediment export elsewhere within the same basin (Pujalte et al., 2015). These changes have been interpreted as a response to the onset of high-energy storms with analogues drawn to modern-day megafans which form in regions with highly seasonal precipitation. Low-latitude PETM sections are scarce, but the Tanzanian Drilling Project (TDP) has provided indirect evidence for a change in subtropical precipitation regimes. Leaf wax biomarkers are isotopically enriched in deuterium at the PETM, which has been interpreted to reflect elevated evaporative enrichment in a more arid (i.e. reduced P–E) climate (Handley et al., 2012). However, these coincide with an increase in terrestrially-sourced biomarkers and elevated sedimentation rate, which led the authors to suggest that the region experienced increases in intense episodic, perhaps seasonal, precipitation events. Finally, at East Tasman Plateau (IODP Site 1172), the PETM is associated with a peak in the dinoflagellate *Eocladopyxis*. Based on studies of extant Goniodomidae – the family to which *Eocladopyxis* belongs – it has been suggested that the region experienced more storms at the PETM, at least seasonally, since in many regions this seems to be a requirement to re-suspend dormant cysts prior to their hatching (Sluijs et al., 2011 and references therein).

Reconstructing spatial changes in the characteristics of precipitation regimes at the PETM is a relatively new endeavour and is compounded by a scarcity of sections from low latitudes and terrestrial settings (e.g. Handley et al., 2012; Kraus et al., 2013). While thermodynamics suggests an increase in intense precipitation events should be expected during a global warming event such as the PETM, it is currently unknown whether particular regions were more susceptible than others to extremes. Furthermore, the existing evidence for extreme PETM precipitation comes from different proxies and spans a range of latitudes and environmental settings, such that it is unclear whether other regions also experienced changes in intense, episodic rainfall, or whether existing proxies for hydrological change at some locations have been erroneously interpreted as mean annual climatic signals. For example, several proxies for PETM hydrological changes relate to continental weathering and erosion (such as increased sedimentation rate, kaolinite deposition and geomorphological evolution, e.g. John et al., 2008; Foreman et al., 2012) or increased nutrient delivery to continental margins (Sluijs et al., 2014). Such proxies may incorporate sub-annual climatic signals, rather than integrating a mean annual response given that rainfall intensity is often recognised as being of greater importance in erosion than rainfall amount alone (e.g. Nearing et al., 2004; Baartman et al., 2012). As such, the interpretation of these proxies is limited without further insight into the relationship between means and extremes.

Although the proxy record provides potentially important information on the hydrological cycle in a warm world, it can only give a geographically-limited perspective, and it does not provide information on underlying mechanisms. However, modelling can provide context for local data, and can elucidate mechanisms. Despite this, there have not been any published modelling studies to date which have analysed changes in the global occurrence of extreme precipitation for the Eocene. The aims of this paper are (1) to use a GCM to investigate whether changes in the occurrence of precipitation extremes are simulated across the PETM; (2) to identify regions which are most likely to have been influenced by extreme, episodic precipitation events; and (3) to inform interpretation of proxy records by exploring the relationship between mean changes in precipitation and changes in precipitation extremes. In Section 2, we outline the modelling setup used for the PETM simulations. In Section 3, we characterise the occurrence of extreme precipitation events within the model for a series of Eocene-relevant model locations and develop global metrics for analysing spatial variations in extreme precipitation. In Section 4, we consider in detail the changes simulated at three case study locations, making comparisons with proxy data, and we also further discuss the ability of the model to represent precipitation extremes by comparison to preindustrial climate data, before drawing conclusions in Section 5.

2. Methods

The simulations in this paper are performed using HadCM3L, a fully-coupled atmosphere–ocean General Circulation Model (GCM), one of the suite of climate models developed by the UK Met Office (Gordon et al., 2000). HadCM3L has been used widely in the study of Eocene paleoclimate (Lunt et al., 2010; Loptson et al., 2014; Dunkley-Jones et al., 2013; Carmichael et al., 2017). Previous work in the context of future climate utilising HadCM3 – which operates at the same atmospheric resolution, but a higher oceanic resolution than HadCM3L – has shown that changes in the global precipitation frequency–intensity relationship, and therefore the increased occurrence of extremes, are seen in high CO_2 simulations (Allen and Ingram, 2002). The simulation of extreme precipitation events in the Indian monsoon region has also been investigated for future climate projections and has been shown to be related to Clausius–Clapeyron scaling (Turner and Slingo, 2009). However, extremes in the geological past have not been studied using this model.

The simulations presented here are initialised from those published by Loptson et al. (2014) to which the reader is referred for further details of model setup. Briefly, our equilibrium simulations are performed with atmospheric CO_2 at 2*x* and 4*x* preindustrial concentrations, utilising an early Eocene (∼55 Ma) paleogeography (Lunt et al., 2010) and with a dynamically-evolving vegetation distribution (TRIFFID). Both the atmosphere and ocean modules operate on a grid of 2.5 degrees latitude by 3.75 degrees longitude and are resolved at a 30 minute time-step. In the nomenclature of Valdes et al. (2017), this model setup is described as HadCM3L-M2.1aD. The solar constant is reduced by 0.4% relative to modern day and the orbital configuration is set to preindustrial. Simulations were run for 99 model years, giving total integrations longer than 4000 model years. To study changes in occurrence of extreme events, precipitation rates were saved at every model hour for the 99 years. A preindustrial simulation with a modern-day land–sea mask was also performed at $1 \times CO_2$.

Within the simulations performed for this paper, the model-predicted global mean 1.5 m air temperatures increase from 18.99 °C in the $2 \times CO_2$ simulation to 24.00 °C in the $4 \times CO_2$ simulation, whilst global mean precipitation rate increases from 3.22 mm/day in the $2 \times CO_2$ simulation to 3.41 mm/day in the $4 \times CO_2$ simulation. The temperature anomaly between the new simulations discussed in this paper is therefore ∼5 °C globally and