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Carbon dioxide forcing alone insufficient to explain Palaeocene–Eocene Thermal Maximum warming

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The Palaeocene–Eocene Thermal Maximum (about 55 Myr ago) represents a possible analogue for the future and thus may provide insight into climate system sensitivity and feedbacks[1,2]. The key feature of this event is the release of a large mass of ^{13}C-depleted carbon into the carbon reservoirs at the Earth's surface, although the source remains an open issue[3,4]. Concurrently, global surface temperatures rose by 5–9 °C within a few thousand years[5–9]. Here we use published palaeorecords of deep-sea carbonate dissolution[10–14] and stable carbon isotope composition[10,15–17] along with a carbon cycle model to constrain the initial carbon pulse to a magnitude of 3,000 Pg C or less, with an isotopic composition lighter than −50‰. As a result, atmospheric carbon dioxide concentrations increased during the main event by less than about 70% compared with pre-event levels. At accepted values for the climate sensitivity to a doubling of the atmospheric CO_2 concentration[1], this rise in CO_2 can explain only between 1 and 3.5 °C of the warming inferred from proxy records. We conclude that in addition to direct CO_2 forcing, other processes and/or feedbacks that are hitherto unknown must have caused a substantial portion of the warming during the Palaeocene–Eocene Thermal Maximum. Once these processes have been identified, their potential effect on future climate change needs to be taken into account.

The magnitude of future global warming from anthropogenic CO_2 forcing remains unknown because of uncertainties in predicting climate system feedbacks[1]. Studying past episodes of global warming and rapid carbon release such as the Palaeocene–Eocene Thermal Maximum (PETM) may help to reduce those uncertainties or at least isolate the possible sources[2]. The onset of the PETM was marked by a global increase in surface temperatures by 5–9 °C within a few thousand years[5–9]. At nearly the same time, a substantial carbon release occurred, as demonstrated by a large drop in the $^{13}C/^{12}C$ ratio of surficial carbon reservoirs. The carbon release led to ocean acidification and widespread dissolution of deep-sea carbonates[10,18]. Different sources for the carbon input have been suggested, which has led to speculations concerning the mechanism. Some, such as volcanic intrusion, imply that the carbon drives the warming. Others, such as the destabilization of oceanic methane hydrates, imply that the carbon release is a feedback that can exacerbate warming[3,4,19]. Remarkably, however, even the lower estimates for the carbon release during the onset of the PETM ($\sim$1 Pg C y^{-1}) and over the past 50 years from anthropogenic sources seem to be of a similar order of magnitude (see the Methods section). The PETM may therefore serve as a case study for the consequences of the carbon dioxide released at present by human activities.

We have used deep-sea carbonate dissolution records[10–14] and stable carbon isotope records across the PETM (refs 10, 15–17) in combination with carbon cycle modelling[2,18,20] to constrain the mass of the PETM carbon input (Fig. 1). The observed drop in the stable carbon isotope composition (δ^{13}C) of the surficial carbon reservoirs is about 3‰. However, the δ^{13}C signal alone is insufficient to determine the mass and δ^{13}C value of the carbon input. In this study, the input mass is estimated from carbonate dissolution records. The δ^{13}C composition of this carbon was then constrained by requiring the model outcome to match observed marine δ^{13}C records at the given input mass (see Supplementary Information). For our model simulations, we used the long-term ocean–atmosphere–sediment carbon cycle reservoir model LOSCAR (see refs 2, 18, 20 and Supplementary Information).

To simulate the observed time-dependent profile (that is, magnitude and duration) of the carbon isotope excursion (CIE) during the PETM main phase (Fig. 1b,c), we assumed a large initial input pulse followed by further smaller pulses and a low, continuous carbon release during the main event (Fig. 1a). Without the further release, the model was unable to reproduce the CIE duration because δ^{13}C values returned to pre-excursion values too quickly (Fig. 1b, dotted green line). A pulsed carbon release (rather than a single input peak) is consistent with δ^{13}C records from most marine and terrestrial sections[21,22].

The prolonged carbon release is also important to simulate the observed duration of deep-sea carbonate dissolution (Fig. 1d–f). For example, the carbonate records from Walvis Ridge in the Atlantic Ocean show that wt% $CaCO_3$ values at various palaeowater depths return to pre-excursion values only after more than 70 kyr (Fig. 1e). The extended duration of the dissolution event could not be reproduced in the model without the continued carbon release (Fig. 1d).

The size of the carbon input, on the other hand, is determined by the magnitude of $CaCO_3$ dissolution or shoaling of the calcite compensation depth (CCD) in the different ocean basins (Fig. 1f,g). Note that for the quantification of the carbon input, the position of the CCD before the event is as critical as the actual shoaling. For example, the late Palaeocene CCD was about 1–1.5 km shallower than today in all ocean basins, including the Pacific basin, which was much larger than today (see refs 23, 24 and references therein). Just before the event, Ocean Drilling Program core sites 1208 (Pacific Shatsky Rise) and 1221 (Equatorial Pacific) at 3,350 m and 3,200 m palaeowater depth, respectively, were located very close to the CCD, indicating a Pacific pre-event CCD shallower than 3,500 m. This depth is consistent with other reconstructions[11,23] (see Supplementary Fig. S5). In the late-Palaeocene Pacific basin, the erodible sediment $CaCO_3$ inventory in the depth range 3.5–4.5 km would have been $\sim$2,000 Pg C, which has the capacity to neutralize $\sim$2,200 Pg C of CO_2 (see the Methods section). Setting the pre-event CCD at a depth below that indicated by observations

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Additional information

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