



# 1 Response of Coastal California Hydroclimate to the Paleocene- 2 Eocene Thermal Maximum

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11 **Abstract.** The effects of anthropogenic warming on the hydroclimate of California are becoming  
12 more pronounced, with increased frequency of multi-year droughts and flooding. As a past  
13 analog for the future, the Paleocene-Eocene Thermal Maximum (PETM) is a unique natural  
14 experiment for assessing global and regional hydroclimate sensitivity to greenhouse gas  
15 warming. Globally, extensive evidence (i.e., observations, climate models with high  $p\text{CO}_2$ )  
16 demonstrates hydrological intensification with significant variability from region to region (i.e.,  
17 dryer or wetter, or greater frequency and/or intensity of extreme events). Central California  
18 (paleolatitude  $\sim 42^\circ\text{N}$ ), roughly at the boundary between dry subtropical highs and mid-latitude  
19 low pressure systems, would have been particularly susceptible to shifts in atmospheric  
20 circulation and precipitation patterns/intensity. Here, we present new observations and climate  
21 model output on regional/local hydroclimate responses in central California during PETM. Our  
22 findings based on multi-proxy evidence within the context of model output suggest a transition to  
23 an overall drier climate punctuated by increased precipitation during summer months along the  
24 central coastal California during the PETM.

## 25 1 Introduction



26 Global warming of a few degrees Celsius over the next century is projected to intensify the  
27 hydrological cycle on a range of temporal and spatial scales, manifested primarily by amplified  
28 wet-dry cycles(Held and Soden, 2006; Douville et al., 2021). Indeed, just over last few decades  
29 there has been an increasing frequency in the severity of extremes characterized by compound  
30 heat waves and intense drought(Büntgen et al., 2021; Williams et al., 2020; Zscheischler and  
31 Lehner, 2022), and/or heavy precipitation and flooding(Liu et al., 2020; Risser and Wehner,  
32 2017). As greenhouse gas driven warming continues, such precipitation extremes (wet or dry)  
33 are expected to intensify(Stevenson et al., 2022).

34 California, a region vulnerable to amplified wet-dry cycles, is already experiencing multiyear  
35 extreme droughts with longer precipitation deficits interspersed with anomalously wet  
36 years(Zamora-Reyes et al., 2022). For example, the prolonged drought from 2012 to 2016  
37 preceded the exceptionally high numbers of atmospheric river storms-related winter flooding of  
38 2017(Simon Wang et al., 2017). Collectively, climate models (e.g., CESM, CMIP etc.) show that  
39 the occurrence of such extremes in droughts and excessive seasonal precipitation in California is  
40 expected to increase by the end of the century(Vogel et al., 2020; Swain et al., 2018). In addition,  
41 such ‘whiplash’ hydroclimate shifts related to anthropogenic warming are generally supported by  
42 historical records of California climate cycles(de Wet et al., 2021; Polade et al., 2017).

43 The most robust evidence for greenhouse warming-induced intensification of the hydrological  
44 cycle comes from global warming events of the deep past(Carmichael et al., 2017). In particular,  
45 the Paleocene-Eocene Thermal Maximum (PETM) has emerged as a unique natural experiment  
46 for assessing global and regional hydroclimate sensitivity to greenhouse gas warming(Zachos et  
47 al., 2008). Extensive evidence exists for a major mode shift of local/regional precipitation  
48 patterns and intensity(Pagani et al., 2006; Slotnick et al., 2012; Schmitz and Pujalte, 2003; Sluijs  
49 and Brinkhuis, 2009; Smith et al., 2007; Handley et al., 2012; Kozdon et al., 2020) including  
50 enhanced erosion and extreme flooding in fluvial sections (e.g., Pyrenees; Bighorn basin), and  
51 increased weathering and sediment fluxes to coastal basins (e.g., Bass River, Wilson Lake, mid-  
52 Atlantic coast; Mead Stream, New Zealand etc.) along with other observations(John et al., 2008;  
53 Nicolo et al., 2010; Stassen et al., 2012; Self-Trail et al., 2017; Wing et al., 2005; Kraus and  
54 Riggins, 2007; Foreman, 2014).



55 These observations of regional hydroclimate change serve as the basis for climate model  
56 experiments forced with proxy-based estimates of  $\Delta p\text{CO}_2$  for the PETM (i.e., 3x-6x pre-  
57 industrial)(Kiehl and Shields, 2013; Carmichael et al., 2016; Zhu et al., 2020). Using such  
58 estimates, model simulations show an overall increase in poleward meridional water vapor  
59 transport as manifested by a net increase in evaporation of subtropical regions, balanced by  
60 higher precipitation of tropical/high latitudes characterizing the ‘wet-gets-wetter and dry-gets-  
61 drier’ hydrological response. The latest simulations using high-resolution climate models display  
62 several key regional responses including increased frequency of extreme precipitation events,  
63 especially the coastal regions where atmospheric rivers (AR) are common(Rush et al., 2021).  
64 Indeed, observations of high-energy flooding events in SW Europe (i.e., the Pyrenees) during the  
65 PETM(Schmitz and Pujalte, 2003) can be explained by increased frequency of North Atlantic  
66 ARs contributing landfall in that region. Pacific AR activity as simulated for the PETM also  
67 becomes more intense but less frequent along the central California coast by shifting northward  
68 with the storm tracks(Shields et al., 2021), not unlike the projections for California in the  
69 future(Shields and Kiehl, 2016; Massoud et al., 2019). This pattern is consistent with warming  
70 scenarios in general which have weakened zonal wind belts (i.e., the westerlies) that are shifting  
71 poleward(Abell et al., 2021; Douville et al., 2021).

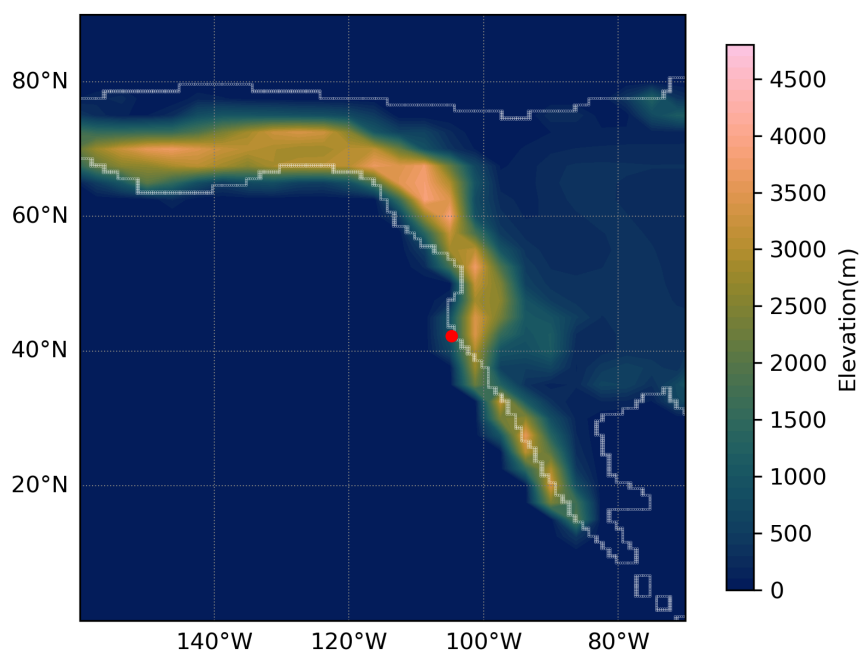
72 Testing the theoretical response of Northeast Pacific ARs and seasonal precipitation along North  
73 America’s western coast in general is challenging and still limited by the lack of observations.  
74 Here we constrain the regional hydroclimate response along the central California coast during  
75 the PETM using several independent proxies (i.e., clay mineralogy, grain size distribution,  
76  $\delta^{13}\text{C}_{\text{org}}$  stratigraphy, and leaf wax  $\delta^2\text{H}_{\text{n-alkane}}$  isotope records), which are either directly or  
77 indirectly sensitive to shifts in precipitation patterns/intensity. These proxies are then compared  
78 against sophisticated Earth System model simulations of the PETM climate to characterize the  
79 relative changes in regional precipitation (i.e., pattern/intensity). The new records complement  
80 data from a previous study(John et al., 2008), and along with the latest climate modeling  
81 experiments provide a unique case study of the sensitivity of regional hydroclimate to major  
82 greenhouse warming.

## 83 2 Materials and methods



## 84 2.1 Site Location

85 The studied outcrop section is part of the late Paleocene-early Eocene Lodo Formation located in  
 86 the Panoche Hill of central California (Fig. 1). During the late Paleocene, the section was  
 87 situated at a paleolatitude  $\sim 42^\circ\text{N}$ , roughly at the boundary between the dry subtropical highs and  
 88 mid-latitude low-pressure systems. The Lodo Formation is comprised primarily of siltstone with  
 89 a relatively low abundance of calcareous microfossils truncated by thin glauconitic sand  
 90 layers (Brabb, 1983). Depositional facies are consistent with neritic-bathyal setting along the  
 91 outer shelf (John et al., 2008).



92

93 Figure 1. Paleogeography and location of the Lodo Gulch section (red spot) along the Pacific  
 94 coast at 56 Ma. Late Paleocene-early Eocene topography of North America is adapted from Lunt  
 95 et al. (2017).

96



## 97 2.2 Methods

### 98 2.2.1 Stable isotopes

99 Sediment samples used for this study include those originally collected by John et al. (2008). In  
 100 addition, new samples were collected from the upper Paleocene for organic C isotopic analysis to  
 101 better establish pre-PETM baseline. Samples were analyzed in the UCSC Stable Isotope  
 102 Laboratory using a CE instruments NC2500 elemental analyzer coupled with Thermo Scientific  
 103 Delta Plus XP iRMS via a Thermo-Scientific Conflo III. All samples are calibrated with VPDB  
 104 (Vienna PeeDee Belemnite) for  $\delta^{13}\text{C}$  and AIR for  $\delta^{15}\text{N}$  against an in-house gelatin standard  
 105 reference material (PUGel). Analytical reproducibility precision is  $\pm 0.1\text{‰}$  for  $\delta^{13}\text{C}$  and  $\pm 0.2\text{‰}$   
 106 for  $\delta^{15}\text{N}$ .

### 107 2.2.2 Grain Size analysis

108 Particle size was measured by laser diffraction using Beckman Coulter with Polarization  
 109 Intensity Differential Scatter (PIDS) housed at UCSC. 2 to 5 mg of bulk sediments was powered  
 110 in each sample for measurement. Each sample was performed 2 or 3 replicates to ensure  
 111 reproducibility.

### 112 2.2.3 Clay Assemblages analysis

113 Sample preparation follows a slightly modified version of (Kemp et al., 2016). Roughly 5 to 10 g  
 114 of sediment was powdered in a pestle and mortar and then placed in a Calgon (Sodium  
 115 hexametaphosphate) solution on a shaker table for 72 hours. Samples were sorted through a 63  
 116  $\mu\text{m}$  sieve while collecting the fluid with the  $<63\text{ }\mu\text{m}$  fraction. The collected fluid and suspended  
 117 fine fraction ( $< 63\text{ }\mu\text{m}$ ) were allowed to settle for a period determined by Stokes' Law to keep  $<$   
 118  $2\text{ }\mu\text{m}$  size clay particles remaining in suspension. The fluid is then decanted and dried in the oven.  
 119 Approximately 150 mg clay of each sample is used to prepared oriented mounts for X-ray  
 120 diffraction (XRD) analysis. A total of 38 clay samples were prepared from the Lodo Formation.  
 121 The sample residues are measured on a Philips 3040/60 X'pert Pro X-ray diffraction instrument  
 122 at UCSC. Clay species are identified based on peak positions and intensities representing each  
 123 clay mineral.

### 124 2.2.4 Leaf wax



125 Sediment extraction, compound isolation, and compound-specific isotope measurements were  
 126 conducted following Tipple et al., 2011. Briefly, sediments were freeze-dried, powdered (~500  
 127 g), and extracted with dichloromethane (DCM): methanol (2:1, v/v) using a Soxhlet extractor.  
 128 Total lipid extracts were concentrated and then separated by column chromatography using silica  
 129 gel. Normal-alkanes were further purified from cyclic and branched alkanes using urea adduction  
 130 following (Wakeham and Pease, 2004). Normal-alkane abundances were determined using gas  
 131 chromatograph (GC) with a flame ionization detector (FID). Isotope analyses were then  
 132 performed using a GC coupled to an isotope ratio mass spectrometer interfaced with a GC-C III  
 133 combustion system or a High Temperature Conversion system for  $\delta^{13}\text{C}$  and  $\delta^2\text{H}$  analyses,  
 134 respectively.  $\delta^{13}\text{C}$  and  $\delta^2\text{H}$  values are expressed relative to Vienna Pee Dee belemnite (VPDB)  
 135 and Vienna Standard Mean Ocean Water (VSMOW). Individual n-alkane isotope ratios were  
 136 corrected to n-alkane reference materials (for  $\delta^{13}\text{C}$ , C20, C25, C27, C30, and C38 of known  
 137 isotopic ratio and for  $\delta^2\text{H}$ , “Mix A” from Arndt Schimmelmann, Indiana University) analyzed  
 138 daily at several concentrations. In addition,  $\text{H}_2$  reference gas of known isotopic composition was  
 139 pulsed between sample n-alkane peaks to confirm if normalizations were appropriate. Standard  
 140 deviations (SD) of n-alkane reference materials was  $\pm 0.6\text{‰}$  for  $\delta^{13}\text{C}$  and  $\pm 6\text{‰}$  for  $\delta^2\text{H}$ .

#### 141 2.2.5 Earth System Models

142 Two different set of climate simulations were used in this paper for (1) comparison with leaf wax  
 143 proxy data and (2) extreme events analysis. (1) Water isotope-enabled Community Earth System  
 144 Model version 1.2 (iCESM1.2) simulates changes in climate and water isotopic composition  
 145 during the PETM (Zhu et al., 2020) with a horizontal resolution of  $1.9 \times 2.5^\circ$  in atmosphere and  
 146 land, and a nominal 1 degree in the ocean and sea ice components. Water isotope capabilities  
 147 have been incorporated into all the components of CESM 1.2 (Brady et al., 2019), which include  
 148 the Community Atmosphere Model, version 5(CAM5) for the atmosphere, the Parallel Ocean  
 149 Program, version 2(POP2) for the ocean, the Community Land Model, version 4(CLM4) for the  
 150 land, River Transport Model (RTM) for river flow, and Community Ice Code, version 4 for sea  
 151 ice. (2) Using the same CESM1.2 framework, high resolution ( $0.25^\circ$ ) simulations were  
 152 conducted with forced sea surface temperatures (SSTs) and active atmosphere and land  
 153 components (CAM5, CLM4). RTM was run at  $1^\circ$  resolution, and forced SST were calculated  
 154 from consistent  $2^\circ$  fully coupled PETM simulations (see details in Rush et al., 2021 and



reference therein). The much higher horizontal resolution in the atmosphere enables improved simulation of the extreme events. Hourly, daily (CAM5), and monthly(iCESM1.2) temporal resolution precipitation outputs from both sets of climate simulations were utilized in this paper, with 100 years taken from the equilibrated iCESM1.2 simulations, and 15 years from the forced SST high resolution CAM5 simulations.

### 3 Results

#### 3.1 Carbon isotopes

A carbon isotope excursion is present in both bulk organic and carbonate based  $\delta^{13}\text{C}$  records across the P-E boundary (Fig. 2a), marking the PETM onset of the Lodo section(John et al., 2008). The terrestrial leaf wax n-alkane record captures the carbon isotope excursion (CIE) with a pattern that roughly parallels the other records. The magnitude of the  $\delta^{13}\text{C}_{\text{n-alkane}}$  change is roughly 4 ‰ (average of n-C<sub>27</sub>, n-C<sub>29</sub>, n-C<sub>31</sub>) at the onset, followed by a gradual recovery that is truncated marking the top of the PETM body (Fig. 3b).

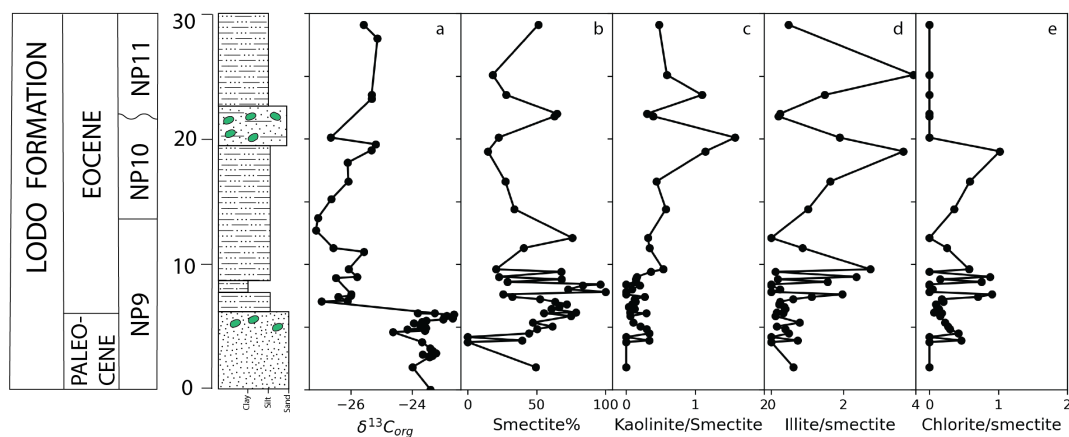


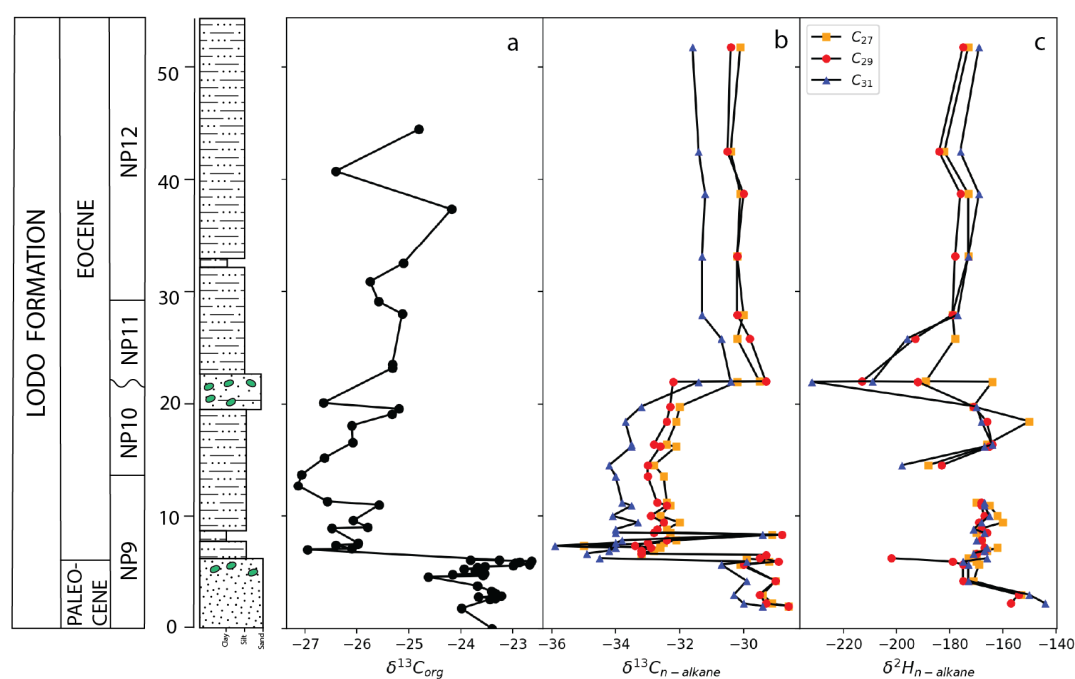
Figure 2. Integrated C isotope and clay assemblage records of Lodo Fm in the Lodo Gulch of central California (a) bulk organic carbon isotope, (b,c,d,e) clay assemblage ratios.



## 176 3.2 Hydrogen isotopes

177 The leaf wax  $\delta^2\text{H}_{\text{n-alkane}}$  values decrease by 25‰ just prior to the CIE onset followed by a slight  
178 enrichment of in the main body PETM (Fig. 3c). The relatively invariable  $\delta^2\text{H}_{\text{n-alkane}}$  through the  
179 PETM is punctuated with one or two brief intervals of more negative values.

180



181  
182 Figure 3. Marine  $\delta^{13}\text{C}$  and terrestrial higher plant leaf wax n-alkane  $\delta^{13}\text{C}$  and  $\delta^2\text{H}$  records. (a)  
183 bulk organic carbon isotope record of Lodo Fm. (b,c) leaf wax compound specific  
184 carbon/hydrogen isotope records in n-C<sub>27</sub>(yellow), n-C<sub>29</sub>(red), n-C<sub>31</sub>(blue).

185

## 186 3.3 Clay Assemblage and grain Size

187 Clay assemblage data (Fig. 2) shows smectite dominated in the Lodo Formation during PETM,  
188 along with increasing illite/smectite and chlorite/smectite ratios. The lower Lodo Formation,  
189 with relative coarse sandy size, shows slight spikes of kaolinite associated with other minerals.  
190 Grain size, largely silt and clay, shows a distinct shift toward finer fractions (i.e., clay) with the  
191 onset of the CIE (Fig. S1).

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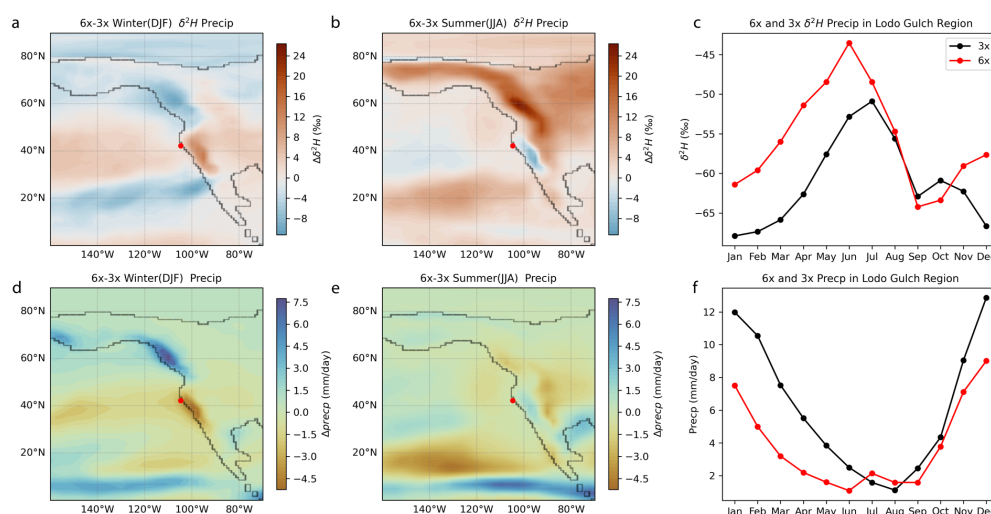




### 193 3.4 Earth system model simulations

194 Precipitation output from two earth system models: isotope enabled iCESM1.2 under enhanced  
195 greenhouse gas simulations (1x,3x,6x,9x  $p\text{CO}_2$  pre-industrial) and high-resolution CAM5 models  
196 (daily precipitation over 15 years), were analyzed. For this study we used 3x to 6x  $p\text{CO}_2$  forcing  
197 that best replicate the observed  $\Delta\text{SST}$  from pre-PETM to PETM (Zhu et al., 2020). Overall,  
198 monthly precipitation for the study region decreases during the PETM in both simulations but  
199 with a slight increase in the summer (Fig. 4,5). CAM5 output shows a modest decrease in mean  
200 annual precipitation with significant seasonal shifts during PETM (Fig. 5a). Seasonal changes of  
201 monthly averaged  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  from mean monthly precipitation (MAP) in iCESM1.2 of  
202 central California are consistent with CAM5. On average the  $\delta^2\text{H}$  increases by ca. 10 ‰ from  
203 pre-PETM to PETM, especially in the winter/spring, with a smaller shift in summer/fall (Fig 4.  
204 a,b,c). The Extreme value index ( $\xi$ ), a representation of the distribution of exceedance right tail  
205 (supplemental information), shows a small but statistically robust increase in wet extremes of  
206 winter (DJF) with a significant increase in summer (JJA) wet exceedances during the PETM in  
207 the precipitation output from CAM5 simulations (Fig. 5b).

208



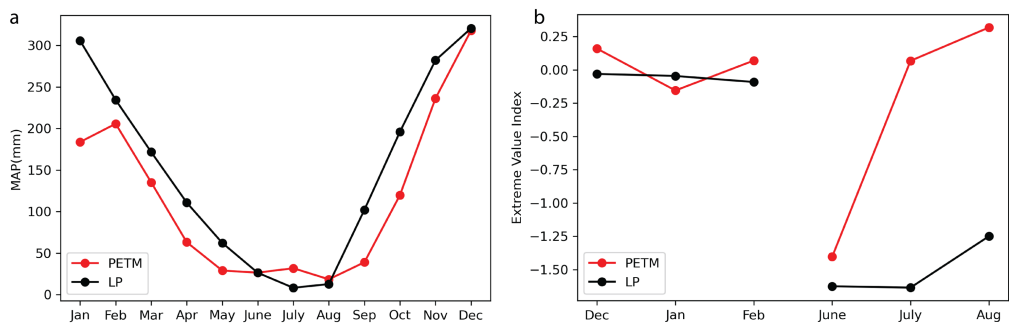
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210 Figure 4. Water isotope-enable iCESM1.2 model output (Zhu et al., 2020) of monthly hydrogen  
211 isotope record of meteoric precipitation under different  $p\text{CO}_2$  forcing to pre-industry (3x in black



represents pre-PETM, 6x in red represents PETM) in east Pacific coast (red spot represents the Lodo Gulch study site). The iCESM1.2 simulations used the DeepMIP boundary conditions (Lunt et al., 2017). Difference in winter (a) and summer (b) hydrogen isotope composition between pre-PETM(3x) and PETM(6x). (c) Annual seasonal cycle of hydrogen isotope composition of precipitation in Lodo Gulch region. Difference in winter(d) and summer(e) precipitation amount between pre-PETM(3x) and PETM(6x) in east Pacific coast. (f) Annual seasonal cycle of precipitation amount in Lodo Gulch region. Site values of Lodo Gulch region are calculated by area-weighted average over 4° x 4° box around study site.

220



221

Figure 5. (a) High resolution CAM5 model output of mean monthly precipitation over 15 model years in central coastal California regions during pre-PETM (Late Paleocene/LP) under low  $p\text{CO}_2$  (680 ppmv) and PETM under high  $p\text{CO}_2$  (1590ppmv). (b) Extreme value index ( $\xi$ ) results of mean monthly precipitation in winter versus summer of central coastal California region.

226

#### 227 4 Discussion

Independent proxies (i.e, sediment flux, clay assemblages, and water isotopes ( $^2\text{H}/^1\text{H}$  or  $^{18}\text{O}/^{16}\text{O}$ ), though each has limitations, collectively can contribute toward a general picture of how the mode of precipitation changed (i.e., wetter or dryer, and/or greater seasonality or extremes). For central California, model simulations of the PETM with low and high resolutions exhibit an overall decrease in mean annual precipitation (Fig. 4,5). For a mountainous coastal environment (Fig. 1), siliciclastic sedimentation rates should be highly susceptible to hydrologic changes among other factors. In addition to relief and lithology, the seasonality of precipitation and vegetation cover would be major controls on erosion and siliciclastic sediment fluxes. However, constraining sedimentation rates in shelf sections is challenging given the limitations of

236



237 chronostratigraphy in such facies. As such, we rely largely on biostratigraphic constraints with  
 238 carbon isotope stratigraphy as the CIE is well captured in both organic and inorganic (calcite)  
 239 fossil materials in Lodo (John et al., 2008). This expanded CIE interval indicates higher  
 240 sedimentation rates during the PETM (John et al., 2008). Sedimentation rates on the continental  
 241 shelf margin are highly sensitive to terrestrial sediment discharge and relative sea-level change.  
 242 Assuming the latter was relatively static or rising (Sluijs et al., 2008), the higher sedimentation  
 243 rates suggest increasing sediment supply from river runoff to the continental margin, reflecting a  
 244 mode shift in regional hydroclimate.

245

#### 246 4.1 Hydroclimate response from clay mineralogy

247 Clay assemblages in nearshore settings can reflect physical and chemical weathering changes as  
 248 influenced by regional climate change. Indeed, an increase in the relative abundance of kaolinite  
 249 fluxes has been widely observed across the CIE onset in many PETM sections from mid to high  
 250 latitudes (Tateo, 2020; Gibson et al., 2000) and interpreted as evidence of a major mode shift in  
 251 local hydroclimates. In contrast, the clay mineralogy (Fig. 3) for the Lodo Formation is  
 252 dominated mainly by smectite at the onset of the PETM, consistent with seasonal wet/dry cycles  
 253 under warm conditions (Gibson et al., 2000). A subtle increase in the kaolinite/smectite hints  
 254 slightly enhanced humidity, possibly related to enhanced seasonally subtropical  
 255 conditions (Foreman, 2014). Such inferences of hydroclimate changes in the context of coastal  
 256 deposition are complicated by fluvial runoff conditions (i.e., provenance, discharge, sediment  
 257 influx) and precipitation (i.e., seasonal vs mean annual). Skewed grain size distribution of clay  
 258 sediments coinciding with illite/kaolinite peaks (Fig. S1) indicates higher fluvial velocity and  
 259 increased erosion as observed in other locations (Chen et al., 2018; Foreman et al., 2012;  
 260 Foreman, 2014). The lower Lodo Formation, with relative coarse sandy size distribution  
 261 preceding the PETM, shows a slight pulse of kaolinite associated with other minerals, possibly  
 262 indicating an early change of hydrological condition in the latest Paleocene before the PETM as  
 263 observed elsewhere (Rush et al., 2021). The CIE onset likely represents a transient response to  
 264 warming-induced hydroclimate changes, whereas the pre-PETM shift as well as minor variations  
 265 post-CIE onset are likely orbitally forced (Kiehl et al., 2018).

#### 266 4.2 Hydroclimate response from earth system simulations



In all model simulations forced with higher pCO<sub>2</sub> (e.g., 3x to 6x pre-industrial), the hydrological cycle during PETM intensifies as manifested by increases in global mean precipitation and meridional vapor transport (Kiehl and Shields, 2013; Kiehl et al., 2018; Carmichael et al., 2016; Zhu et al., 2020). Regionally however, the magnitude and even the sign of precipitation change can differ considerably from global means. This is most evident in the latest low and high-resolution model simulations of the PETM. For central California, the simulations yield modest changes in mean annual precipitation but significant seasonal shifts with a notable decline in winter precipitation and a slight increase in summer (Fig. 4). This pattern is produced by both the water isotope enabled iCESM1.2 and the higher resolution CAM5 with an overall shift into lower amplitude seasonal cycles as a drier winter/spring and a slightly wetter summer (Fig. 4, 5). This seasonal wet-dry shift appears to be driven in part by a pronounced northward shift of atmospheric rivers (ARs) in winter along the Pacific coast (Shields et al., 2021). Given the ARs delivering the majority of winter precipitation to the mid-latitude Pacific coast, less frequent AR occurrences would result in relatively drier winters during PETM. Moreover, the extreme value index ( $\xi$ ) shows a small but statistically robust increase winter (DJF) wet extremes with a significant increase in the probability of summer (JJA) wet exceedance during PETM (Fig. 5b). Although AR related coastal winter storms reduced in frequency (Shields et al., 2021), summer precipitation increased in intensity thus potentially enhancing individual extremes in this region, possibly related to an increase in summer tropical storm activity along the Pacific coast during PETM (Fig. S4).

4.3 <sup>2</sup>H/<sup>1</sup>H composition of leaf waxes.

Terrestrial archives exhibit considerable evidence of environmental response to intensified hydrological cycle during the PETM (McInerney and Wing, 2011). In western North America, plant fossils show widely expansion (up to 40°N) of tropical rainforest during the PETM along the east Pacific in mid-latitude (Willis, K.J., McElwain, 2002; Korasidis et al., 2022). Terrestrial higher plant hydrogen isotope composition (i.e.,  $\delta^2\text{H}_{\text{n-alkane}}$ ) provide evidence for regional mode shifts of precipitation (Handley et al., 2008, 2011; Jaramillo et al., 2010; Pagani et al., 2006; Tipple et al., 2011). Generally,  $\delta^2\text{H}$  significantly increases in most of these records as expected with warming, but regionally, notable similarities and differences existed. In subtropical/mid-latitude regions,  $\delta^2\text{H}$  increases prior to the PETM followed by a large negative excursion (ca ~20‰) across the onset of PETM (Handley et al., 2008, 2011; Jaramillo et al., 2010; Tipple et



al., 2011). In sharp contrast, high latitudes  $\delta^2\text{H}_{\text{n-alkane}}$  show a positive excursion of 55‰ at CIE onset during PETM, consistent with a reduced meridional temperature gradient and decreasing isotope distillation during vapor transport (Pagani et al., 2006). However, the Lodo  $\delta^2\text{H}_{\text{n-alkane}}$  displays a comparatively muted response, initially decreasing by 25‰ just prior to the CIE onset followed by a slight  $^2\text{H}$  enrichment in the main body PETM followed by several shifts toward more negative values (Fig. 3c). The shift to more negative  $\delta^2\text{H}_{\text{n-alkane}}$  values prior to the onset of CIE in Lodo likely represents background variability related to orbital forcing.

Inferring and comparing the hydroclimate response from leaf water  $\delta^2\text{H}$  at any location can be complicated. Hydrogen isotope fractionation in plants is tightly related to photosynthetic pathways, source water availability, and atmospheric humidity (Sachse et al., 2012; Tipple et al., 2015). Along the west coast of North America, no detailed records of vegetation response have been generated for the PETM. Lack of knowledge about vegetation changes limits our ability to compute rainwater  $\delta^2\text{H}$ . Further, under higher weathering rates during the PETM, deep weathering of Paleocene n-alkanes (Tipple et al., 2011) would possibly dampen of isotopic n-alkane signals deposited at Lodo. Nevertheless, if we assume the  $\delta^2\text{H}_{\text{n-alkane}}$  record reflects only on changes in source water, the observed modest change of  $\delta^2\text{H}_{\text{n-alkane}}$  values at Lodo could be interpreted in several ways with respect to T-related changes on isotope fractionation offset by changes in dominant season of precipitation, and/or vapor sources and distance of transport. For example, a shift in precipitation seasonally between winter and late summer/fall could offset the effects of warming assuming a shift from a proximal (north or central Pacific) to a more distal (Gulf of Mexico) source of vapor (Hu and Dominguez, 2015). At ground level, stronger evapotranspiration during biosynthesis can isotopically be offset by external water source availability (i.e. seasonal precipitation). Local/regional ground water table variations caused by hydrological change would also affect the source water-use efficiency of plants since surface water tends to be more depleted in some perennial species after intense storms in the groundwater (Hou et al., 2008; Krishnan et al., 2014). Hydrogen isotope fractionation in plants can also be biased by seasonal shift in regional vegetation growth regime. For example, leaf wax lipids from terrestrial plants usually record hydrological conditions earlier in the season rather than fully integrating the entire growing season (Hou et al., 2008; Tipple et al., 2013). Finally, episodic extremes in precipitation may dominate the hydrogen isotopic composition of the leaf wax (Krishnan et al., 2014). If most soil water from extreme events during the growth season, the



329 Lodo  $\delta^2\text{H}_{\text{n-alkane}}$  changes might reflect a combination effect of intensified seasonal storms with  
 330 more  $^2\text{H}$ -depleted precipitation offset by warming induced  $^2\text{H}$ -enrichment in leaf water.  
 331

332 In iCESM1.2 simulations with increasing  $p\text{CO}_2$  (i.e., 3x to 6x pre-industry) and SST, the  
 333 seasonal shifts in  $\delta^2\text{H}$  of mean monthly precipitation from pre-PETM to PETM is significant.  
 334 Regional  $\delta^2\text{H}_{\text{precip}}$  increases by 10‰ during wet winter while decreasing by ~1 to 5‰ during late  
 335 summer/fall in central California (Fig. 4). To estimate how this seasonal change of  $\delta^2\text{H}_{\text{precip}}$  and  
 336 precipitation amount influences leaf water  $\delta^2\text{H}$ , we apply a leaf wax proxy model (supplemental  
 337 information) which computes the combined effects of changes in seasonal precipitation and  
 338 growing season length. The model shows leaf water  $\delta^2\text{H}$  enriched ca. 4 to 7‰ from pre-PETM to  
 339 PETM consistent with  $\delta^2\text{H}_{\text{n-alkane}}$  proxy record in Lodo section. Therefore, this relative muted  
 340 leaf wax  $\delta^2\text{H}_{\text{n-alkane}}$  response can be potentially explained by a seasonal shift of heavy  
 341 precipitation events. Alternatively, the change in leaf water  $\delta^2\text{H}$  may also reflect source water  
 342 shift of a mixing endmember between proximal and distal sources of water in the coast (Romero  
 343 and Feakins, 2011). For example, with a summer shift of source water from the Pacific to  
 344 subtropics (i.e., summer monsoons), the effect of increasing distance and distillation would  
 345 isotopically deplete vapor (Hu and Dominguez, 2015), thus offsetting the temperature related  
 346 enrichment of local  $\delta^2\text{H}_{\text{precip}}$ . Infrequent but high intensity tropical cyclones-induced heavy  
 347 rainfall in the summer in mid-Pacific during PETM (Kiehl et al., 2021) can also bring the  
 348 precipitation more depleted in hydrogen isotope (i.e., a more negative  $\delta^2\text{H}$ ).  
 349

350 Finally, a related record that might indirectly reflect on precipitation amount (i.e., atmospheric  
 351 humidity) is the n-alkane  $\delta^{13}\text{C}$  and magnitude of the CIE. Recalcitrant higher plants leaf wax  
 352 carbon isotope ratios of long-chain n-alkane ( $n > 25$  with odd-over-even preference) reflect  
 353 mainly carbon source (Diefendorf et al., 2010). However, photosynthetic carbon isotope  
 354 fractionation ( $\Delta_p$ ) is sensitive to atmospheric  $p\text{CO}_2$  variations, generally increase with rising  
 355 concentrations assuming a constant photosynthetic fractionation factor and humidity (Diefendorf  
 356 et al., 2010). The  $\delta^{13}\text{C}_{\text{n-alkane}}$  of Lodo section displays a sharp negative shift of ca. 4 ‰ (average  
 357 of  $n\text{-C}_{27}$ ,  $n\text{-C}_{29}$ ,  $n\text{-C}_{31}$ ) across the onset of CIE (Fig. 3b), which is consistent with global mean  
 358 atmospheric CIE (Sluijs and Dickens, 2012) but generally smaller than observed in other leaf  
 359 wax records (Handley et al., 2008, 2011; Jaramillo et al., 2010; Pagani et al., 2006; Tipple et al.,



2011). The smaller  $\delta^{13}\text{C}_{\text{n-alkane}}$  CIE recorded in Lodo could reflect on reduction in local humidity which preferentially tends to reduce the magnitude of  $\Delta_p$  during photosynthetic carbon fixation.

## 5 Conclusion

With PETM greenhouse gas forcing (~56 Ma), climate simulations show an overall decrease in winter precipitation along the central California margin due in part to a reduction in AR frequency (Shields et al., 2021), whereas summer precipitation increases slightly. This is generally consistent with the observations from Lodo Gulch Section based on various sedimentological and geochemical records, and thus would support a modest reduction in precipitation (i.e. MAP) along with the possibility of an increase magnitude of extreme precipitation events during the PETM. In this regard, the observed hydroclimate response during the PETM as simulated in climate models in response to a doubling (or more) of  $\text{CO}_2$  could serve as a past analog for potential hydroclimate changes in California.

Data availability. Data will be available via the PANGAEA repository.

Author contribution. JCZ conceived the project idea, acquired funding and provided overall supervision. XZ, BJT, WDR, JBN conducted experiments and analyzed the results. JZ, CAS provide technical expertise in model simulations. All authors contributed to the review and editing of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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