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1 Cyclic evolution of phytoplankton forced by changes in tropical seasonality

2

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13

14 **The effect of global climate cycles driven by Earth's orbital variations on evolution is poorly understood because of difficulties achieving**
15 **sufficiently-resolved records of past evolution. The fossil remains of coccolithophores, a key calcifying phytoplankton group, enable an**
16 **exceptional assessment of the impact of cyclic orbital-scale climate change on evolution because of their abundance in marine sediments,**
17 **and because coccolithophores demonstrate extreme morphological plasticity in response to the changing environment^{1,2}. Recently,**
18 **evolutionary genetic analyses linked broad changes in Pleistocene fossil coccolith morphology to species radiation events³. Here, using**
19 **high-resolution coccolith data, we show that during the last 2.8 million years coccolithophore evolution was forced by Earth's orbital**
20 **eccentricity with rhythms of ~100,000 years and 405,000 years - a distinct spectral signature to that of coeval global climate cycles⁴.**
21 **Simulations with an Earth System Model⁵ including the marine carbon cycle⁶ demonstrate that eccentricity directly impacts the diversity**
22 **of ecological niches occurring over the annual cycle in the tropical ocean. Reduced seasonality favours species with mid-size coccoliths**
23 **that bloom year-round, increasing coccolith carbonate export and burial. We posit that eccentricity pacing of phytoplankton evolution**
24 **contributed to the strong 405,000-year pacing seen in records of the global carbon cycle.**

25

26 Coccolithophores are important producers of CaCO₃ in the ocean and their fossil remains (calcite platelets called coccoliths) first appeared in
27 sediments during the late Triassic (~210 million years ago, Ma). Coccolithophores rose to dominance in the open ocean during the early
28 Cretaceous⁷ and thereafter become a key biological modulator of the global carbon cycle, via both photosynthesis and calcification⁸. In the
29 dominant Noëlaerhabdaceae family (including the cosmopolitan genera *Emiliana*, *Gephyrocapsa* and *Reticulofenestra*), species are defined by
30 the morphological characteristics of their coccoliths, with size being a key criterion⁹. For *Gephyrocapsa* and *Emiliana*, phylogenies
31 reconstructed from gene sequence data indicate that morphology-based definitions correspond to biological species^{3,10}. Yet, within a given
32 Noëlaerhabdaceae population, interspecific and intraspecific changes in coccolith length and mass (the latter encoding degree of calcification as
33 well as size) occur in response to environmental parameters such as carbonate chemistry¹ and temperature². Existing studies of coccolithophore
34 evolution have focused on geological-timescale changes in species richness and turnover¹¹, coccolith carbonate accumulation^{7,12}, or calcification
35 potentially driven by carbon cycle changes¹³. However, to date a lack of records that are both long-term and high-resolution has precluded an
36 understanding of the impact of orbital cycles (on timescales of tens to hundreds of thousands of years) on coccolithophore evolution and
37 carbonate production.

38

39 Here, we quantify the history of tropical Noëlaerhabdaceae evolution throughout the Pleistocene at high resolution (~2 thousand years, kyr),
40 using coccoliths preserved in nine well-dated sedimentary sections from the tropical Indian and Pacific Oceans (Fig. 1; Extended Data Table 1;
41 Methods). We use artificial intelligence microscopy to create an unprecedented biometric database of over 7 million coccoliths from >8000
42 samples (see Methods). The remarkable similarity of morphometric patterns observed at each site has led us to build evolutionary histograms of
43 coccolith size and mass. To create these, we binned data into 30-kyr intervals to erase any precession-band variability driven by ecology¹⁴ and to
44 increase the statistical robustness of each point, now composed of measurements of tens of thousands of individual coccoliths (Fig. 2a;
45 Methods). Evolutionary histograms for size and mass show identical trends and variability, we therefore only discuss the size record. The data
46 show multiple phases of contraction alternating with phases of dilation characterised by bimodal or broader morphological distributions (Fig.
47 2a). Patches of high abundance of a particular morphotype correspond in many cases to described acmes of Noëlaerhabdaceae species¹⁵⁻¹⁷. The
48 most recent dilation phase that started around 450 thousand years ago (ka) has been attributed to a radiation event and the emergence of new
49 *Gephyrocapsa* species, based on a consensus phylogeny reconstructed from genome sequence data and its temporal correlation to low-resolution
50 coccolith morphometric data³. Over the entire record, average coccolith size shows an increasing trend that corresponds to a gradual shift in
51 dominance from smaller to larger coccoliths during the Pleistocene (Fig. 2b). On orbital time scales, coccolith size and global ice volume and
52 temperature cycles as represented by the $\delta^{18}\text{O}$ of benthic foraminifers¹⁸ show very different temporal evolution (Fig. 2c). Instead the size
53 contraction and dilation alternations follow a regular cycle that is highly coherent (>99.9%) with the orbital eccentricity periods of 405 kyr
54 (e405) and of 124 and 95 (e100)¹⁹ (Extended Data Figure 1a), with contractions (dilations) occurring at low (high) eccentricity with a slight time
55 lag (Fig. 2b).

56
57 The average size or mass of coccoliths in a Noëlaerhabdaceae population may vary over time because of macro- and/or micro-evolution, or
58 because ecological changes modulate the relative abundances of species in different size ranges. To remove the effect of relative abundance
59 changes, we create a novel Morphological Divergence Index, MDI, that represents the difference in average coccolith mass between two size
60 classes, larger and smaller than $3\mu\text{m}$ (Extended Data Figure 2; Methods). MDI records from individual sites are highly intercorrelated (Extended
61 Data Figure 3) and all show significant e405 and e100 periods (Extended Data Figure 1), despite coming from distinct oceanographic biomes²⁰
62 and climatic regimes (e.g. Warm Pool, monsoon-dominated; see Extended Data Table 1). We therefore produce a composite MDI stack,
63 preserving the high resolution of each dataset (Fig. 3c; Methods). Evolutionary cross-spectral analysis indicates that the stack has highly
64 significant (>90%) coherency with the frequencies of Earth's eccentricity since 2.8 Ma (Fig. 3b, b'). This pattern cannot be the result of
65 differential dissolution on coccolith morphology, because MDI values are similar regardless of core depths, and because in contrast to MDI,
66 Pleistocene deep-sea CaCO_3 dissolution generally follows a glacial-interglacial (G-IG) pattern²¹. The MDI stack, interpreted as primarily
67 reflecting evolutionary changes in morphology, shows strong 405-kyr pacing throughout the Pleistocene, irrespective of G-IG background state.
68 While eccentricity forcing on coccolithophore productivity has previously been suggested^{22,23}, our new high-resolution multi-million-year dataset
69 reveals that eccentricity cycles imprinted the evolution of the Noëlaerhabdaceae. Such cyclicity may have had important consequences for the
70 oceanic carbon cycle on multiple time scales via coccolith carbonate production and burial in sediments^{12,24}. Coccolithophores are known to
71 produce high amounts of calcite during blooms^{22,25}, and sediments are often dominated by few species, for example *Emiliania huxleyi* (0-90 ka)¹⁵
72 and *Gephyrocapsa caribbeanica* (280-570 ka)¹⁶ in the late Pleistocene. We estimate the CaCO_3 mass accumulation rate (MAR) of
73 Noëlaerhabdaceae coccoliths in our cores and produce a stacked CaCO_3 MAR record (Fig. 3e, Methods). This reveals that higher MARs
74 correspond to lower MDI values when mid-size bloom species, which contribute the most to coccolith carbonate export, dominate. The
75 dominance of these bloom species coupled with high coccolithophore production and accumulation in sediments during eccentricity minima is
76 also recorded in the extra-tropics²², attesting to the global significance of these observations. In our records, the two main components, production

77 of coccoliths and individual mass, often have opposing effects on MAR since medium-size and low-mass species, such as *E. huxleyi* and *G.*
78 *carribeana*, are the most productive (Extended Data Figure 4). In addition, local ecological conditions affecting productivity and export, and
79 potentially water depth affecting coccolith preservation, likely also influence MAR, although it is not possible to quantify the relative effects of
80 these factors. Nevertheless, the composite MAR record shows strong eccentricity periodicities that are significantly coherent with MDI
81 throughout the Pleistocene (Fig. 3d, d'), demonstrating a strong imprint of coccolithophore evolution on carbonate production and burial.

82

83 **MDI as a recorder of seasonality**

84 We hypothesise that our new coccolith index reflects variations in the amplitude of tropical seasonality. In low latitudes, seasonal contrast is
85 related to the eccentricity of Earth's orbit, (1) directly because the ellipticity of the orbit determines the distance between the Sun and the Earth
86 during each season, affecting radiation intensity, and (2) indirectly because eccentricity modulates the effect of precession on seasonal insolation
87 contrast. Seasonal contrast is greater during periods of high eccentricity. To our knowledge, the eccentricity-paced rhythm of surface-ocean
88 seasonality that dominates MDI has not been documented previously because most proxies record integrated annual average conditions or a
89 specific season. The seasonal succession of coccolithophore species, a characteristic of phytoplankton ecology, is indicative of their adaptation
90 to the different ecological niches created by seasons²⁶. Those seasonal niches are more diverse in a climate with stronger seasonality²⁰. In the
91 modern ocean, the highest phytoplankton diversity is found in the tropical band, a pattern probably related to high temperatures and temporal
92 stability, whereas the seasonal species turnover is highest at mid-latitudes because of a strong seasonal contrast²⁷. Annual records of Net Primary
93 Production (NPP) are good descriptors of the range of oceanographic niches and biomes²⁰. To demonstrate the effect of orbital configuration on
94 NPP and therefore niche availability, we simulated monthly oceanic NPP using the fully-coupled IPSL-CM5A-2 model⁶, which includes the
95 ocean biogeochemistry model PISCES-v2⁵, for seven early Pleistocene time intervals chosen to cover a large eccentricity spectrum with different
96 precession conditions but with similar ice volume and obliquity (lines in Fig. 2; Extended Data Table 2). The results of these simulations for the
97 tropical eastern Indian and western Pacific Oceans show that the seasonal range of NPP increases with eccentricity, a trend that parallels the
98 eccentricity sorted values of MDI (Fig. 4).

99

100 In the simulations, the increase in the amplitude of the NPP seasonal cycle (Fig 1; Extended Data Figure 5b-e) is primarily driven by higher
101 productivity during boreal summer, especially in the eastern Indian ocean. This increase is forced by modification of atmosphere-ocean
102 dynamics in response to variations in the amplitude and seasonality of insolation forcing that is amplified at extreme eccentricity values
103 (Extended Data Figure 5g-j and 6a-c). During high eccentricity periods at precession minima (maxima), increasing (decreasing) boreal summer
104 insolation (Extended Data Figure 6b, c) is responsible for increasing (decreasing) sea-level pressure over continental Asia (Extended Data Figure
105 6e-h). Induced modifications of sea-level pressure gradients over the tropical Indian and Pacific Oceans in turn translate into changes in the low-
106 level wind circulation over the Indo-Pacific Warm Pool, IPWP, (Extended Data Figure 5g-j). Anomalous easterlies at precession minima
107 (westerlies at precession maxima) in the equatorial region generate anomalous upwelling along the equator (SW of India) that are responsible for
108 the increasing nutrient content at the surface triggering large enhancement of productivity (Extended Data Figure 7a-c). NPP is, in addition,
109 amplified by modifications of the hydrological cycle that create more favourable conditions related to changes in salinity, water temperature
110 and/or amount of solar radiation at the surface. At maximum precession and eccentricity, for example, higher sub-surface salinity (+0.5 to 1.6
111 psu) and lower temperatures (-1.2 to -2°C) in the western Bay of Bengal relative to in other simulations (Extended Data Figure 7c) reduce
112 stratification of the upper-water column, which favours vertical mixing and contributes to enhanced productivity. Overall, those localized
113 increases in the amplitude of the seasonal cycle lead to a less homogeneous upper ocean in the IPWP region at high eccentricity (Fig. 1 and
114 Extended Data Figure 5a-c). We propose that during high eccentricity times, the higher seasonal range of NPP in our model simulations is

115 indicative of more diverse ecological niches that coccolithophores can adapt to. A greater diversity of ecological niches when seasonality is
116 high²⁰ leads to a larger range of morphotypes because Noëlaerhabdaceae adaptation is characterised by the adjustment of coccolith size and
117 degree of calcification (therefore mass) to thrive in the new environments¹².

118

119 **Eccentricity lags, species origination, and dominance**

120 The MDI reflects periods of dominance of a particular species or morphotype, rather than species origination events, and is clearly modulated by
121 eccentricity. In stark contrast to most Pleistocene climate proxy records (e.g.^{14,18}), precession and obliquity cycles are absent from the high-
122 resolution MDI records (Extended Data Figure 3), suggesting that evolutionary processes smooth the records. Significant lags exist between
123 eccentricity forcing and coccolith morphology (Fig. 2b), which we hypothesize result from the time taken for favourable conditions to reoccur
124 that allow a species to rise to dominance following its first emergence. For example, *E. huxleyi* first appeared at 290 ka, but did not become
125 dominant until 90 ka¹⁵. Yet speciation events spread rapidly throughout the oceans^{15,17}, a phenomenon reflected in the small genetic diversity
126 amongst the global Noëlaerhabdaceae population¹⁰. This time lag could result from interspecific competition. When *E. huxleyi* originated,
127 *Gephyrocapsa oceanica* and *Gephyrocapsa ericsonii* already dominated coccolithophore assemblages, and the time required for *E. huxleyi* to
128 become widespread while favourable conditions persisted was not sufficient for it to become dominant. It was not until two e100 cycles later,
129 under similar eccentricity conditions, that *E. huxleyi* gained a competitive advantage and rose to dominance. The delay between species
130 appearance and dominance is thus intrinsic in the MDI record, acting as a low pass-filter with a cut-off frequency of 1/200 kyr⁻¹ (Fig. 2b,
131 Extended Data Figure 8). For other species, the lag might have been one or two e100 cycle, providing an explanation for the non-stationary
132 nature of the phase lag between e100 and MDI.

133

134 **Long-eccentricity forcing, coccolithophores, and the global carbon cycle**

135 The persistence of the long eccentricity cycle e405 in Cenozoic and Mesozoic records of the ocean carbon cycle (e.g., weight percent CaCO₃ and
136 foraminiferal $\delta^{13}\text{C}$)^{28,30}, independent of G-IG climate state, testifies to the importance of biogeochemical processes operating at this timescale
137 throughout Earth's history. In the Pleistocene, Mediterranean surface $\delta^{13}\text{C}$ records record e405 cycles more faithfully than deep open-ocean sites,
138 suggesting a low-latitude climatic origin of this signal²³. Similar to our coccolith records, a significant phase lag between $\delta^{13}\text{C}$ and eccentricity is
139 observed in the e405 band, which has been explained by the long residence time of carbon in the oceans and resultant transfer of energy from
140 precession into eccentricity bands via a non-linear process²⁸. Previous studies spanning up to ~1 Myr have linked coccolithophore production to
141 eccentricity forcing^{14,22}. However, the hypothesis proposed by Rickaby *et al.*²² that eccentricity-driven changes in growing season length may be
142 responsible for the ~400-kyr cycle in coccolithophore production cannot adequately explain changes reconstructed at our low latitude sites.
143 Instead, our data and model results lead us to the alternative hypothesis that changes in seasonality caused by the eccentricity of the Earth's orbit
144 paced tropical Noëlaerhabdaceae production and evolution throughout the Pleistocene. Although these changes clearly impact carbonate
145 accumulation patterns (Fig. 3), coccolithophore productivity alone cannot be responsible for the expression of long eccentricity cycles in climate
146 records. Other phytoplankton groups, some with little or no fossil record, must also have been influenced by variations in tropical seasonality on
147 these timescales. In this case, the impact of changes in the ratio of exported organic carbon production to carbonate mineral production, known
148 as the rain ratio³¹, may have been strong enough to modulate the carbon cycle. Our data, showing cyclic evolution of calcifying phytoplankton on
149 eccentricity timescales in response to seasonality, provide a new perspective in support of the hypothesis of Pälike *et al.*²⁸ that biosphere
150 productivity must have responded directly to changes in solar insolation in order to explain the strong e405 signature in carbon cycle records.

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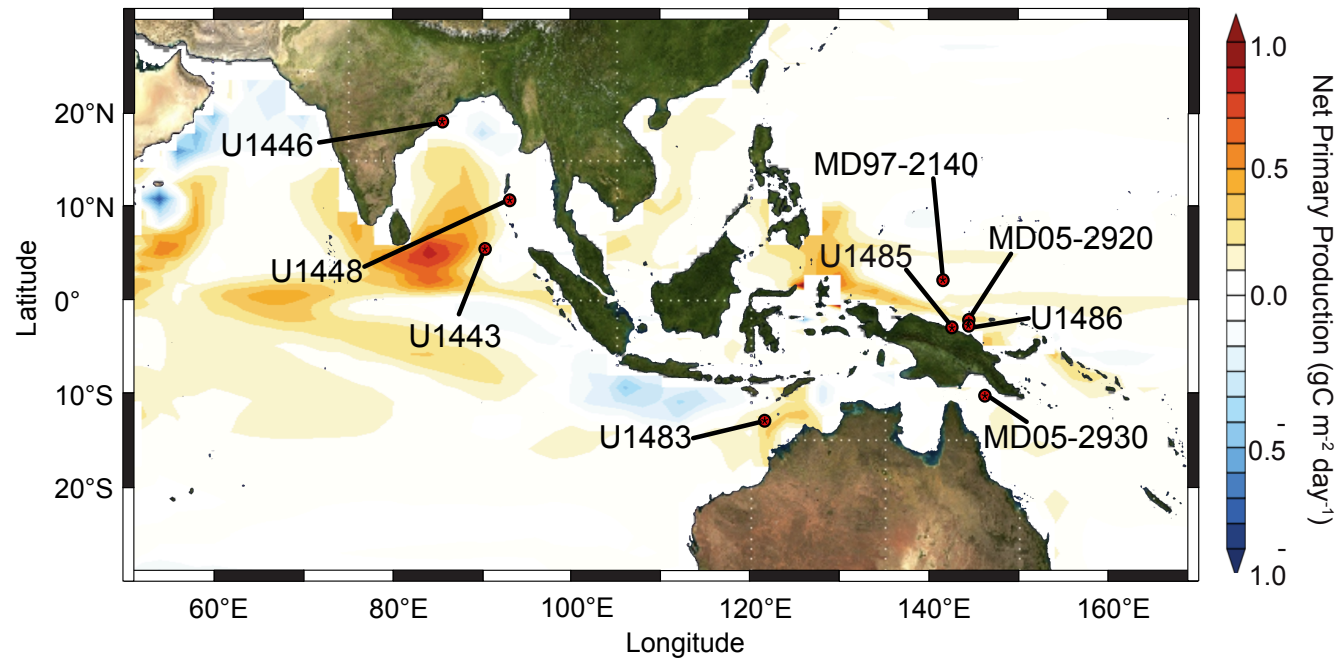
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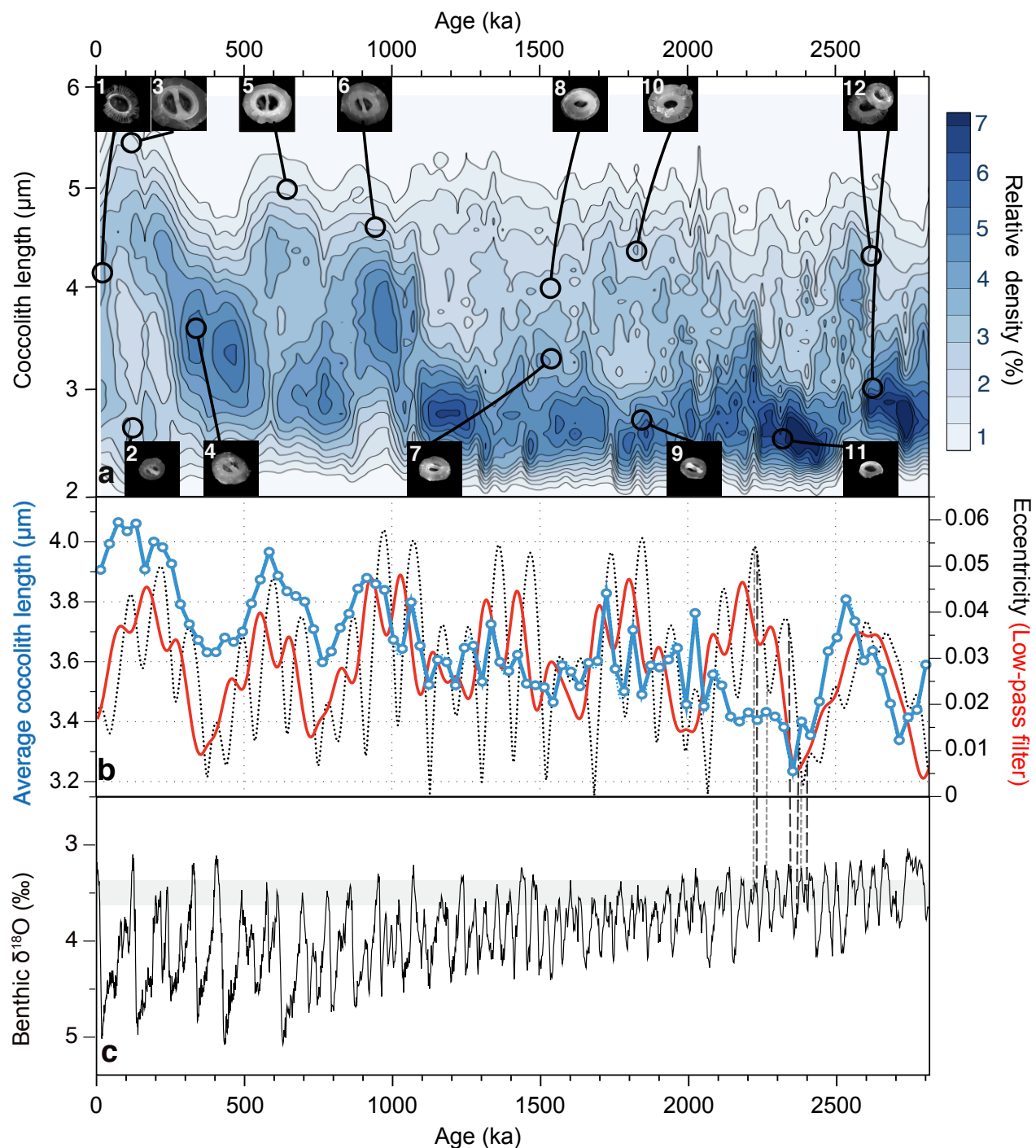
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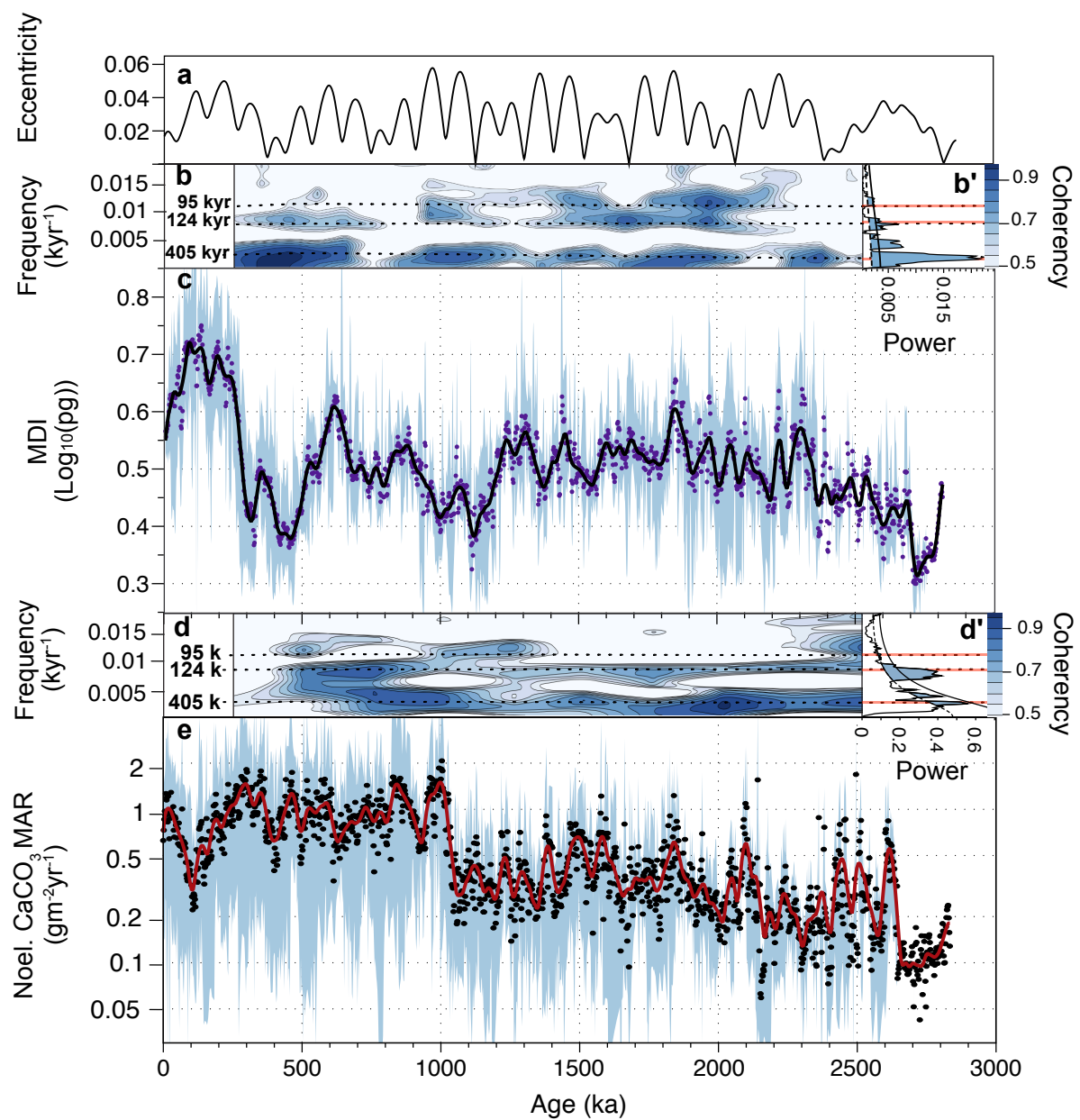
216 **Figure 1: Core site locations and eccentricity-driven changes in seasonality of primary production in the tropical Indo-Pacific.** Colour
 217 scale shows the vertically integrated net primary productivity difference between numerical model outputs computed at maximum and minimum
 218 eccentricity, each run at perihelion in June (Pmin) and December (Pmax) and then averaged (see Methods). Red (blue) colours imply higher
 219 (lower) seasonality at high eccentricity compared to low eccentricity.

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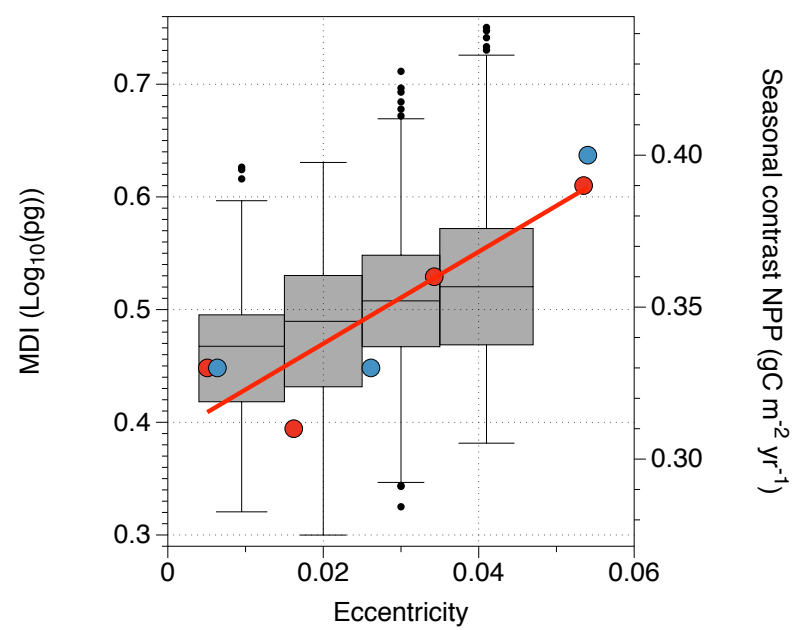
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222 **Figure 2: Cocolith size variability over the last 2.8 million years.** a: Evolutionary histogram of coccolith length. Samples in each core were
 223 grouped into 30 kyr bins, standardised (%) and merged into a single stack (see Methods). Length bins are $0.1 \mu\text{m}$. Scanning electron microscope
 224 images represent typical Noëlaerhabdaceae morphologies. 1: *Emiliana huxleyi*, 2: *Gephyrocapsa ericsonii*, 3: *Gephyrocapsa oceanica*, 4:
 225 *Gephyrocapsa caribbeanica*, 5-6: *Gephyrocapsa omega*, 7-8: mid-size *Gephyrocapsa*, 9: small *Gephyrocapsa*, 10: *Pseudoemiliana ovata*, 11:
 226 *Reticulofenestra minuta*, 12: left: *P. ovata*, right: *Reticulofenestra minutula*. b: Average length (blue) of coccoliths in the multi-site stack, plotted
 227 with Earth's eccentricity⁹ (dotted black line) and low-pass filtered eccentricity with an angular frequency of 0.021 kyr^{-1} (red) and average
 228 coccolith length detrended (blue). c: LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸. Vertical dashed lines between panels b and c show orbital
 229 configurations used in model simulations (black long dash = Pmin, grey short dash = Pmax; see Methods). Grey band in c illustrates the small
 230 range of benthic $\delta^{18}\text{O}$ between simulations.



231

232 **Figure 3: Eccentricity, coccolith morphological divergence, and Noëlaerhabdaceae CaCO₃ mass accumulation rates.** a: Earth's
 233 eccentricity¹⁹, b: Evolutive cross-spectral analysis between MDI and eccentricity (see Methods). Colour-scale shows coherency (90% Confidence
 234 Level (CL) above 0.7); Horizontal dashed lines show eccentricity periods. b': MTM spectral analysis of detrended MDI stack. Shaded areas are
 235 above the 90%CL (dashed line). Solid black line is 95%CL. Frequency scale is aligned with b. c: MDI Stack (2 kyr resolution, see Methods).
 236 Blue shading shows maximum and minimum values from all records. d: Evolutive cross-spectral analysis between MAR and MDI (CLs as in b).
 237 d': MTM spectral analysis of detrended MAR stack. CLs as in b'. e: Noëlaerhabdaceae CaCO₃ MAR stack (2 kyr resolution, see Methods). Blue
 238 shading shows maximum and minimum values from all records. MDI and MAR stacks are smoothed with a LOESS function.



239

240 **Figure 4: Morphological divergence index and modelled seasonality both increase with eccentricity.** Box-whiskers plot of all MDI values,
 241 sorted and binned by increasing low-pass filtered eccentricity, compared to the seasonal contrast of net primary production (maximum minus
 242 minimum month) from numerical simulations (see Methods). Blue dots are model runs with perihelion in December (Pmax: 2222 ka, 2265 ka,
 243 and 2380 ka), red dots are runs with perihelion in June (Pmin: 2230 ka, 2346 ka, 2369 ka, and 2395 ka) – illustrating that eccentricity has a much
 244 larger effect on seasonality than precession at a given eccentricity.

245 **Methods**

246 **Coccolith data acquisition**

247 Over eight thousand samples were extracted from sediment cores for coccolithophore analysis at depth intervals to achieve a high stratigraphic
248 resolution (0.5 to 2.3 kyr, Extended Data Table 1). Samples were prepared using the settling method^{32,33}: sediments were disaggregated in water
249 and suspensions were settled onto a 12x12 mm cover slip and mounted with Norland Optical Adhesive 74, with 8 cover slips per microscope
250 slide. Some samples were prepared as independent duplicates. Two slides (16 samples) were placed at the same time onto the stage of an
251 automated polarizing microscope (Leica DM6000). Following auto-focusing, 165 contiguous fields of view (with an area of 125 x 125 μm each)
252 were imaged in each sample using a black and white SPOTFLEX camera (Diagnostic Instrument). SYRACO, a software program based on an
253 Artificial Neural Network³⁴, identified all specimens belonging to 33 groups of coccolithophore taxa in the images³⁵. The gephyrocapsid
254 specimens, the dominant group studied here, were classified into six distinct classes that were merged into one group. On average, 888
255 Noëlaerhabdaceae coccoliths were identified in each sample. Among other morphometric parameters, size and mass of the coccoliths were
256 measured. Coccolith mass is measured using birefringence, following published state-of-the-art methods^{33,36}. The use of Artificial Intelligence in
257 this type of work is essential because it is the only way to measure such a large number of specimens (>7 million) in a reasonable time, and thus
258 obtain the high-resolution multi-site records required for this study.

259

260 **Site-specific chronologies**

261 **IMAGES core MD97-2140³⁷**: The age model for Site MD97-2140³⁷, on the Eauripik Rise in the Western Pacific Warm Pool, is based on tuning
262 of a high-resolution planktonic foraminiferal *Globigeronoides ruber* $\delta^{18}\text{O}$ record to the astronomically calibrated ODP Site 677 $\delta^{18}\text{O}$ *G. ruber*
263 record³⁸, located in the eastern equatorial Pacific. This age model yields a chronology consistent with major micropaleontological (disappearance
264 of *G. ruber* pink variety) and palaeomagnetic (Brunhes–Matuyama boundary) events³⁹.

265 **IMAGES core MD05-2920⁴⁰**: The age model for Site MD05-2920⁴⁰, on the southern bank of Manus Island, is based on ten Accelerator Mass
266 Spectrometer (AMS) ^{14}C dates obtained from the surface-dwelling planktonic foraminifera *G. ruber* (white), and a correlation between the
267 benthic foraminiferal $\delta^{18}\text{O}$ record and the reference LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸.

268 **IMAGES core MD05-2930⁴¹**: The age model for Site MD05-2930⁴¹, in the Coral Sea, is based on ten AMS ^{14}C measurements of *G. ruber sensu*
269 *stricto* (*ss*), and on correlation of the MD05-2930 $\delta^{18}\text{O}$ *G. ruber ss* record with the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸.

270 **IODP Site U1443⁴³**: The age model for Site U1443, on the Ninetyeast Ridge in the southernmost Bay of Bengal, is based on correlation of
271 physical properties data on the primary shipboard splice to the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸. Physical properties were measured
272 onboard the RV *Joides Resolution* on archive halves from all holes at Site U1443, and correlation and splicing were based on magnetic
273 susceptibility, natural gamma ray, and reflectance spectroscopy b^* data⁴⁴.

274 **IODP Site U1448⁴³**: The age model for Site U1448, in the Andaman Sea, is based on correlation of the Site U1448 Ti/Ca record, derived by X-
275 Ray Fluorescence (XRF) core scanning, to the XRF Ti/Ca record of Indian National Gas Hydrate Program (NGHP) Site 17 – a very close site
276 with age control based on a benthic foraminiferal oxygen isotope record tuned to the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack^{18,45,46}.

277 **IODP Site U1446⁴³**: The age model for Mahanadi Basin Site U1446 is based on correlation of a high-resolution benthic foraminiferal oxygen
278 isotope stratigraphy to the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸ (S.C. Clemens, unpublished data, pers. comm.)

279 **IODP Site U1483⁴⁷**: The age model for Scott Plateau Site U1483 is based on the shipboard integrated Magneto-biostratigraphy, and on
280 correlation of the U1483 L^* record, which presents strong G/IG variability, to the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸.

281

282 **IODP Site U1485**⁷⁷: The age model of the northern Papua Margin Site U1485 is based on correlation between the benthic foraminiferal $\delta^{18}\text{O}$
283 record of this site and the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸.

284 **IODP Site U1486**⁷⁷: The age model of the upper 100 m (the last 1.6 Ma) of Site U1486, from the southern bank of Manus Island, is based on a
285 correlation between the benthic foraminiferal $\delta^{18}\text{O}$ record and the LR04 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸. Below 100 m, the age model is based
286 on the shipboard integrated magneto-biostratigraphy and correlation of the U1486 L* record (that shows strong G/IG variability) with the LR04
287 benthic foraminiferal $\delta^{18}\text{O}$ stack¹⁸.

288

289 **Construction of composite histograms of coccolith size and mass**

290 The distribution of coccolith mass values is skewed toward heavy values. We therefore used the logarithm of the mass to obtain a symmetrical
291 mass distribution. Measurements were grouped into morphological bins of $0.1\ \mu\text{m}$ for coccolith length and $0.05\ \log_{10}(\text{pg})$ for coccolith mass in
292 every sample. Samples were binned into 30-kyr time windows in each core, chosen such that it is larger than the length of a precession cycle
293 (23-19 kyr). This will prevent any bias in the size/mass distribution resulting from changes in the relative abundance of large versus small
294 geophycosid species on precessional timescales⁸⁸. Another advantage of using a 30 kyr time window is that the high number of measurements
295 included in each 30 kyr bin (on average 16650 measurements) make it extremely precise but easier to discern trends. To standardise each time
296 window at each site, the numbers contained in each bin are divided by the total number of coccoliths in that time window and multiplied by 100.
297 To stack the records and produce evolutionary size histograms (Fig. 2a) and mass, all records are summed by bin and divided by the number of
298 records.

299

300 **Morphological Divergence Index (MDI)**

301 In each sample, individual coccoliths were divided into two size classes: coccoliths longer and shorter than $3\ \mu\text{m}$. The average $\log_{10}(\text{mass})$ is
302 calculated in both classes. MDI is the difference between the two averages (Extended Data Figure 2). The size of $3\ \mu\text{m}$ corresponds to the best
303 cut-off value between the two modes (2.8 and $3.9\ \mu\text{m}$) of the size distribution. Other size cut-offs were tested (2.9 , 3.25 and $3.5\ \mu\text{m}$) without
304 notable differences in the resulting MDI values and temporal trends. The records are resampled (by linear integration) at 2 kyr intervals for
305 further analysis (time series, statistics, and stacking). A stacked record composed of all records is calculated for each time window. This stacked
306 MDI reflects the variability seen in all individual records (Extended Data Figure 4). Because not all records cover the entire 2.8 Myr interval (3
307 records are over 2.3 Myr long, 3 are between 0.7 and 1.8 Myr long, and 3 are 0.4-0.6 Myr long), the stack is composed of more records in the
308 younger part than in the older part. Because of the phase lag between MDI and eccentricity we use band-passed eccentricity (red line in Fig. 2b)
309 to sort and bin DMI values used for Fig. 4.

310

311 **Mass accumulation rates**

312 Mass accumulation rates of Noëlaerhabdaceae coccoliths were estimated in seven cores (all cores excluding MD05-2530 and U1446) for which
313 a quantitative sample preparation technique was applied⁸³: The samples were prepared by settling onto coverslips that were weighed before and
314 after settling, the weight difference providing the amount of sediment deposited. The number and the mass of the Noëlaerhabdaceae is estimated
315 by SYRACO. From these quantities it is possible to estimate the weight of Noëlaerhabdaceae per gram of sediment. Noëlaerhabdaceae CaCO_3
316 MAR (only called MAR hereafter) is obtained by multiplying weight per gram by the sedimentation rate and the dry bulk density of sediment.
317 The dry bulk density was estimated from continuous measurements of wet bulk density from gamma ray attenuation (GRAPE) and transformed
318 by the linear relationship for each site between discrete shipboard measurements of wet bulk density and dry bulk density⁸⁹. MARs for the 7 cores
319 were stacked together after resampling each record at 2 kyr intervals (Fig. 3e), using the same method as for MDI. Other stacking methods, such

320 as assembling LOESS-detrended records, were tried and produced consistent results. Differences exist between individual MAR records due to
 321 regional difference in coccolithophore productivity, export dynamics, and preservation (although only 2 cores, MD97-2140 and U1443, were
 322 retrieved from sediments deeper than 2000 m). However, three common patterns emerge in all individual records: an increasing trend in MAR
 323 towards the present, a sharp stepwise increase at ~1 Ma, and the clear presence of eccentricity cycles. Noëlaerhabdaceae coccolith flux
 324 (Extended Data Figure 5c) is calculated as the number of coccoliths per gram of sediment multiplied by the sedimentation rate.

325

326 **Time series analysis**

327 Time series analyses were performed using the software packages Analyseries⁵⁰ and Acycle⁵¹ on detrended records. Cross-spectral analyses were
 328 performed in Analyseries using Blackman-Turkey transforms⁵². For evolutive analyses (Fig. 3) a window of 500 kyr (250 data points) and a step
 329 of 100 kyr was used. Coherence values above 0.56 are above the 80% confidence level (Fig. 2b). Spectral analyses were performed with the
 330 Multi Taper Method (MTM)⁵³ with both evolutive and entire series (Extended Data Figure 1). Spectral properties are similar in all individual
 331 MDI records, and show that the absence of precession (19-23 kyr) and obliquity (~41 kyr) is not a result of chronological bias in constructing the
 332 stack that would have smoothed the record. Each record has a ~2 kyr resolution with a precise independent age model. The absence of precession
 333 and obliquity is therefore a common and robust feature of all of the MDI series as well as the stacked record.

334

335 **Low-pass filters**

336 We designed 2nd order low-pass filters in order to reproduce the effect of the time needed for a new evolved species to fully succeed (200 kyr for
 337 *E. huxleyi*). We transformed the following classical low-pass filter complex transfer function H :

$$338 \quad H(j\omega) = \frac{A}{1 + \frac{j\omega}{Q\omega_0} + \frac{\omega^2}{\omega_0^2}}$$

339 (where A is the amplitude, Q is the quality factor, ω is the angular frequency $2\pi f$, (f the frequency)) in its associated differential equation:

$$340 \quad \frac{d^2y}{dt^2} + \frac{\omega_0}{Q} \frac{dy}{dt} + \omega_0^2 y = \omega_0^2 x \quad \text{where } y \text{ is the output series and } x \text{ the input series.}$$

341 We solved it numerically as follow:

$$342 \quad y_t = \frac{1}{1 + \frac{\omega_0}{Q} + \omega_0^2} ((2 + \omega_0)y_{t-1} - y_{t-2}) A \omega_0^2 x_t$$

343 Two configurations have been chosen: one produces a delay of 200 kyr for the new species' success, the second produces a delay of 130 kyr
 344 (Extended Data Figure 8a). To obtain those delays, we used the following values:

345 First case (delay of 200 kyr), $\omega_0 = 0.021$, $Q = 1$, $A = 1$

346 Second case (delay of 130 kyr), $\omega_0 = 0.035$, $Q = 1.02$, $A = 0.65$

347 The delay of 200 kyr corresponds to the time between the First Appearance Datum (FAD) and the beginning of the acme (BA) of *E. huxleyi*¹⁷.

348 The FAD of this species is well documented because its characteristic T shape elements are a morphological feature that appeared suddenly,

349 without gradation. The other *Gephyrocapsa* species have been described using criteria that are subject to gradation between species: coccolith

350 length, size of the central opening, and orientation of the bridge⁵⁴. For example, the FAD of a typical *G. ercisonii*, (a small gephyrocapsid) that

351 appeared at about the same time as *E. huxleyi*³ is not reported precisely because it evolved progressively from *G. caribbeanica* (a mid-size

352 species). It is interesting to note that the FAD and the BA of *E. huxleyi* occurred similarly in times of eccentricity decrease, but two cycles apart.

353 The intermediate cycle may have been too high to allow *E. huxleyi* to begin its dominance. This may not have been the case for other species

354 under different orbital configurations. This is why we did a filter with a different configuration, which produces a delay of about one eccentricity

355 cycle between a FAD and a BA. In order to express the response of those filters, we built their Bode magnitude plots, expressing the frequency
356 response, and their Bode phase plots, expressing the phase shift (Extended Data Figure 8b, c).

357

358 **Model Description**

359 To simulate changes in Net Primary Production (NPP) related to changes in eccentricity we used the Earth System Model IPSL-CM5A2⁵ that
360 simulates the interactions between ocean, atmosphere, land and ice. The following section provides a brief description of model components and
361 experiments setup. We then describe the model behaviour at low eccentricity and discuss how the large-scale ocean-atmosphere circulation at
362 high eccentricity in our simulations compare to previous modelling studies.

363

364 The IPSL-CM5A2 coupled model is a combination of the LMDz5A atmospheric model⁵⁵, the ORCHIDEE⁵⁶ land surface model and the
365 NEMOv3.6 oceanic model⁵⁷. The NEMO model includes an ocean dynamic component (OPA⁵⁸), a sea-ice thermodynamics model (LIM2⁵⁹) as
366 well as a biogeochemistry model (PISCES-v2⁶) and has an horizontal resolution of 2° by 2° (refined to 0.5° in the tropics) and 31 vertical levels,
367 whose thickness increases from 10 m at the surface to 500 m at the bottom. The atmospheric grid has a horizontal resolution of 1.875° in latitude
368 by 3.75° in longitude with 39 vertical levels. The ocean-atmosphere coupling is ensured by the OASIS coupler⁶⁰ that interpolates and exchange
369 variables between the two components. Detailed description of IPSL-CM5A2 and performances in simulating pre-industrial climate can be
370 found in references 61,62. PISCES-v2 simulates the main oceanic biogeochemical cycles (C, P, Si, N and Fe) and has a simple representation of
371 the lower trophic levels of the marine ecosystem⁶, with two phytoplankton (nannophytoplankton and diatoms) and two zooplankton (micro- and
372 meso-zooplankton) size classes and five limiting nutrients (Fe, NO₃⁻, NH₄⁺, Si and PO₄³⁻). Phytoplankton growth is controlled by nutrients, light
373 availability, and water temperature. In the version of the model we used, river supply to the ocean of all elements apart from DIC and alkalinity
374 is taken from the GLOBAL-NEWS2 data sets⁶³ and does not vary from one simulation to another. Model parameterizations are detailed in
375 reference 6.

376

377 Simulations were performed for seven early Pleistocene time slices and differ only by their respective orbital parameters (Extended Data Table
378 2, Figure 2). The time slices were chosen in order to target the signal produced by the 405-kyr eccentricity cycle. Land-sea mask, ice-sheets
379 configuration as well as CO₂ and other greenhouse gases concentrations are set at pre-industrial values. Each simulation was started from the
380 same equilibrated pre-industrial simulation⁶² and was run for 500 years. NPP is integrated over the whole water-column and averaged over the
381 last 100 model years.

382

383 At low eccentricity (EminPmax and EminPmin) the eastern Indian ocean surface dynamics is forced by the summer westerlies that blow
384 northward over the Bay of Bengal (Extended Data Figure 6f), associated with high precipitation over India and the Himalayan foreland region,
385 while strong easterlies are recorded south of the equator. Winds force strong westward surface currents along the equator and south of Sumatra
386 Island that generate upwelling (Extended Data Figure 7b). The latter advects nutrients to the surface (Extended Data Figure 7a) and triggers high
387 productivity during summer. This peak productivity contributes to the strong seasonal cycle in this region. The winds reverse during boreal
388 winter, triggering a second productivity bloom of lesser intensity (not shown). The productivity minimum is recorded during late spring when
389 low-level winds along the equator are weak westerlies that favour downwelling and prevent strong convective mixing, which results in lower
390 nutrient content within the surface layer of the ocean. The seasonal cycle of productivity in this region is very similar to the cycle simulated for
391 the present-day EIO⁶.

392

393 At high eccentricity, the simulated patterns of atmosphere-ocean circulation and surface ocean physical state (Extended Data Figure 6g-j and 8b,
394 c) are in line with previous modelling study under similar orbital configurations⁶⁵⁻⁶⁷. In addition, our simulations also illustrate how these changes
395 impact the seasonal productivity cycle. The increasing amplitude of the seasonal cycle in the surface ocean at high eccentricity is probably not
396 limited to the IPWP area. For example, Erb *et al.*⁶⁸ also simulate enhancement of the surface ocean temperature cycle at high eccentricity in the
397 Eastern Equatorial Pacific, with higher amplitude than in the Western Equatorial Pacific.

398

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477

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485

486 **Author Contributions**

487 LB designed the study. LB, YG, NB and MT developed automated artificial intelligence methods. LB, CTB, JCM, PC, EG, and SB prepared
488 samples and/or generated data. ACS designed and ran the model simulations, in collaboration with YD. LB and CTB analysed the morphometric
489 data. LB, CTB, ACS, BSM, YD, and YR discussed interpretations. LB, CTB and ACS wrote the manuscript with important contributions from
490 BSM, YD, and YR.

491

492 **Additional Information**

493 Correspondence and requests for materials should be addressed to Luc Beaufort (beaufort@cerege.fr). Reprints and permissions information is
494 available at www.nature.com/reprints.

495

496 **Competing interest declaration**

497 The authors declare no competing interests.

Site	Expedition	Longitude	Latitude	Water Depth (m)	Biome	Record length (kyr)	Mean Resolution (kyr)	Number of samples	Number of Measurements
U1446	IODP 353	85°441	19°050 N	1440	INDE	468	0.5	952	222 119
U1448	IODP 353	93°00.00	10°38.03 N	1096	MONS	716	1.1	624	617 138
U1443	IODP 353	90°21.71	5°23.01 N	2940	MONS	2818	1.6	1717	1 337 793
MD97-2140	IMAGES 3	141°45.49	2°02.59 N	2547	WAR M	1758	1.4	1241	540 523
U1486	IODP 363	144°36.08	2°22.34 S	1332	WAR M	2661	2.2	1195	1 004 860
MD05-2920	IMAGES 13	144°32	2°51.48 S	1843	WAR M	387	1.1	353	436 984
U1485	IODP 363	142°47.59	3°06.16 S	1145	SUND	535	0.9	587	580 612
MD05-2930	IMAGES 13	146°15.73	10°25.30 S	1490	AUSE	793	2.1	372	620 736
U1483	IODP 363	121°5.24	13°05.24 S	1733	ISSG	2332	2.3	994	1 777 406
							Average = 1.6	Sum =8035	Sum=7 138 171

499

500 **Extended Data Table 1:** Characteristics of the nine marine records used in this study. Biome codes³⁰: INDE = Eastern India Coastal province,
501 MONS = Indian Monsoon Gyres Province, WARM = Western Pacific Warm Pool province, SUND = Sunda-Arafura Shelves Province, AUSE =
502 East Australian Coastal Province, ISSG = Indian South Subtropical Gyre Province. These cores were retrieved during four expeditions:
503 IMAGES 3³⁹ and 13⁴⁰, and International Ocean Discovery Program (IODP) Expeditions 353⁴¹ and 363⁴⁷, which took place in the Western Pacific
504 and Indian Tropical Oceans (Figure 1).

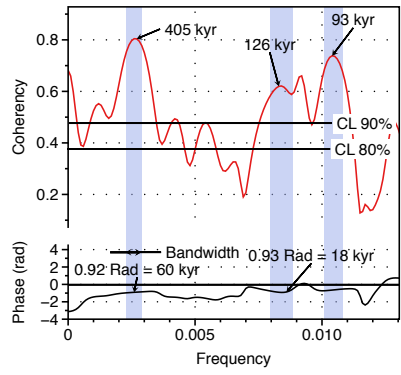
505

Configuration (kyr)	Eccentricity	Precession	Longitude of perihelion (°)	Obliquity (°)	Mean YCR at Equator (W.m ⁻²)
C2222 (E _{max} P _{max})	0.054	0.054	87	23.73	74
C2230 (E _{max} P _{min})	0.053	-0.037	315	23.84	83
C2265	0.026	0.024	115	24.28	59
C2346	0.034	-0.033	287	24.27	62
C2369	0.016	-0.015	256	22.26	52
C2380 (E _{min} P _{max})	0.006	0.006	77	23.74	37
C2395 (E _{min} P _{min})	0.005	-0.003	310	23.42	39

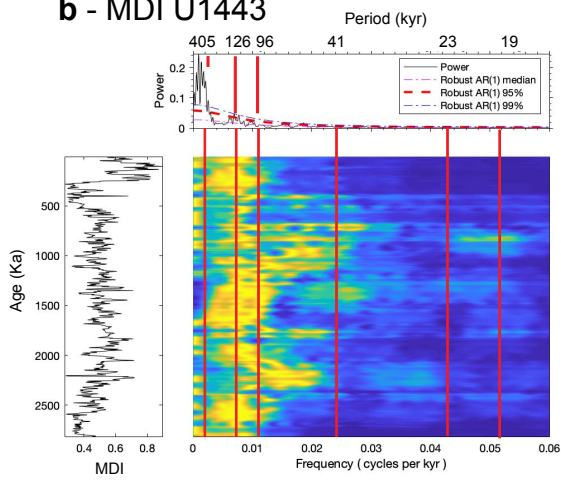
506

507 **Extended Data Table 2:** Summary of orbital parameters¹⁹ used for each simulation and Mean Yearly Contrast of Radiation at Equator (Wm⁻²)
508 derived from IPSL-CM5A2 (see Methods).

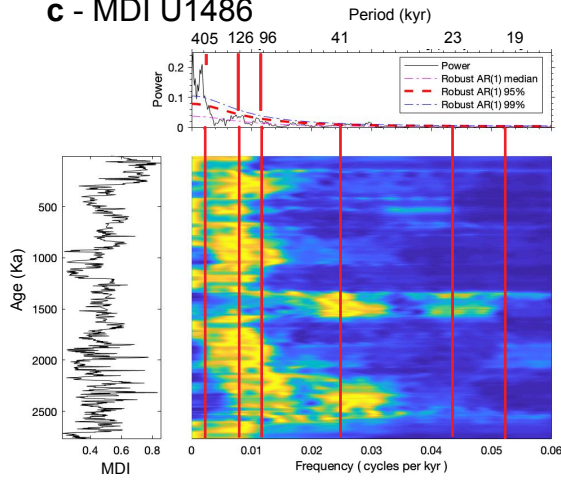
a - Cross BT : Ecc. vs Size stack



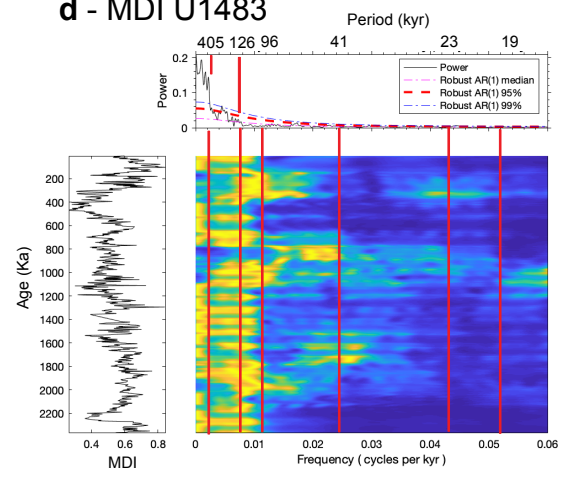
b - MDI U1443



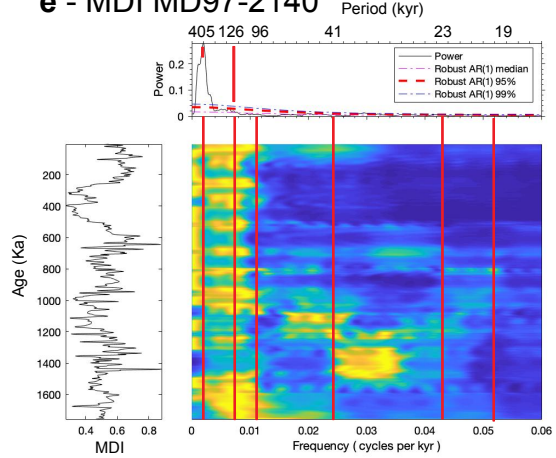
c - MDI U1486



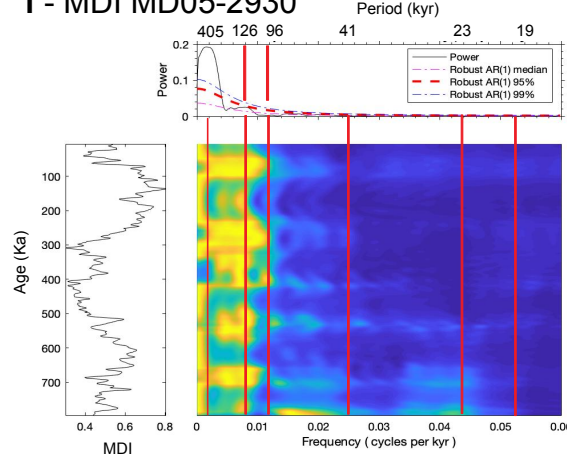
d - MDI U1483



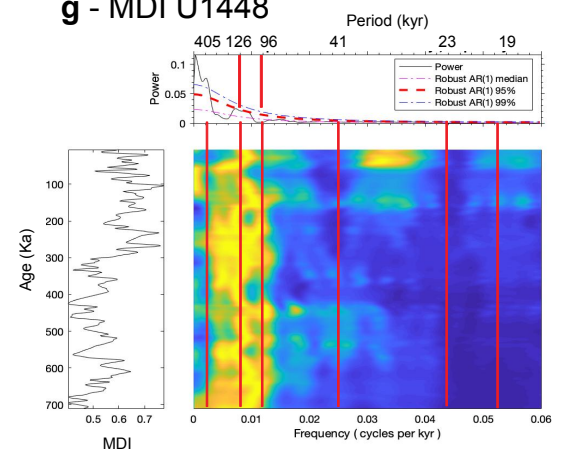
e - MDI MD97-2140



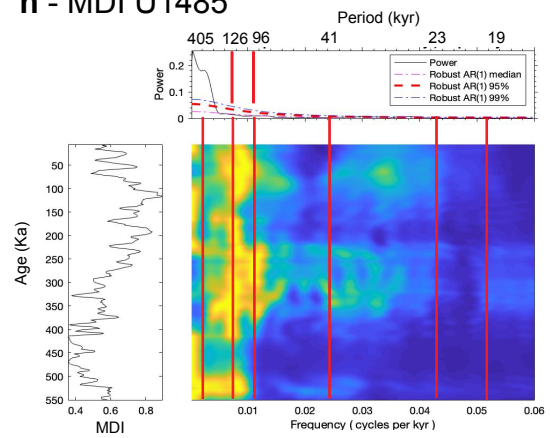
f - MDI MD05-2930



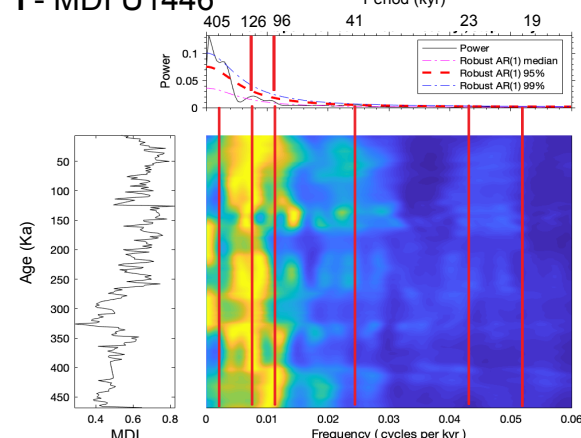
g - MDI U1448



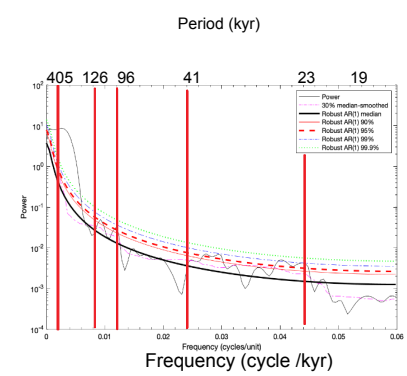
h - MDI U1485



i - MDI U1446

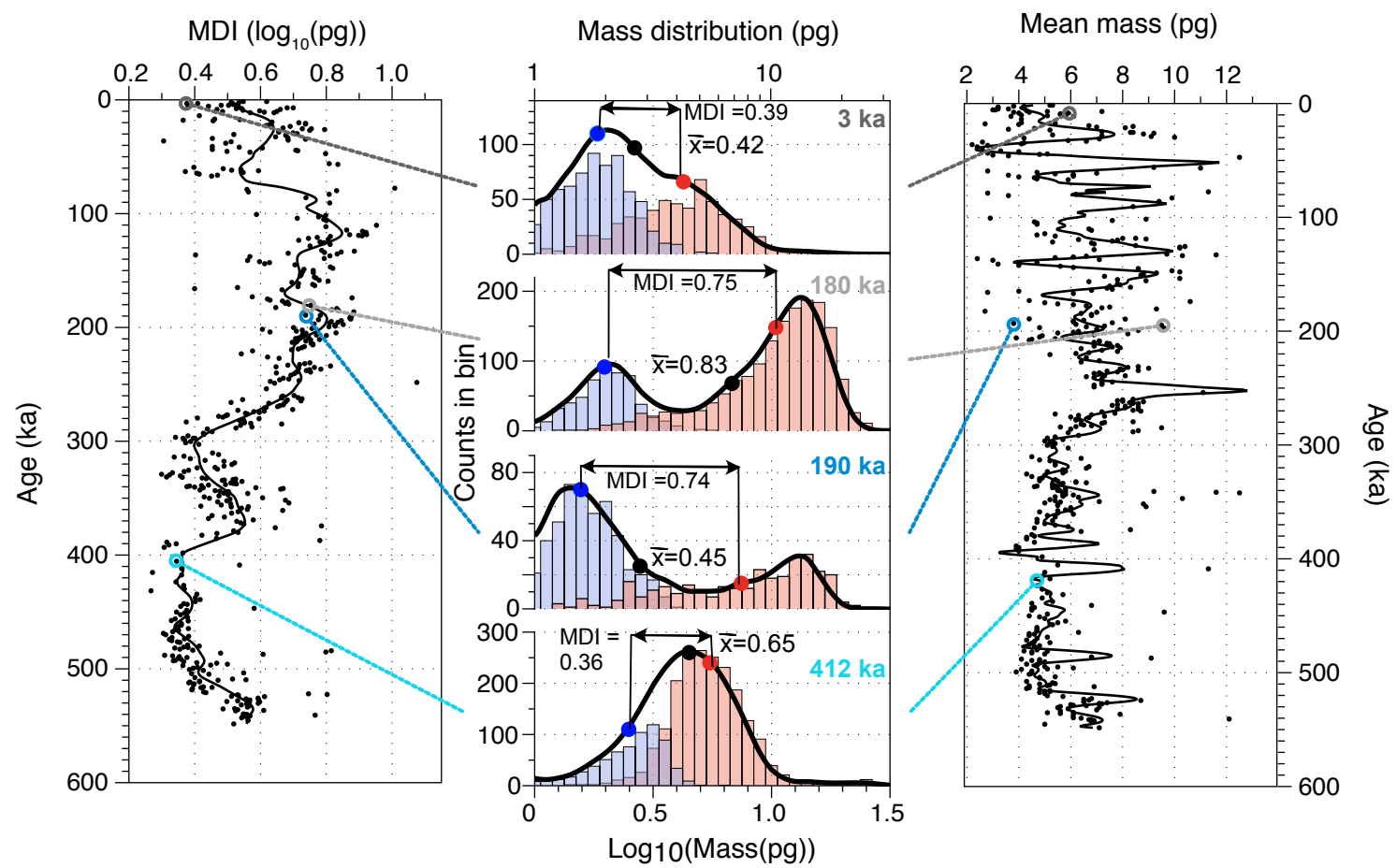


j - MDI MD05-2920



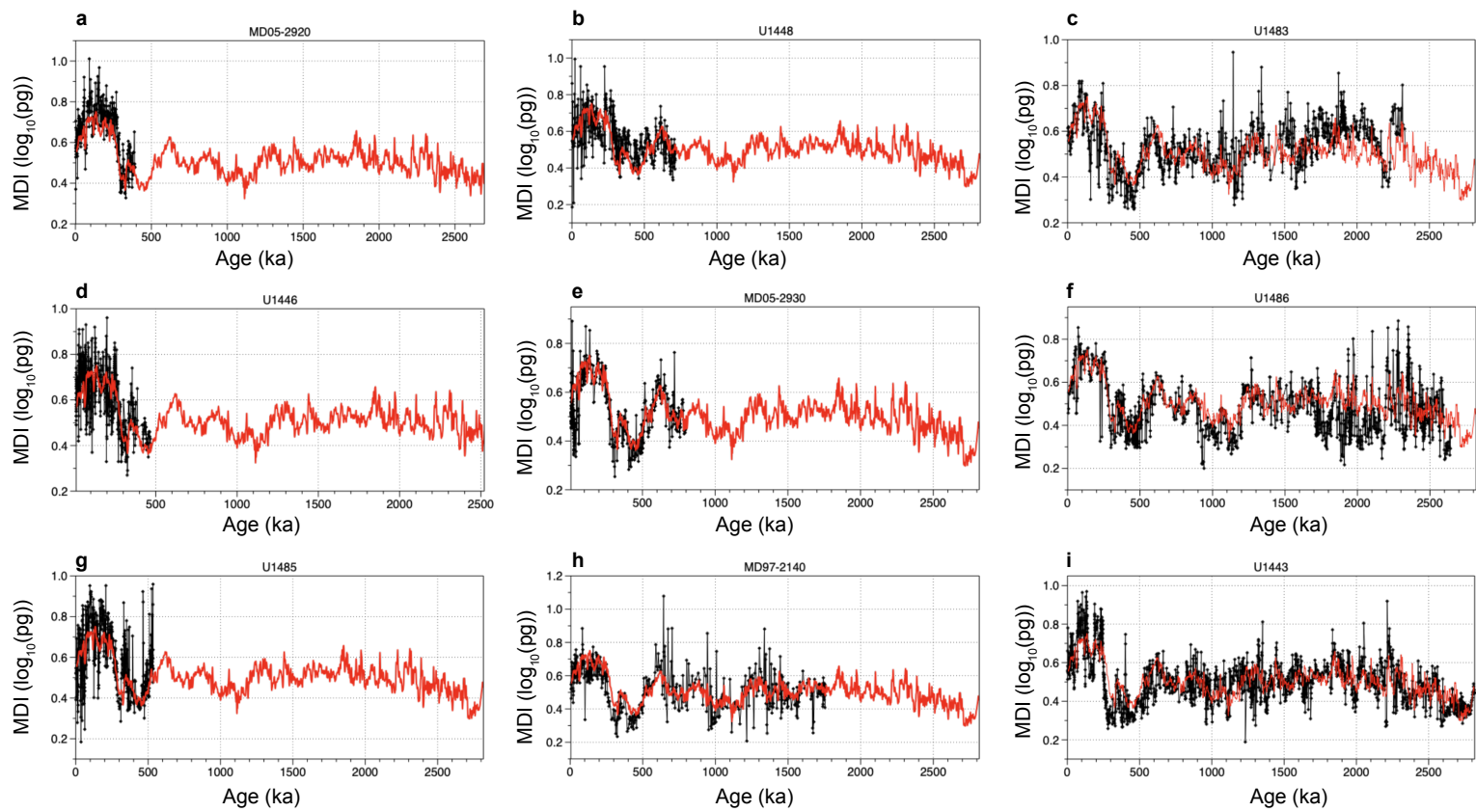
509

510 **Extended Data Figure 1:** a: Cross-spectral analysis between eccentricity and stacked average coccolith length. Top: coherence; Bottom: phase
 511 (radian). **b to j:** MTM and evulsive spectral analyses (see Methods) of detrended individual MDI series resampled at 2 kyr intervals (shown on
 512 left of each evulsive analysis. Primary orbital periods are shown by red lines.



513

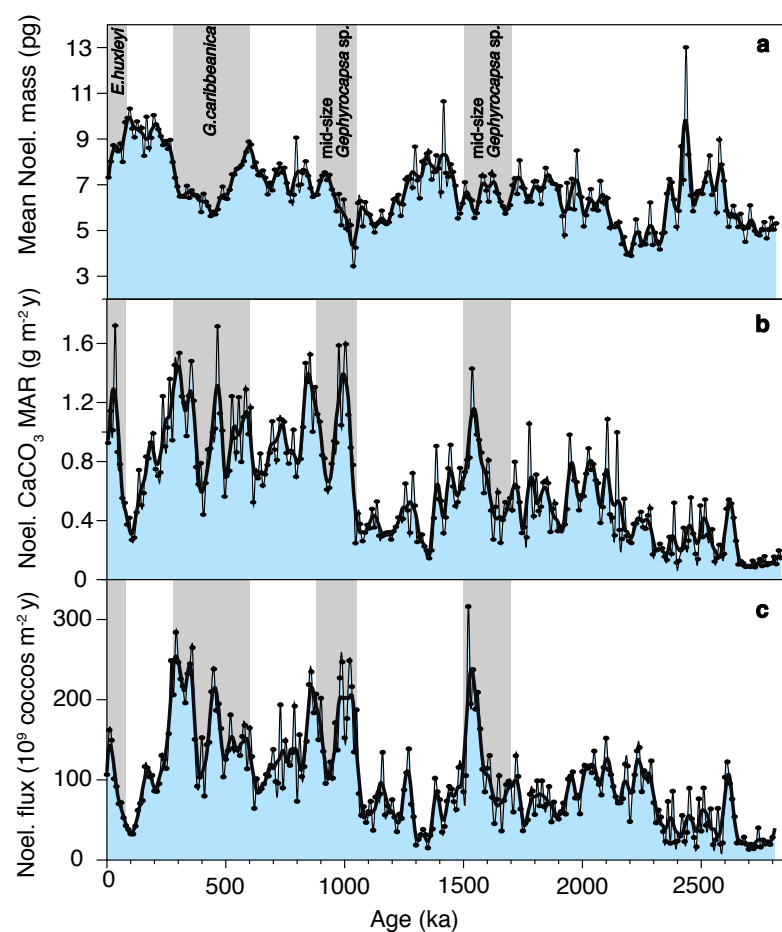
514 **Extended Data Figure 2:** Schematic illustrating how MDI is calculated (also see Methods), and how it represents morphological diversity,
 515 using data from Site U1485 as an example. In each sample, two size classes are created: coccoliths shorter and longer than $3 \mu\text{m}$ (blue and red
 516 histograms). The average $\log(\text{mass})$ is calculated in both classes (blue and red dots on the histograms). MDI is the difference between these two
 517 averages. Thus, MDI can differ substantially from average coccolith mass of the whole population (black dots on mass distribution plots), and
 518 two samples can have a similar MDI but very different average mass and mass distributions (e.g., examples at 180 ka and 190 ka), or very
 519 different MDI but similar averages (e.g., 3 ka vs 190 ka). In this way, MDI isolates morphology variability that results from evolutionary
 520 contractions and dilations in the number of different morphotypes present within the population.



521

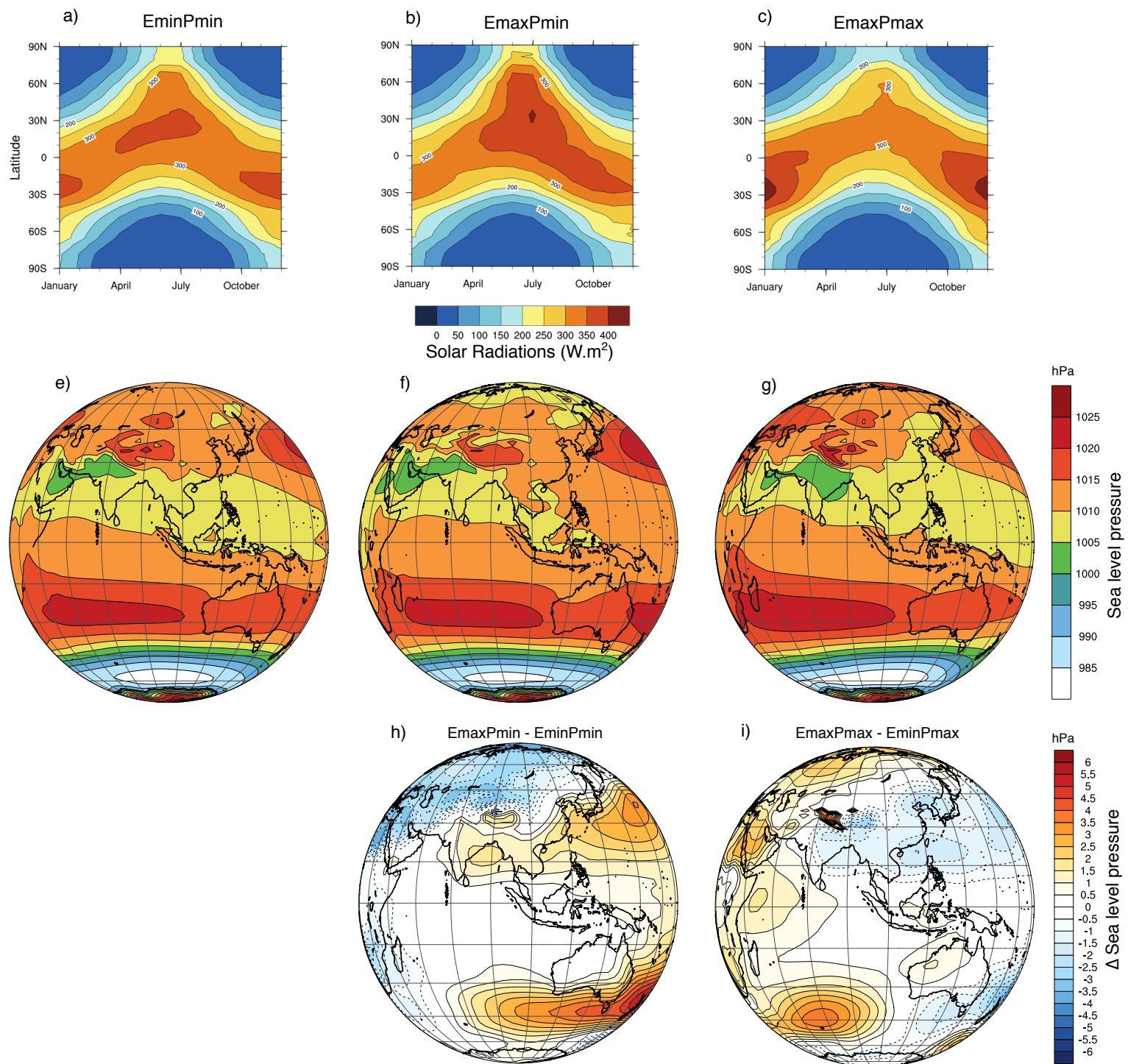
522 **Extended Data Figure 3:** Individual MDI records for each site (black lines and points) plotted with the stacked MDI record (red line). Pearson
 523 correlation coefficients between individual sites and the stack vary between 0.71 and 0.93 (p-values are all <0.00001).

524



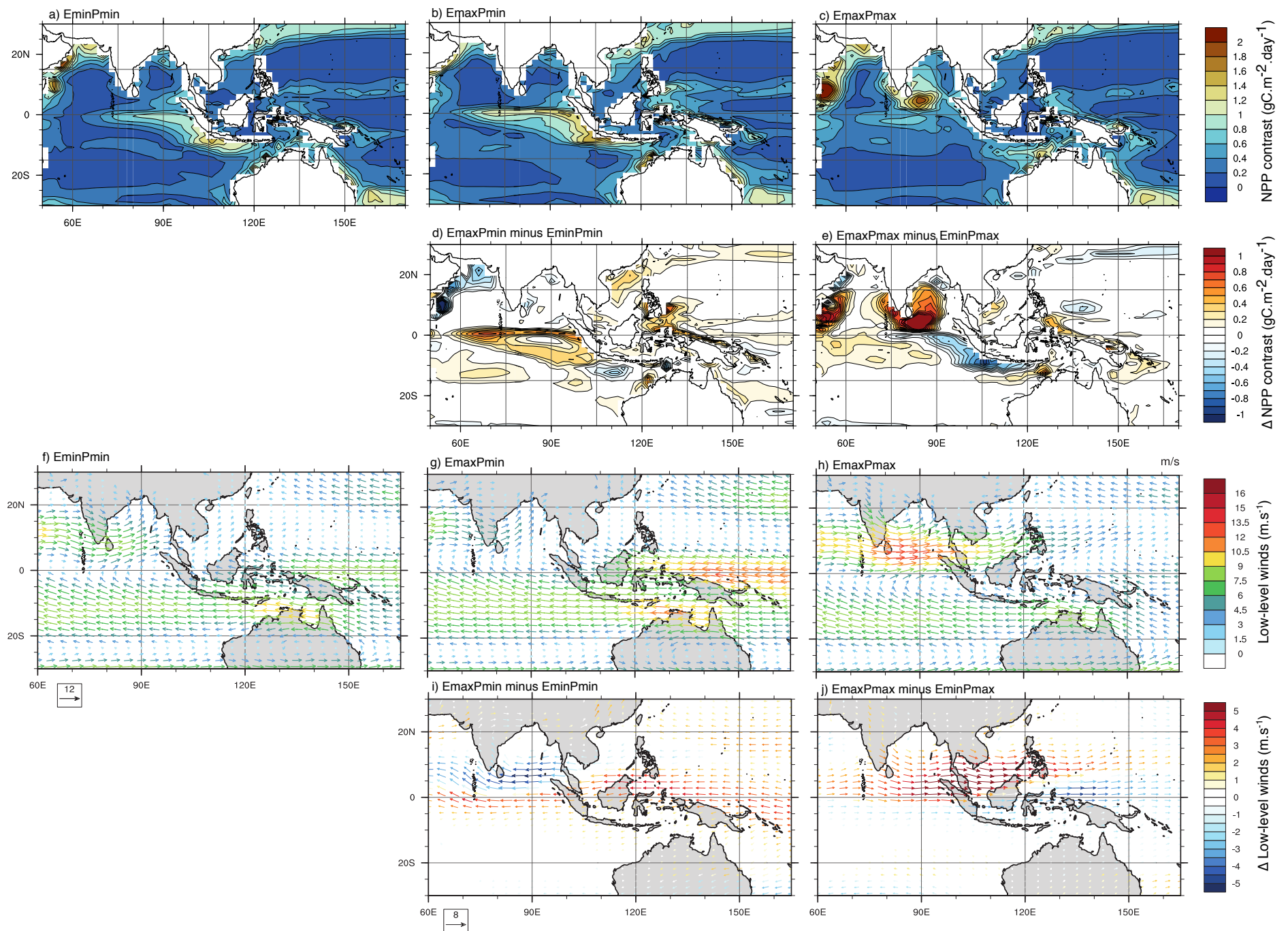
525

526 **Extended Data Figure 4:** Figure comparing stacked records, binned into 10-kyr intervals, of Noëlaerhabdaceae average coccolith mass (a),
 527 Noëlaerhabdaceae CaCO₃ mass accumulation rates (b), and Noëlaerhabdaceae coccolith flux to the seafloor (c) (see Methods). Grey shaded areas
 528 represent four described acmes of mid-size Noëlaerhabdaceae species^{15-17,70,71}.



529

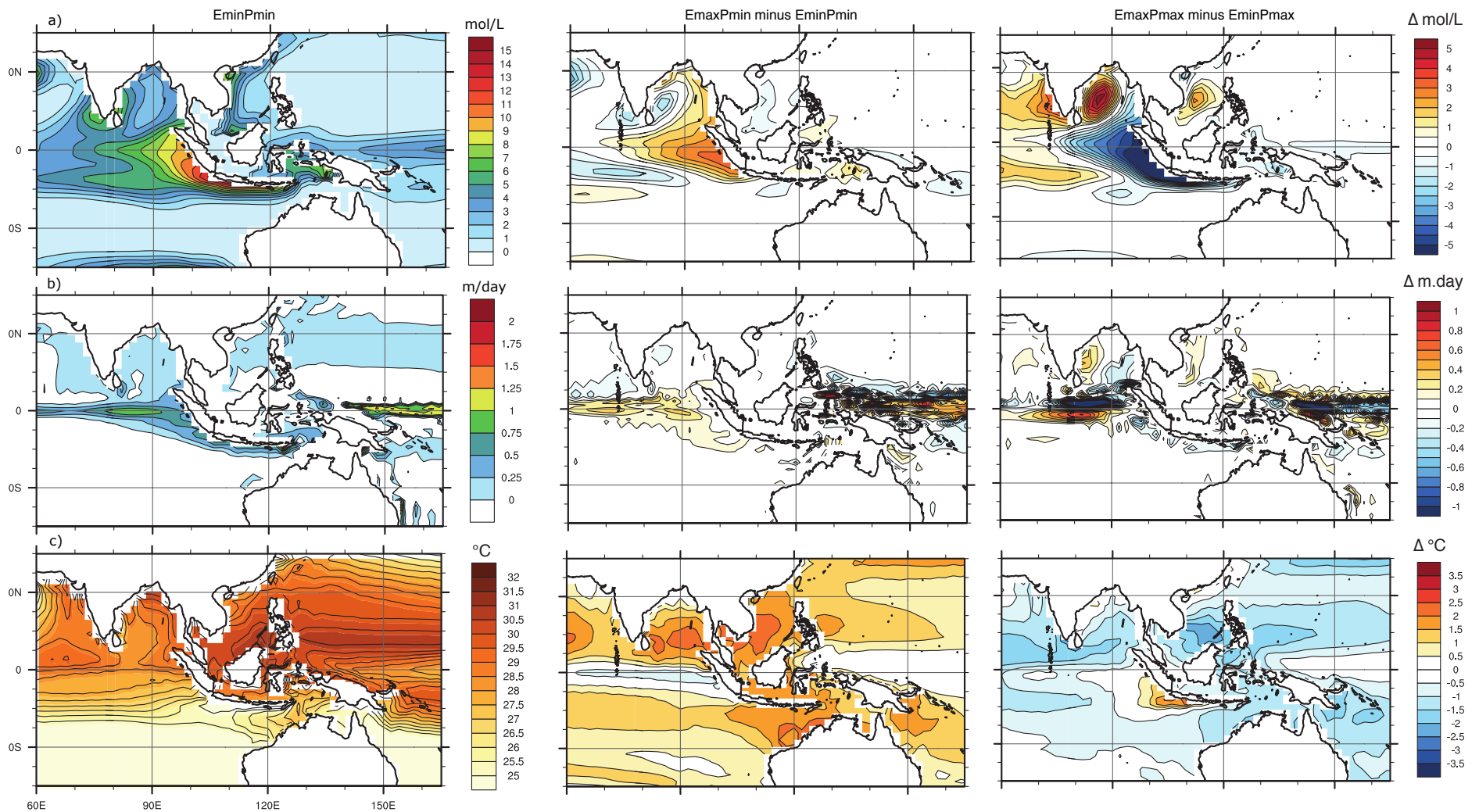
530 **Extended Data Figure 5:** Top: Yearly maximum contrast in NPP ($\text{gC.m}^2.\text{day}^{-1}$) for (a) EminPmin, (b) EmaxPmin and (c) EmaxPmax. Low
531 eccentricity values minimise the amplitude of precession variability (Extended Data Figure 7a-c), thus we only show results for minimum
532 precession value at minimum eccentricity (EminPmin) but the reader can consider those results to be similar for the EminPmax simulation. (d)
533 and (e) represent the anomaly of yearly maximum contrast in NPP. At EmaxPmax, the eastern equatorial Indian Ocean exhibits moderate
534 seasonality (a) due to inhibition of the summer productivity induced by lower nutrient concentrations in this area (Extended Data Figure 8a). In
535 this case, high productivity areas during boreal summer are shifted to south-west of India. Bottom: Late summer (JASO) low-level winds for (f)
536 EminPmin (g) EmaxPmin (h) EmaxPmax simulations. (i) and (j) represent the anomaly in late summer low-level winds. At EmaxPmax the
537 north-equatorial westerlies (c, e) are confined to south of 10°N due to the extension above India of the low-pressure area (Figure 1).



538

539 **Extended Data Figure 6:** Seasonal latitudinal variations of solar radiation at the top of the atmosphere derived from the model ($\text{W}\cdot\text{m}^{-2}$). (a)
 540 EminPmin, (b) EmaxPmin, (c) EmaxPmax. See Extended Data Table 2 for details of orbital configurations of each simulation. Late summer
 541 (JASO) low-level winds for (d) EminPmin (e) EmaxPmin (f) EmaxPmax simulations and anomaly in late summer low-level winds (g)
 542 EmaxPmin minus EminPmin (h) EmaxPmax minus EminPmax.

543

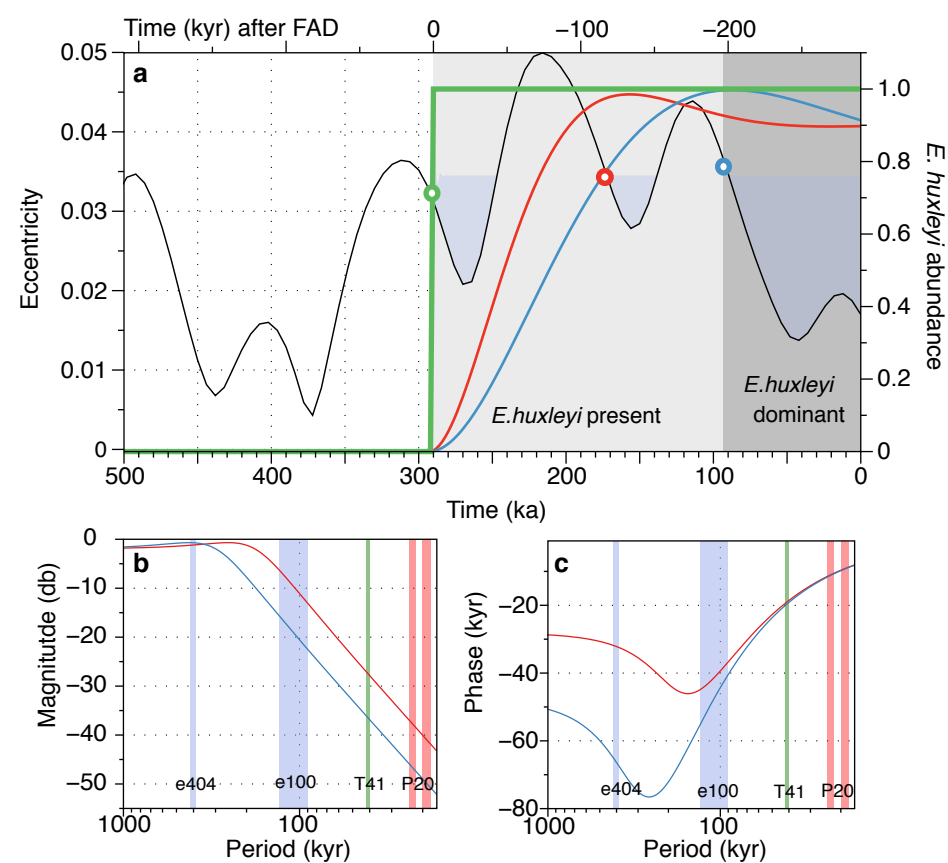


544

545 **Extended Data Figure 7:** (a) NO_3 concentrations in the surface layer (0-100m), (b) upwelling velocity (averaged between 40 and 80m), (c) SST.

546 All variables are averaged over JASO. Left : Emin, Middle : EmaxPmin minus EminPmin, Right : EmaxPmax minus EminPmax.

547



548

549 **Extended Data Figure 8:** a and b: Bode plots of the 130 kyr delay filter (red) and the 200 kyr delay filter (blue) for magnitude (a) and phase (b)

550 (see Methods). Earth's primary orbital periods are indicated by shading. c: Low-pass filter design, for the delay between First Appearance

551 Datum (FAD) and the beginning of the acme (BA) for *E. huxleyi* (blue line) and other geophycocapsids (red line). The stepped green line

552 represents *E. huxleyi*'s existence (filtered such that 0 means absence and 1 presence). The blue and red curves are the output series of the 2 low-

553 pass filters described in the methods. The black curve represents coeval eccentricity values.

554 **Data and Code availability**

555 All morphological data are available at www.microautomate.cerege.fr/data/evolveason.

556 LMDZ, XIOS, NEMO and ORCHIDEE are released under the terms of the CeCILL license. OASIS-MCT is released under the terms of the

557 Lesser GNU General Public License (LGPL). IPSL-CM5A2 source code is publicly available through svn, with the following commands line:

558 `svn co http://forge.ipsl.jussieu.fr/igcmg/svn/modipsl/branches/publications/IPSLCM5A2.1_11192019 modipsl ; cd modipsl/util ; ./model`

559 `IPSLCM5A2.1`

560 The mod.def file provides information regarding the different revisions used, namely:

561 - NEMOGCM branch nemo_v3_6_STABLE revision 6665

562 - XIOS2 branches/xios-2.5 revision 1763

563 - IOIPSL/src svn tags/v2_2_2

564 - LMDZ5 branches/IPSLCM5A2.1 rev 3591

565 - branches/publications/ORCHIDEE_IPSLCM5A2.1.r5307 rev 6336

566 - OASIS3-MCT 2.0_branch (rev 4775 IPSL server)

567 The login/password combination requested at first use to download the ORCHIDEE component is anonymous/anonymous. We recommend that

568 you refer to the project website: http://forge.ipsl.jussieu.fr/igcmg_doc/wiki/Doc/Config/IPSLCM5A2 for a proper installation and compilation of

569 the environment.