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1 **Eocene greenhouse climate revealed by coupled clumped isotope-**  
2 **Mg/Ca thermometry**

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26 seawater Mg/Ca

27

28 **Past greenhouse periods with elevated atmospheric CO<sub>2</sub> were characterized by globally**  
29 **warmer sea surface temperatures (SST). However, the extent to which the high-latitudes**  
30 **warmed to a greater degree than the tropics (polar amplification) remains poorly**  
31 **constrained, in particular because there are only a few temperature reconstructions from**  
32 **the tropics. Consequently, the relationship between increased CO<sub>2</sub>, the degree of tropical**  
33 **warming and the resulting latitudinal SST gradient is not well known. Here, we present**  
34 **coupled clumped isotope ( $\Delta_{47}$ )-Mg/Ca measurements of foraminifera from a set of globally**  
35 **distributed sites in the tropics and mid-latitudes.  $\Delta_{47}$  is insensitive to seawater chemistry**  
36 **and therefore provides a robust constraint on tropical SST. Crucially, coupling these data**  
37 **with Mg/Ca measurements allows the precise reconstruction of Mg/Ca<sub>sw</sub> throughout the**  
38 **Eocene, enabling the reinterpretation of all planktonic foraminifera Mg/Ca data. The**  
39 **combined dataset constrains the range in Eocene tropical SST to 30-36°C (from sites in all**  
40 **basins). We compare these accurate tropical SST to deep ocean temperatures, serving as a**  
41 **minimum constraint on high-latitude SST. This results in a robust conservative**  
42 **reconstruction of the early Eocene latitudinal gradient, which was reduced by at least**  
43 **32±10% compared to present-day, demonstrating greater polar amplification than**  
44 **captured by most climate models.**

45

#### 46 **Significance statement**

47 Reconstructing the degree of warming during geological periods of elevated CO<sub>2</sub> provides a way  
48 of testing our understanding of the Earth system and the accuracy of climate models. We present  
49 accurate estimates of tropical sea surface temperatures (SST) and seawater chemistry during the  
50 Eocene (56-34 million years before present, CO<sub>2</sub> >560 ppm). This latter dataset enables us to  
51 reinterpret a large amount of existing proxy data. We find that tropical SST are characterized by  
52 a modest warming in response to CO<sub>2</sub>. Coupling these data to a conservative estimate of high-  
53 latitude warming demonstrates that most climate simulations do not capture the degree of Eocene  
54 polar amplification.

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57  
58 Greenhouse periods in the geological past have received much attention as indicators of the  
59 response of the Earth to elevated CO<sub>2</sub>. Of these, the Eocene is the most recent epoch  
60 characterized by *p*CO<sub>2</sub> at least twice pre-industrial, i.e. >560 ppm (1). Furthermore, as the  
61 quantity of paleoclimate reconstructions have increased the Eocene has become a target for  
62 comparison to climate models (2), as proxy data of past warm periods are required to assess  
63 model competence at elevated CO<sub>2</sub> (3). Existing geochemical proxy data suggest that the Eocene  
64 latitudinal SST gradient was greatly reduced: the mid-high latitude (>40°) surface oceans were  
65 10-25°C warmer than today throughout the Eocene (4, 5), yet there is no evidence for tropical  
66 SST warming of a similar magnitude, even during peak warm intervals such as the Paleocene-  
67 Eocene Thermal Maximum (PETM) (6, 7). In fact, several studies have reported moderate  
68 tropical warmth (30-34°C) throughout the Eocene (8, 9). This is in contrast to most Eocene  
69 climate model simulations (10, 11), which indicate the latitudinal gradient was within 20% of  
70 modern (with notable exceptions (12), discussed below). However, using proxies to validate  
71 model output is problematic because many paleothermometers are associated with relatively  
72 large (often systematic) errors and are sensitive to diagenetic alteration after burial in sediment.  
73 For example, initial reconstructions of the Eocene tropics were biased by the analysis of poorly-  
74 preserved material, resulting in the cool-tropics hypothesis (13). Subsequently, it was shown that  
75 well-preserved samples yield Eocene tropical SST at least as warm as present (14–16).  
76 Furthermore, carbonate-bound proxies such as foraminiferal δ<sup>18</sup>O and Mg/Ca are highly sensitive  
77 to poorly-constrained secular variations in salinity and seawater chemistry (17), TEX<sub>86</sub> is  
78 associated with calibration complications (18, 19), and all proxies may be seasonally biased to  
79 summer temperatures at mid-high latitudes (20). As a result, absolute tropical SST are not  
80 constrained to better than ±~5°C at any given site (21), in part derived from uncertainties over

81 whether modern calibrations are applicable to Eocene material (20). Similarly, atmospheric  
82 processes, in particular clouds and aerosol-cloud interactions are a large source of uncertainty  
83 within climate models (22), whilst variable inter-model sensitivities to CO<sub>2</sub> (10) complicate the  
84 use of these to directly constrain absolute Eocene temperatures. Given these uncertainties in both  
85 the data and models, there is no consensus regarding the degree of polar amplification or the  
86 precise response of the tropical oceans to increasing CO<sub>2</sub>. Specifically, much debate has focused  
87 on whether the tropics underwent substantial warming and the latitudinal gradient was only  
88 moderately reduced (23, 24), or if tropical warmth was limited and the gradient was far lower  
89 than today (9, 25). Hence, improved reconstructions, especially in the tropics, are of fundamental  
90 importance in understanding both the response of SST to increased CO<sub>2</sub> as well as the accuracy  
91 of climate models. We address these issues through coupled clumped isotope-Mg/Ca  
92 measurements of shallow-dwelling large benthic foraminifera (LBF) of the family  
93 Nummulitidae. Our fossil samples come from seven globally-distributed sites, four of which are  
94 in the tropics, including the equatorial West Pacific/Indian Ocean (Fig. 1). In order to expand this  
95 dataset to produce a global picture of Eocene tropical climate, we also produce a precise Eocene  
96 seawater Mg/Ca curve and use it to reinterpret all published Mg/Ca data from an additional 12  
97 sites.

### 98 **Eocene surface ocean temperature from foraminifera clumped isotopes**

99 The carbonate clumped isotope thermometer (26, 27), hereafter denoted  $\Delta_{47}$ , is based on the  
100 increasingly preferential binding of heavy isotopes to each other (e.g. <sup>13</sup>C-<sup>18</sup>O in carbonate) at  
101 lower temperatures. The principal advantage over existing geochemical temperature proxies is  
102 that there is no resolvable dependence on seawater elemental or isotopic composition (28), and

103 uncertainty is dominated by analytical noise so that, unlike other carbonate-bound proxies,  
104 paleotemperature errors are random rather than systematic.

105 The epifaunal foraminifera utilized here live at approximately the same depth as planktonic  
106 species considered to be surface dwelling (29) (<50 m, within 1°C of SST in the tropics; see SI  
107 Appendix, Fig. S6), and calcify at a constant rate in locations characterized by a large seasonal  
108 cycle (30). Therefore, our paleotemperatures reflect mean annual SST. The abundance of the  
109 nummulitids in the Eocene tropics and mid-latitudes, where they are rock-forming in some  
110 locations, demonstrates that they were well-adapted to the climate at the time. Three LBF species  
111 live-collected from seven locations are characterized by a  $\Delta_{47}$ -temperature slope within error of  
112 the Yale inorganic calcite calibration (27) (see SI Appendix, Fig. S1, Tab. S1), and there is no  
113 evidence for a significant vital effect influence on shell  $\delta^{18}\text{O}$ . These observations provide the  
114 basis for the use of this calibration to reconstruct paleotemperatures from extinct LBF of the  
115 same family.

116 All fossil samples were analyzed by laser-ablation ICPMS for a suite of trace elements to assess  
117 their geochemical preservation, together with SEM images (see SI Appendix, Fig. S4, Tab. S3).  
118 Trace element ratios indicative of contamination and overgrowths (Al/Ca and Mn/Ca) show no  
119 correlation with Mg/Ca, indicating the absence of any Mg-bearing secondary phase. SEM images  
120 of broken specimens show that Eocene and modern foraminifera are characterized by equivalent  
121 chamber wall micro-textures, demonstrating the absence of micron-scale recrystallisation.  
122 Furthermore, high-Mg calcite, such as that of LBF shells, recrystallizes fully to low-Mg, low-Sr  
123 calcite during diagenesis (see SI Appendix, Fig. S5), enabling the unambiguous identification of  
124 geochemically well-preserved material. On the basis of these screening techniques, only samples  
125 that were exceptionally well-preserved were utilized for  $\Delta_{47}$  analysis, i.e. those with no

126 discernable diagenetic modification. Finally, because these foraminifera live at shallow water  
127 depths, there is no potential for a large difference between calcification and diagenetic  
128 temperature, unlike tropical planktonic species (15).

129 The mean tropical SST derived from samples that passed this rigorous screening is  $32.5 \pm 2.5^\circ\text{C}$   
130 (Fig. 3A). The maximum reconstructed Eocene  $\Delta_{47}$  temperature is  $36.3 \pm 1.9^\circ\text{C}$  from Java at  $\sim 39$   
131 Ma (all uncertainties are 1SE), with a paleolatitude of  $6^\circ\text{S}$  (30), possibly placing it within an  
132 expanded Indo-Pacific warm pool. Samples spanning the early Eocene (55.3-49.9 Ma) from  
133 Kutch, India, which was within  $5^\circ$  of the equator at that time, are characterized by temperatures  
134 of  $30.4 \pm 2.5$  to  $35.1 \pm 2.6^\circ\text{C}$ . The difficulty in precisely temporally correlating shallow sites means  
135 that we cannot definitively assign these samples to specific intervals, although the youngest and  
136 warmest Kutch sample probably falls within the Early Eocene Climatic Optimum (EECO;  $\sim 52$ -  
137 50 Ma). Although the peak temperature from equatorial India in the early Eocene is marginally  
138 cooler than that from middle Eocene Java, the two are within error, and this small difference may  
139 be explained by regionally cooler SST on the West coast of India compared to the West Pacific.  
140 A latest Eocene sample from Tanzania (33.9 Ma;  $21^\circ\text{S}$ ) records  $29.7 \pm 3.1^\circ\text{C}$ .

141 In addition, samples spanning the early-middle Eocene from northwest Europe were analyzed for  
142  $\Delta_{47}$  and Mg/Ca. The principal aim of doing so was to fill temporal gaps in our seawater  
143 chemistry reconstructions (see below), but these also provide new Eocene SST for this region.  
144 We observe a  $9^\circ\text{C}$  warming between the earliest Eocene ( $18$ - $20^\circ\text{C}$ ) and the EECO ( $28$ - $31^\circ\text{C}$ ),  
145 followed by a long-term cooling trend through the mid-Eocene to  $23.1 \pm 2.5^\circ\text{C}$  at 42.5 Ma. This  
146 pattern of global change is in good agreement with mid-high latitude  $\text{TEX}_{86}$  (see SI Appendix,  
147 Fig. S8 and (31)).

148 Finally, calculated  $\delta^{18}\text{O}_{\text{sw}}$ , derived from  $\delta^{18}\text{O}_{\text{c}}$  measured simultaneously with  $\Delta_{47}$ , yield values  
149 that are in agreement with an ice-free world. Specifically,  $\delta^{18}\text{O}_{\text{sw}}$  reconstructed from our tropical  
150 samples is within error of -1‰, with the exception of Tanzania (-0.2‰).  $\delta^{18}\text{O}_{\text{sw}}$  at our mid-  
151 latitude sites is temporally variable and characterized by overall more negative values, consistent  
152 with mid-latitude freshwater contribution to these proximal sites (-4 to -1.5‰). These data  
153 further demonstrate that our samples are well-preserved, and that the sample site salinity was not  
154 substantially lower than open ocean (all  $\delta^{18}\text{O}_{\text{sw}}$  within 3‰ of mean Eocene seawater). Because a  
155 >10 psu salinity reduction is necessary to significantly change seawater Mg/Ca ( $\text{Mg}/\text{Ca}_{\text{sw}}$ ), our  
156 LBF Mg/Ca data discussed below must also represent normal seawater conditions (see SI  
157 Appendix, Fig. S7).

158 Our samples do not include the PETM, and only one falls within the EECO. Therefore, our  
159 results do not preclude warmer tropical temperatures during those time intervals (6).

160 Nonetheless, we find no evidence for tropical SST >38°C based on our  $\Delta_{47}$  data. Indeed, all of  
161 our tropical data are within uncertainty of each other, and could be interpreted as indicating  
162 stable warm conditions in the tropics throughout the Eocene ( $32.5 \pm 2.5^\circ\text{C}$ ), in line with several  
163 previous studies (8, 14, 32), although possible temporal trends will be discussed below. To assess  
164 whether a similar picture is evident in other proxy SST data, and therefore to address the broader  
165 questions of the Eocene evolution of tropical SST and early Eocene polar amplification, we use  
166 these  $\Delta_{47}$  paleotemperatures, together with Mg/Ca analyses of the same samples, to accurately  
167 and precisely reconstruct seawater Mg/Ca ( $\text{Mg}/\text{Ca}_{\text{sw}}$ ). This allows us to reevaluate all Eocene  
168 planktonic foraminifera Mg/Ca data, providing an additional constraint on tropical SST at higher  
169 temporal and spatial resolution than the  $\Delta_{47}$  data alone. Furthermore, by combining information  
170 from these proxies we create a large dataset consisting mostly of open ocean data, suitable for

171 comparison to climate simulations. Doing so minimizes potential bias associated with the  
172 regional paleoceanography of any individual site.

173

#### 174 **Seawater Mg/Ca reconstruction**

175 Coupling Mg/Ca- $\Delta_{47}$  data of the same specimens allows us to simultaneously reconstruct  
176 temperature and Mg/Ca<sub>sw</sub> because shell Mg/Ca is a function of both, and we independently  
177 constrain the temperature component of Mg incorporation using  $\Delta_{47}$ . Although much work has  
178 focused on reconstructing past variation in Mg/Ca<sub>sw</sub> (33, 34), a different approach is required.  
179 Whilst these studies show that Mg/Ca<sub>sw</sub> has approximately doubled since the Oligocene (35),  
180 precise reconstructions for most of the Paleogene are lacking, and models covering the  
181 Phanerozoic (35, 36) do not agree on epoch-scale variation in seawater chemistry. This has  
182 precluded reliable Mg/Ca-derived paleotemperatures with sufficient accuracy for assessing  
183 model SST competency (17). To overcome this, we use  $\Delta_{47}$  data of LBF spanning the Eocene-  
184 early Oligocene to solve the Mg/Ca<sub>LBF</sub>-Mg/Ca<sub>sw</sub>-temperature calibration for these foraminifera  
185 (37). The uncertainty in these reconstructions is ~2-5 times lower than previous estimates,  
186 reducing the Mg/Ca<sub>sw</sub>-derived error on existing planktonic foraminifera temperatures to <2.5°C.  
187 This is possible because nummulitid Mg/Ca is more sensitive to Mg/Ca<sub>sw</sub> than to temperature,  
188 and unlike planktonic species there are no resolvable salinity or carbonate chemistry effects (30,  
189 37). The composite Paleogene Mg/Ca<sub>sw</sub> curve (Fig. 2) is based on our LBF and data from  
190 inorganic vein carbonates (33), as the uncertainty on these latter data is also relatively small and  
191 the two records are in excellent agreement where they overlap. This reconstruction delineates the  
192 Eocene-early Oligocene as a period of stable Mg/Ca<sub>sw</sub> between 2.1-2.5 mol mol<sup>-1</sup>, ~45% of  
193 modern. Previously, the lack of data before 40 Ma required box-model estimates (35, 36) to be

194 used to assess the impact of secular change in seawater chemistry on fossil Mg/Ca  
195 measurements. The precise LBF-derived Mg/Ca<sub>sw</sub> data (Fig. 2) demonstrate that those models  
196 are inaccurate in the early Eocene, with a large effect on Mg/Ca-derived temperatures. For  
197 example, early Eocene tropical SST calculated using our Mg/Ca<sub>sw</sub> would result in temperatures  
198 6-10°C cooler compared to the model output of ref. (35), yet warmer by a similar magnitude  
199 using the model of ref. (36).

### 200 **Eocene tropical warmth**

201 In light of both our tropical clumped isotope data and revised planktonic foraminifera Mg/Ca  
202 temperatures utilizing the precise Mg/Ca<sub>sw</sub> reconstruction described above, we are able to  
203 estimate low-latitude SST across the globe and throughout the Eocene, thus placing new  
204 constraints on the early-Eocene latitudinal gradient (Fig. 3,4). When doing so it must be  
205 considered that in addition to Mg/Ca<sub>sw</sub>, both salinity and the carbonate system may bias  
206 planktonic foraminifera Mg/Ca-derived SST (21, 38). We consider the impact of pH in detail  
207 (see SI Appendix), but do not apply a salinity correction because mean Eocene ocean salinity  
208 was similar to today (39). Although Mg/Ca and TEX<sub>86</sub> are associated with relatively large  
209 uncertainties ( $\sim\pm 3-5^\circ\text{C}$ ) related to non-thermal influences and calibration complications,  $\Delta_{47}$ ,  
210 reinterpreted planktonic Mg/Ca, and TEX<sub>86</sub> are in good agreement in the tropics. This indicates  
211 that if either of the latter are systematically offset in this region, it is by less than the magnitude  
212 of the stated error, lending support to the interpretation of Eocene GDGTs in terms of SST in the  
213 tropics (cf. ref. (19, 40)).

214 The tropical compilation constrains SST to between 30-36°C throughout the Eocene (Fig. 4),  
215 with the exception of late Eocene TEX<sub>86</sub> from ODP Site 929/925 (31) which range between 27-  
216 32°C, and the earliest Eocene Mg/Ca data from ODP Site 865 (26-31°C). Although the  $\Delta_{47}$

217 reconstructions from the middle Eocene of Java are 1°C higher than the EECO of Kutch this may  
218 simply reflect zonal differences in Eocene tropical SST, which is likely given that the modern  
219 tropics are characterized by similar zonal SST variability (Fig. 4). Additionally, the compilation  
220 highlights that the 2-5°C tropical warming between the earliest Eocene and the EECO shown by  
221 the  $\Delta_{47}$  data from Kutch is in good agreement with planktonic foraminifera Mg/Ca from ODP  
222 Site 865 (recalculated from ref. (41)) and earliest Eocene TEX<sub>86</sub> data (6); early Eocene equatorial  
223 clumped isotope temperatures of 30-33°C are therefore not anomalously cool.

224 These data do not rule out the possibility of higher temperatures over transient events such as the  
225 PETM (6), and therefore do not constrain peak Eocene tropical warmth. They do provide strong  
226 evidence that the early Eocene tropical oceans in general were not warmer than 36°C (mean  
227 ~33°C, upper uncertainty 38°C), unless all proxies are biased towards lower temperatures. Given  
228 that there is no reason to suspect this, our data provide a well-constrained basis to examine the  
229 early Eocene latitudinal gradient and the accuracy of Eocene model simulations.

### 230 **Early Eocene latitudinal sea surface temperature gradient**

231 To use our tropical SST compilation to quantitatively constrain the equator-pole SST gradient for  
232 the early Eocene (the interval to which most model simulations are compared), we first review  
233 the high-latitude proxy data. Eocene SSTs derived from TEX<sub>86</sub> data from the ACEX core (42)  
234 (~80°N), ODP Site 1172 (5) (~54°S) and Wilkes Land (43) (~60°S) greatly exceed deep ocean  
235 temperatures derived from deep benthic foraminifera Mg/Ca and  $\delta^{18}\text{O}$  (44), suggesting either a  
236 seasonal bias, the influence of local warm surface currents, a more stratified ocean, and/or  
237 uncertain calibrations (20). To avoid these complications, we use the deep-benthic foraminifera-  
238 Mg/Ca temperature stack (44) as a lower limit on high-latitude SST. Present-day mean SST at  
239 high-latitudes is within 1°C of the deep ocean (see the SI Appendix), and the coolest Eocene

240 high-latitude  $\Delta_{47}$  data based on long-lived shallow benthic molluscs from Seymour Island (45)  
241 are within error of coeval deep-ocean temperatures where both are available (Fig. 3B,C).  
242 Although the coherence of these reconstructions supports the use of deep ocean Mg/Ca as a  
243 minimum constraint on high-latitude SST through time, model evidence suggest that Eocene  
244 deep water formation in the Southern Ocean may have been limited to winter (20), resulting in  
245 colder deep water compared to mean annual high-latitude SST. Therefore, we emphasize that  
246 using the benthic foraminifera Mg/Ca dataset as a proxy for the high-latitude SST produces an  
247 estimate of the *maximum* steepness of the latitudinal SST gradient and does not necessarily  
248 represent the mean annual gradient. Similarly, it does not in itself provide a means of assessing  
249 high-latitude SST proxy data given that these may be biased towards a different season, and there  
250 is evidence for a zonal SST heterogeneity in the Eocene Southern Ocean (45). The merit in this  
251 approach is that it provides a conservative constraint on the degree to which the gradient was  
252 reduced in the Eocene, and therefore represents the minimum that model simulations must  
253 achieve in order to be considered representative of Eocene climate. We calculate the early  
254 Eocene latitudinal gradient as the difference between the mean tropical and deep-ocean data  
255 between 48-56 Ma ( $\pm 2\text{SE}$  variability in both datasets); it is therefore representative of  
256 background early Eocene conditions (i.e. not the PETM, for which there is evidence for a further  
257 reduction in the latitudinal SST gradient (21)).

258 Based on this analysis, we find a reduction of at least  $32\pm 10\%$  in the mean difference between  
259 tropical and high-latitude SST during the early Eocene (48-56 Ma), relative to present-day (Fig.  
260 5A). The quantity ( $n = 123$ ) and coherence of tropical early Eocene data from  $\Delta_{47}$  and two other  
261 proxies means that we can confidently use this as a conservative estimate to assess model  
262 competency. Splitting the early Eocene into intervals approximating the EECO (50-52.5 Ma)

263 versus post-PETM, pre-EECO (55-52.5 Ma) does not significantly alter our finding as the  
264 latitudinal gradient for both intervals is within the uncertainty of the early Eocene data overall.  
265 Therefore, for the purposes of model-data comparison we do not split the early Eocene in this  
266 way because the overall sparsity of data may result in a regionally biased comparison.

### 267 **Eocene model-data comparison**

268 Polar amplification in climate models of past warm periods has received much attention as it has  
269 long been suggested that simulations may not capture the extent to which the latitudinal SST  
270 gradient is reduced. In the Eocene, this debate has focused in part on the magnitude of tropical  
271 warming (23). For example, if tropical SST were far higher than at present and if high-latitude  
272 proxy data were summer-biased, then some models are in overall agreement with the data (20).  
273 Our  $\Delta_{47}$  reconstructions and SST compilation (Fig. 3,4) demonstrate that early Eocene tropical  
274 warming was of a substantially lower magnitude than in most models, and therefore indicate that  
275 the proxy data are irreconcilable with these simulations even when accounting for complicating  
276 factors in the high-latitudes. Other simulations indicate SST exceeding the proxy estimates in  
277 both the tropics and high-latitudes. For example, the FAMOUS model simulation (46) shown in  
278 the context of the early Eocene proxy data in Fig. 3D is notable because it produces a  
279 substantially reduced latitudinal SST gradient. However, the parameter changes used to achieve  
280 this gradient reduction result in tropical SST that are  $\sim 7^{\circ}\text{C}$  warmer than the proxy data.

281 Extending this comparison (Fig. 5A) by comparing the Eocene data latitudinal gradient to a  
282 number of climate simulations shows that HadCM3L (47) and GISS (48) are characterized by  
283 SST gradients within 10% of their pre-industrial simulation. In contrast, CCSM (as configured  
284 by refs. (49, 50)) approaches the proxy gradient at four  $\text{CO}_2$  doublings (4480 ppm), whilst the  
285 CCSM models of ref. (12) (hereafter  $\text{CCSM}_{\text{KS}}$ ) and the warmest FAMOUS simulation (46) fall

286 within the range of the proxy data, achieving latitudinal gradients below 80% of modern at 560  
287 ppm CO<sub>2</sub>. The common feature of these latter models is that both have substantially modified  
288 parameters related to cloud formation including a reduction in low-level stratiform cloud,  
289 increased precipitation rates, and an increase in incoming shortwave radiation. Such clouds are  
290 more prevalent at high-latitudes, resulting in preferential surface warming of these regions.

291 Although models with modified cloud properties are within error of a conservative latitudinal  
292 proxy gradient, this does not imply agreement in terms of absolute temperatures (e.g. compare  
293 FAMOUS to the data in Fig. 3D). Therefore, to assess the ability of models to reconstruct both  
294 absolute SST *and* the latitudinal gradient, and to avoid the potential bias introduced by  
295 condensing model-data comparison into a latitudinal transect, the offsets between the proxy data  
296 and the nearest model grid cells were calculated to produce a location-specific proxy-model  
297 comparison. Fig. 5B and S12-14 display the result of this exercise in terms of the average  
298 tropical and high-latitude proxy-model offset, i.e. the mean of location-specific offsets between  
299 the model and data for the two regions (as above, the high-latitude proxy-model offset was  
300 conservatively estimated based on deep ocean temperatures, see SI Appendix). Models with  
301 Eocene latitudinal gradients similar to present-day such as HadCM3L and ECHAM (Fig. 5A)  
302 consistently underestimate high-latitude SST. Moreover, we find that no simulation captures our  
303 conservative estimate of the latitudinal gradient *and* the absolute proxy temperatures.

304 Specifically, most models that lie close to the 1:1 line in Fig. 5B, representing agreement in  
305 terms of the latitudinal gradient, overestimate both tropical and high-latitude SST and require  
306 pCO<sub>2</sub> greater than that indicated by the proxy data. Nonetheless, three CCSM simulations fall  
307 within 2-3°C of the origin in Fig. 5B, indicating that these are close to reproducing our  
308 conservative analysis of the early Eocene latitudinal gradient, as well as the absolute proxy

309 temperatures. CCSM<sub>KS</sub>, with modified cloud properties, achieves this with pCO<sub>2</sub> within the  
310 range of proxy data (1). However, we stress that our derivation of the early Eocene latitudinal  
311 gradient is conservative. If high-latitude mean annual SST were in fact warmer than the deep  
312 ocean, then the model-data comparison would be considerably less favorable. Similarly,  
313 evidence for further polar amplification during the PETM (21) predicts a less-favorable  
314 comparison. Therefore, our analysis indicates that a further mechanism of polar amplification is  
315 likely to be required to fully reconcile models with peak Eocene warmth, given that CCSM<sub>KS</sub>  
316 (the best performing model in our analysis) is characterized by a similar latitudinal SST gradient  
317 when run under pre-PETM and PETM conditions (Fig. 5A).

318 Our coupled  $\Delta_{47}$ -Mg/Ca data and subsequent reanalysis of planktonic Mg/Ca temperatures via  
319 the precise reconstruction of Mg/Ca<sub>sw</sub> demonstrate that the early Eocene mean latitudinal SST  
320 gradient was at least  $32\pm 10\%$  shallower than modern. Based on a location-specific comparison  
321 that avoids latitudinal averaging, we find that few modelling efforts (12) are close to reproducing  
322 both this gradient and the absolute proxy SST. Further work is required to capture the possible  
323 additional reduction in this gradient during peak warm intervals, or if Eocene mean annual high-  
324 latitude SST were warmer than the deep ocean. The most accurate Eocene simulations with  
325 respect to SST independently achieved this by modifying aerosol and cloud properties,  
326 highlighting the importance of this research direction as a potential mechanism for polar  
327 amplification (51).

328 **Materials and Methods**

329 All fossil samples come from clay or sand horizons (e.g. ref. (30)) and none contained noticeable  
330 carbonate infillings that may bias the data. Additionally, broken chamber wall sections of key  
331 samples were imaged by SEM in order to confirm that  $\mu\text{m}$ -scale recrystallization had not taken  
332 place.

333 Samples were analyzed by laser-ablation ICPMS using the RESOLUTION M-50 system at Royal  
334 Holloway University of London (58). The procedure for non-destructive analysis of LBF has  
335 been described in detail elsewhere (37), and was modified only in that the Agilent 7500 ICPMS  
336 used in that study was replaced with an Agilent 8800 triple-quadrupole ICPMS part-way through  
337 the analytical period. Prior to clumped isotope measurement every specimen was analyzed by  
338 LA-ICPMS to assess preservation on an individual specimen basis. The only exception to this  
339 was sample W10-3c and EF1/2, which contained abundant foraminifera, and all specimens  
340 analyzed were found to be geochemically well-preserved. Therefore, screening of every  
341 foraminifera was unnecessary. Aside from widely used preservation indicators such as Al/Ca for  
342 clay contamination and Mn/Ca for overgrowths, Mg/Ca and Sr/Ca are also useful preservation  
343 indicators as the Mg and Sr concentration of high-Mg calcite decreases substantially upon  
344 recrystallization to values substantially lower than well-preserved Eocene specimens  
345 (pervasively recrystallized samples are shown for comparison, see SI Appendix, Fig. S5).

346 The clumped isotope analytical procedure at Yale University is described in detail elsewhere (45,  
347 59). Larger specimens were crushed before cleaning, smaller specimens were analyzed as  
348 multiple whole shells. Modern samples were ultrasonicated for 30 minutes in  $\sim 7\%$   $\text{H}_2\text{O}_2$ , rinsed  
349 three times in distilled water and dried under vacuum at  $25^\circ\text{C}$ . Fossil samples with lower organic  
350 content were ultrasonicated in methanol followed by distilled water only to remove any clay  
351 adherents. Then  $\sim 3\text{-}5$  mg of sample was reacted overnight with  $103\text{-}105\%$   $\text{H}_3\text{PO}_4$  at  $25^\circ\text{C}$ . The  
352  $\text{CO}_2$  was extracted through an  $\text{H}_2\text{O}$  trap and cleaned of volatile organic compounds using a 30 m  
353 Supelco Q-Plot GC column at  $-20^\circ\text{C}$ . Isotopic analyses were performed on a Thermo MAT253  
354 optimized to measure  $m/z$  44-49. Masses 48 and 49 were used to assess sample purity.  
355 Standardization was performed through the analysis of  $\text{CO}_2$  with a range of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ,  
356 heated to  $1000^\circ\text{C}$  (termed ‘heated gases’) and transferred into the absolute reference frame as  
357 previously described (59, 60) using standards with a  $\Delta_{47}$  range that spans the samples (see SI  
358 Appendix for details).

359  
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## 521 **Figure Legends:**

522

523 **Fig. 1.** Sample sites overlain on early Eocene paleogeography (created using  
524 <http://www.odsn.de/odsn/services/paleomap/paleomap.html>, after ref. (52)). Yellow circles - this  
525 study ( $\Delta_{47}$  and Mg/Ca), red circles - previous  $\Delta_{47}$  reconstructions, blue squares - published  
526 Eocene Mg/Ca data reinterpreted here using the seawater Mg/Ca reconstruction of this study.  
527 Sites without labels are terrestrial outcrops (see SI Appendix, Tab. S2).

528

529 **Fig. 2** Seawater Mg/Ca reconstruction for the Eocene and early Oligocene based on coupled  $\Delta_{47}$ -  
530 Mg/Ca Large Benthic Foraminifera (LBF) data, shown in the context of previous Cenozoic  
531 reconstructions (33, 34, 53, 54) and box-models (35, 36, 55; WA89, SH98 and HS15  
532 respectively), that are commonly used for calculating planktonic and deep benthic foraminifera  
533 Mg/Ca data. [CCV – ridge-flank CaCO<sub>3</sub> veins](#). Coral-derived data younger than 20 Ma are  
534 omitted. The 95% confidence intervals on our Eocene Mg/Ca<sub>sw</sub> curve are derived from  
535 bootstrapping 1000 LOWESS fits, including both geochemical and dating uncertainties.

536

537 **Fig 3.** Eocene clumped isotope SST reconstruction and re-evaluated Mg/Ca temperatures (this  
538 study) shown in the context of organic proxies. **(A)** All clumped isotope-derived SST. Smaller  
539 symbols are previously published data. **(B-D)** Absolute Eocene SST proxy data, split into three  
540 time intervals (34-38, 38-48 and 48-56 Ma). All Mg/Ca data were reevaluated based on our  
541 Mg/Ca<sub>sw</sub> curve (Fig. 2). TEX<sub>86</sub> temperatures were recalculated using the TEX<sub>86</sub><sup>H</sup> calibration (56).  
542 See SI Appendix for references. Horizontal lines show Eocene Mg/Ca-derived deep ocean  
543 temperatures (44). The modern mean annual temperature (MAT) and seasonal range in SST  
544 (MART) are depicted by dark and light grey shading, respectively. Marker and line color depicts  
545 sample age, note the colour scale is the same in all panels. Data are compared to an Eocene GCM  
546 simulation (FAMOUS model E17 (46) at 560 ppm CO<sub>2</sub>) in panel D.

547

548 **Fig 4.** The evolution of tropical (<23°) sea surface temperatures through the Eocene. Note that  
549 scatter in the proxy data is of a similar magnitude as the modern range in tropical SST (grey bar).  
550 Representative errors are 1SE for  $\Delta_{47}$ , propagated uncertainties derived from the influence of  
551 Mg/Ca<sub>sw</sub> and pH on Mg/Ca, and 2SE for TEX<sub>86</sub>. [The modern mean and 95<sup>th</sup> percentiles are based  
552 on the World Ocean Atlas \(see the SI Appendix\).](#)

553

554 **Fig 5.** Early Eocene (48-56 Ma) model-data comparison. **(A)** Zonally-averaged latitudinal  
555 gradients based on proxy CO<sub>2</sub> and SST data (grey box) and climate models (12, 46–48, 50, 57)

556 (circles) over a range of CO<sub>2</sub>. Proxy CO<sub>2</sub> range is from (1) including error, the gradient  
557 uncertainty is the combined 2SE of the tropical and high latitude proxy data (see text). Proxy-  
558 derived gradient is shown relative to present day, Eocene climate model simulations are shown  
559 relative to their pre-industrial counterpart. Most model simulations do not capture the reduced  
560 latitudinal gradient within the range of proxy CO<sub>2</sub> (<2250 ppm). **(B)** Site specific model-data  
561 comparison for the tropics and high latitudes. Model SST competency assessed by comparing the  
562 mean difference between the model and proxy data for low and high-latitudes. Quadrants reflect  
563 different overall patterns of model-data offset. Hypothetical simulations falling on the 1:1 line  
564 would reconstruct the same latitudinal gradient as the data but not the same absolute SST, except  
565 at the origin. All models fall below this line, indicating that Eocene polar amplification is  
566 underestimated.

567

568 **Author contributions:** DE and HPA designed the study. DE carried out the analytical work and,  
569 analyzed the data ~~and wrote the draft manuscript~~. DE, WR, LC, JAT, PKS, PS and PNP collected  
570 samples. HPA and WM directed the clumped isotope and laser-ablation analysis respectively. All  
571 authors contributed ideas in the interpretation of the data and wrote the final manuscript.









