Response of Coastal California Hydroclimate to the PETM

Supplementary information

Grain size analysis

Grain particle size was measured using laser diffraction (i.e., light scattering). The system at UCSC is a Beckman Coulter with Polarization Intensity Differential Scatter (PIDS) which better resolves submicron clay particles. This instrument measures particle size distribution in volume, number and surface area with size ranging from 17 nm to 2000 µm.

Grain size can provide insight into sediment transport dynamics, energy conditions within the fluvial system associated with river discharge intensity (Boggs, 2006). Specifically, grain size distribution can be used to qualitatively assess variations in fluvial activity and thus hydroclimate during the PETM assuming no local tectonic activity on the time scale of the event. Bulk sediments of Lodo Formation were measured, focusing on the clay lithofacies interval across CIE onset. The bimodal skewed grain size distribution of Lodo Formation indicates possible enhanced physical erosion during the PETM onset (Fig S1). Decreased mean grain size (d50) (i.e., silt to clay) is consistent with increasing stream flow velocity and the resuspension of finer clay size particles (see Singer 1984; Van Rijn 2007).

Extreme Value Analysis

To investigate heavy precipitation events occurrence (i.e., thick exceedance tail) in the modeling output, an extreme value analysis (Coles et al., 2001) was utilized to identify extreme deviations from the median of probability distributions in precipitation. We use the CAM5 simulations to test whether substantial changes in the frequency of extreme events locally occur from pre-PETM to PETM. In order to estimate the extreme value index but not rely on fitting certain distribution (i.e., normal, log-normal), we search for consistent behavior based on the central limit theorem. Peaks over threshold (POT) method were used to focus on exceedance over certain thresholds for extreme value distribution fit. To find the consistent behavior of exceedance distribution, Generalized Pareto Distribution (GPD) can represent any kind of exceedance distribution (i.e., exponential, normal etc.). If we have the threshold u, the excess distribution over the threshold u has the distribution function:

$$F_u(y) = P(X \leq u + y | X > u) = \frac{F_X(u+y) - F_X(u)}{1 - F_X(u)}$$

where $y \geq 0$; Then if $u \rightarrow \infty$, no matter the underlying distribution of X, this distribution function (cdf) $F_u(y)$ will converge to a Generalized Pareto distribution $GPD(x)$:

$$GPD(x) = \begin{cases} 1 - \left(1 + \xi \frac{(x-\mu)}{\sigma}\right)^{-\frac{1}{\xi}} & \xi \neq 0 \\ 1 - \exp\left(-\frac{(x-\mu)}{\sigma}\right) & \xi = 0 \end{cases}$$

ξ is the extreme value index. μ is a location parameter, σ is a scale parameter.

If $\xi<0$, there is a upper bound.

If $\xi=0$, the distribution is an exponential distribution, with no upper bound.

If $\xi>0$, the distribution is Pareto distribution (Type IV), with a thicker tail.

Leaf wax proxy model

To investigate how seasonal precipitation affects vegetation leaf wax hydrogen isotope fractionation process during PETM along the central California coast, we use a leaf wax proxy model to compute leaf water δ^2H variations from pre-PETM to PETM. The model calculates the leaf water δ^2H composition ($\delta^2H_{\text{leaf water}}$) based on a summation of monthly precipitation δ^2H estimates weighted by the monthly proportion within the growing season (w_{GS}) and the precipitation amount fraction of the total precipitation over the growing season (w_{PA}):

$$\delta D_{\text{leaf water}} = \sum(\delta D_{\text{monthly precip}} w_{GS} w_{PA})$$

The model assumes negligible fractionation between the soil water and leaf water pools. Given the lack of information on precipitation isotopes during 56Ma, in this model we use water-isotope enabled iCESM1.2 model output to compute leaf water δ^2H in the context of simulated seasonal precipitation and prescribed changes in growing season length. The model-simulated

δ^2H leaf water value is the precipitation amount weighted annual δ^2H precipitation value as it is sampled by plants in the growing season (Fig S2).

The hydrogen isotope composition of leaf waxes reflects the δ^2H composition of precipitation during the growing season (Sachse et al., 2012). Climate conditions (temperature, precipitation) across the PETM may have lengthened the growing season and therefore the δ^2H composition of the soil water pool sampled by plants to synthesize their leaf waxes. To simulate the cross interaction of changes in growing season length and the precipitation seasonality, the model accounts for a variable growing season length by weighting the δ^2H of monthly precipitation by the proportion of that month included in the growing season. Here, we centered the growing season in December, the month of highest simulated precipitation amount (Fig 4b, 4c). Changes in growing season length were made symmetrically; for example, an addition of 30 days to the growing season length is implemented as 15 additional days of spring growth and 15 additional days of fall growth.

Because vegetation type is unconstrained for the Lodo Section across the Paleocene-Eocene boundary (see main text), we cannot directly compare leaf wax model output for the pre-PETM and PETM scenarios and the leaf wax δ^2H data. Instead, we compare the difference between model-estimated leaf water δ^2H differences with proxy leaf wax δ^2H differences from pre-PETM to PETM. Since no significant change in local vegetation type across the PETM is indicated by the average chain length of n-alkanes in our study interval (Fig S3), there was probably little change in the apparent fractionation (ε_p) between precipitation and leaf waxes across the PETM. As such the leaf wax δ^2H change observed in the Lodo section is likely proportional to the change in leaf water δ^2H composition.

The water-isotope enabled iCESM1.2 model output-driven leaf wax model estimates a PETM (-59.14‰) – prePETM (-63.34‰) leaf water δ^2H difference of 4.2‰ assuming a 365-day growing season. Arbitrarily shortening the growing season to 90 days (centered on December) in the pre-PETM (-65.9‰) and lengthening it to 365 days in the PETM yields a leaf water δ^2H difference of 6.7‰. This result suggests any potential change in growing season length across the PETM had little influence on the leaf wax δD signal since the change in growing season length of 275 days only changed the simulated PETM – pre-PETM difference by 2.5‰.

Leaf wax n-alkane extraction and separation

Sediments were freeze-dried, powdered (~500 g), and extracted for 24 hours with dichloromethane (DCM):methanol (2:1, v/v) using a Soxhlet extractor. Total lipid extracts were concentrated under a stream of purified nitrogen using a Zymark Turbovap II evaporator, transferred to 4 ml vials, and further evaporated under a gentle stream of N_2 gas. Extracts were then separated by column chromatography using 1g deactivated silica gel (70-230 mesh) in an ashed Pasteur pipette, and eluted with 2 ml hexane, 4 ml dichloromethane and 4 ml of methanol to obtain the aliphatic, aromatic, and polar hydrocarbons, respectively. Normal-alkane abundances were determined using a Thermo Trace 2000 gas chromatograph (GC) fitted with a programmable-temperature vaporization injector and flame ionization detector (FID). Samples were processed with a fused silica, DB-1 phase column (60 m × 0.25 mm I.D., 0.25 μm film thickness) with helium as the carrier at a flow of 2ml/min. GC oven temperature program was 60-320°C @ 10°C/min and isothermal for 30 min. Normal-alkanes were identified through comparison of elution times with known n-alkane standards.

Biomarker identification and abundance were determined using a Thermo Trace 2000 gas chromatograph (GC) fitted with a split/splitless injector (splitless mode, 300˚C). Samples were processed with a fused silica, DB-5 phase column (30 m × 0.25 mm I.D., 0.25 μm film thickness) with helium as the carrier at a flow of 1.5ml/min. GC oven temperature program was 60-320°C @ 5°C/min and isothermal for 30 min. A Thermo Trace MS was used for detection with the mass spec scanning from 50-800 m/z or exclusively m/z of 191, 217, 218, 370, 372, 386, and 400 for single ion monitoring. Biomarkers were identified by elution time and mass spectra of in-house petroleum standards with published biomarker distributions (Peters et al., 2005).

Isotope analyses were performed using a Thermo Trace 2000 GC coupled to a Finnigan MAT 253 isotope ratio mass spectrometer interfaced with a GC-C III combustion system or a High Temperature Conversion system for $\delta^{13}C$ and $\delta^{2}H$ analyses, respectively. The H3+ factor was determined daily prior to standard calibration and sample analysis for $\delta^{2}H$ measurements. GC column, carrier flow, and ramp conditions were identical to above.

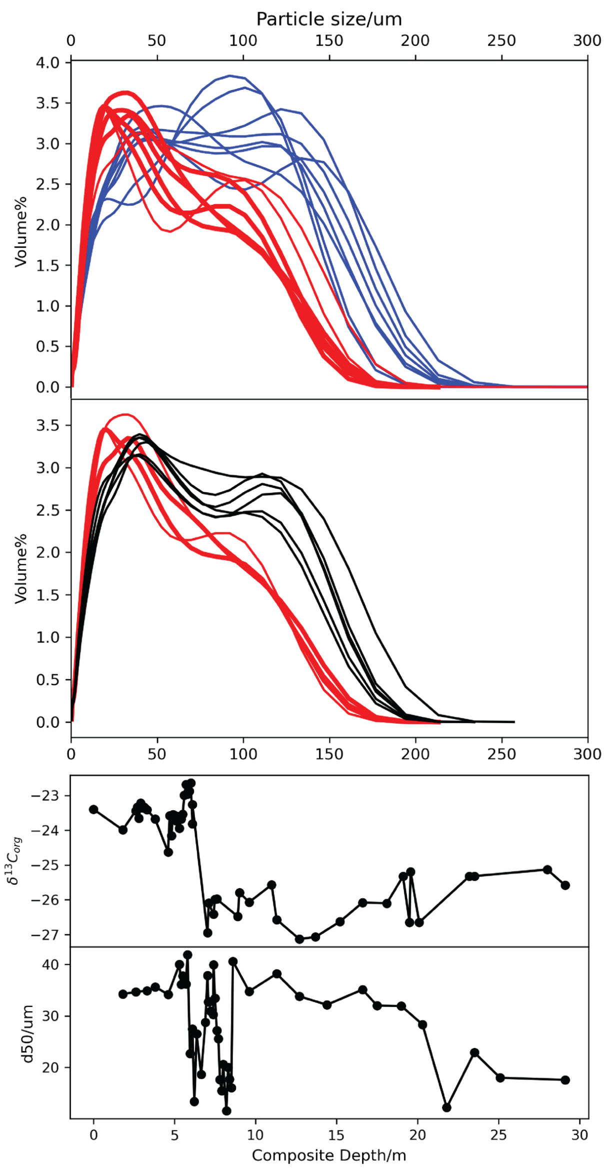

Fig. S1. Grain size distribution in pre-CIE (blue), CIE-onset(red) and PETM main body(black). Large particle size(silt) in pre-PETM with Gaussian distribution with more left skewed distribution across CIE-onset to stable bimodal distribution in the PETM main body. Mean particle size (d50: 50% of the total particle size in sediments) corresponds to CIE onset change showing an increase in the relative flux of finer grain sizes during the PETM.

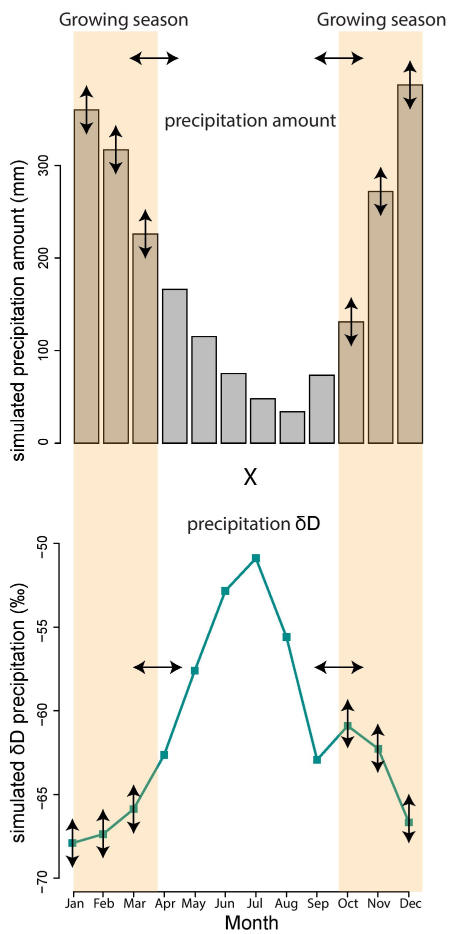

Fig. S2 Illustration of the leaf wax proxy model, which calculates the interactive effects of precipitation amount (grey bars), δD of precipitation (blue squares), and growing season length (orange shading). Arrows show variables that can be manipulated (precipitation amount, δD precipitation, growing season length) to change a calculated leaf water δD value.

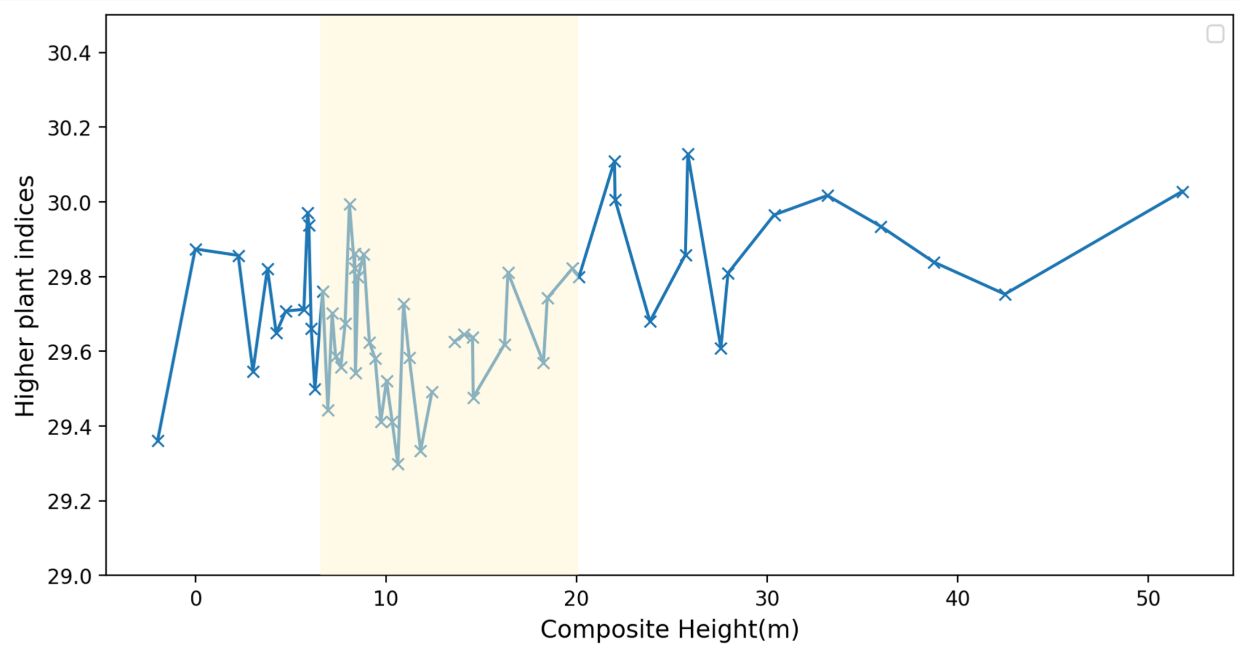

Fig. S3. Higher plant average chain length of Lodo Formation shows noisy but small variations across the CIE onset (light yellow shade) during the PETM.

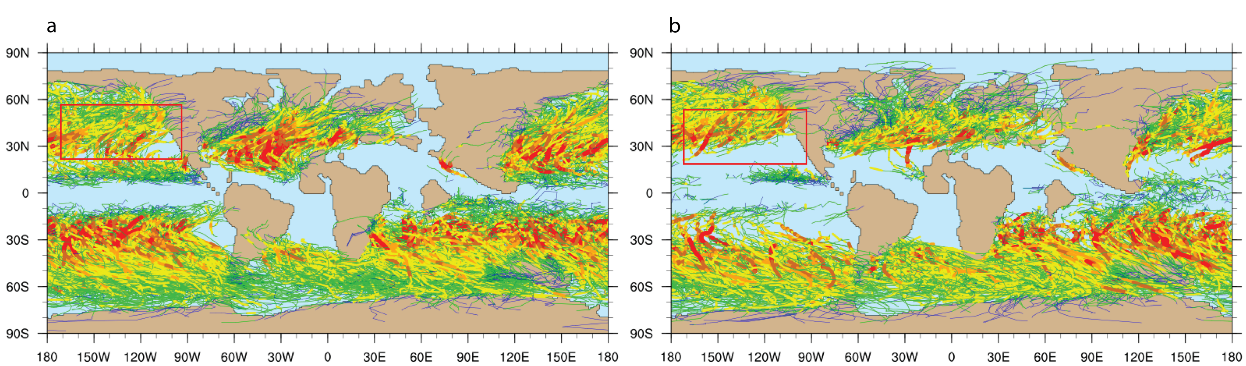

Fig S4. Tropical cyclone tracks for (a) pre-PETM (b) PETM, model simulations. Colour coding follows the Saffir-Simpson intensity scale and is as follows: Blue- tropical depressions, Green-Tropical storm, Yellow – Category 1, Orange – Category 3, and Red Category 4–5. Red square denote study regions. (Modified from Kiehl et al 2021)