Keery et al., Sensitivity of the Eocene Climate to CO2 and Orbital Variability

Response to D. De Vleeschouwer (Referee)

Referee comments in black
Author responses in red

We are very grateful for this thorough review.

This paper reports on an ensemble of 50 Eocene climate-model simulations, each of which characterized by a different combination of eccentricity, obliquity, precession and atmospheric CO2 concentration. The climate model is the PLASIM-GENIE model, a new model of intermediate complexity, recently introduced by Holden et al. (2016). The study aims to summarize the ensemble of paleoclimate simulations by looking at what-they-call "simple metrics", principal component analysis and an emulator approach. This study provides a couple of interesting results. The first is the existence of a seaice-related threshold mechanism in the northern hemispheric high latitudes. From Figure 2 and 3, it seems that when a certain threshold in the extent of DJF-sea-ice is exceeded, temperatures (both sea-surface and maritime air temperatures) drop significantly. It would be interesting to read the author's opinion how this compares to the recent findings of modeling work by Zeebe et al. (2017), who found that "High-latitude mechanisms are unlikely drivers of orbitally paced changes in the late Paleocene-early Eocene". The interesting role of (seasonal) sea-ice in the climate system of the early Eocene aspect remains, however, rather underdeveloped in the present version of the paper.

In our discussion of Figs. 2 & 3 [page 9, line 10] we have stated: "The variation in TPTD across the ensemble thus appears to be essentially driven by the strength of snow and ice albedo feedback", and a little further on, in our discussion of Fig. 5 [page 9, line 22], in particular the plot of CO_2 v northern winter TPTD we have declared: "and it can also be seen that CO_2 strongly affects the northern TPTD in the winter, but not in the summer, when the combined influence of obliquity and precession index is discernible, suggesting that temperature proxies with seasonal bias may have a significant orbital imprint. The plot of atmospheric CO_2 against N. Winter TPTD shows a change in gradient at approximately 1000 ppm CO2 and 32°C. This may be related to the logarithmic dependence of radiative forcing on CO2 concentration, as well as the disappearance of ice above some threshold level, cf Fig. 3."

We will add the additional comment:

> A possible sea ice related threshold mechanism influencing both SST and maritime air temperature in high northern latitudes may be observed in Fig. 3, and this is strongly associated with the increase in northern winter TPTD at low CO_2 levels. Zeebe et al. (2017) have analysed a high resolution benthic isotope record covering the late Palaeocene - early Eocene, and have concluded that orbitally paced cycles are unlikely to have been driven by high latitude mechanisms. Our PLASIM-GENIE modelling suggests that northern TPTD is not orbitally paced in the winter, being controlled by CO_2, but is orbitally paced in the summer, by a combination of obliquity and precession.

The second interesting aspect is the distinct response to precession of monsoonal precipitation and temperature in the different monsoonal systems (e.g. Figure 6). The description and discussion of these Eocene paleoclimate simulations is useful and perfectly fits the scope of the journal. The current version of the manuscript is, however, unsatisfactory for publication in Climate of the Past for the reasons listed below.

Major Comments

1. One of the major conclusions in the current version of the manuscript, is that 95The emulator approach adopted in this study allows for estimating the response of different aspects of the climate system (e.g. wet-season monsoonal precipitation) over the full input space. It would -for example- be interesting to see the response of precipitation and temperatures in the different monsoonal systems to astronomical forcing for specific pCO2 levels. This could be an elegant way to circumvent the disparity in time-scales between CO2 and orbital variability.

We have amended the subplots for obliquity and precession index in Figures 5 and 6 to denote the CO_2 level on a continuous colour scale. This approach gives a simple visual indication of which relationships between the astronomical forcing factors and the temperature and precipitation simple metrics are influenced by CO_2. Figure 6 also now includes an additional row of subplots for the American monsoon index.

We have applied emulators derived from linear modelling of the forcing factors and monsoon indices, to estimate values of each of the monsoon indices over the full range of precession (ω), with fixed high eccentricity (e), for low and high values of CO_2, and low and high values of obliquity (ε).

We will make amendments to the abstract:

> The results demonstrate the importance of orbital variation as an agent of change in climates of the past, and we demonstrate that emulators derived from our modelling output can be used as rapid and efficient surrogates of the full complexity model, to provide estimates of early Eocene climate conditions from any set of forcing parameters.

and to the final paragraph of the introduction:

> By applying the linear modelling and emulation methods of Holden et al. (2015), we regress both the simple scalar metrics and the SVD reduced dimension model outputs onto the forcing parameters, and from the derived relationships, we infer main effects denoting the effect of each explanatory term in the linear model, and total effects denoting the effect of each forcing parameter, on the variation in the scalar metrics and on the temperature and precipitation output fields. We demonstrate that emulators derived in respect of tropical precipitation metrics can be used to estimate Eocene monsoonal responses to any combination of GHG and orbital forcing parameter values.

We will add new Figures 11, 12 and 13, plotting emulated values of the Asian, African and American monsoon indices.

We will add a paragraph to the Results section:

> We apply the linear models derived from the forcing factors and monsoon indices as emulators to estimate values of monsoon indices corresponding to the full range of precession (ω), with eccentricity fixed at its high limit of 0.06, low and high values of CO_2 (300 ppm and 3000 ppm), and low and high values of obliquity (22.0° and 24.5°). Precession index ($e\sin\omega$) and emulated values of the Asian, African and American monsoon indices are plotted in Figures 11, 12 and 13 respectively. Relationships between the precession index and the monsoon indices which are visually suggested in Figure 6 are shown with clear structure in Figures 11, 12 and 13. In each of the monsoon areas, the increase in precipitation due to precession effects is more pronounced at high atmospheric concentration of CO_2, and also at high obliquity.

We will add a paragraph to the Summary;

> We have demonstrated that emulators derived from linear modelling of the PLASIM-GENIE ensemble results can be used as a rapid and efficient method of estimating early Eocene climate conditions from any set of forcing parameters, without the need for further deployment of the EMIC.

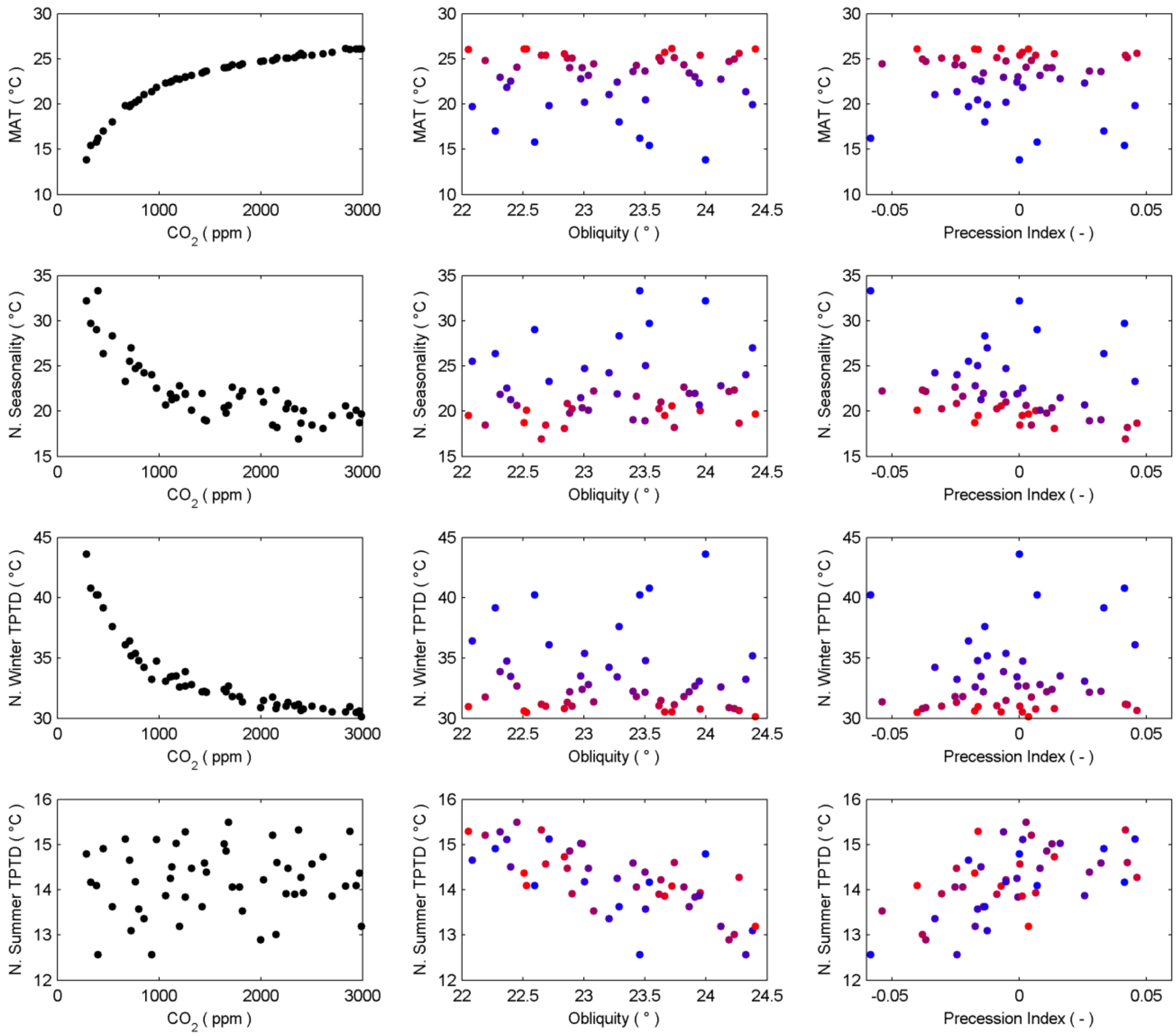

Figure 5 reworked with CO_2 plotted in colour in obliquity and precession plots (blue = low, red = high)

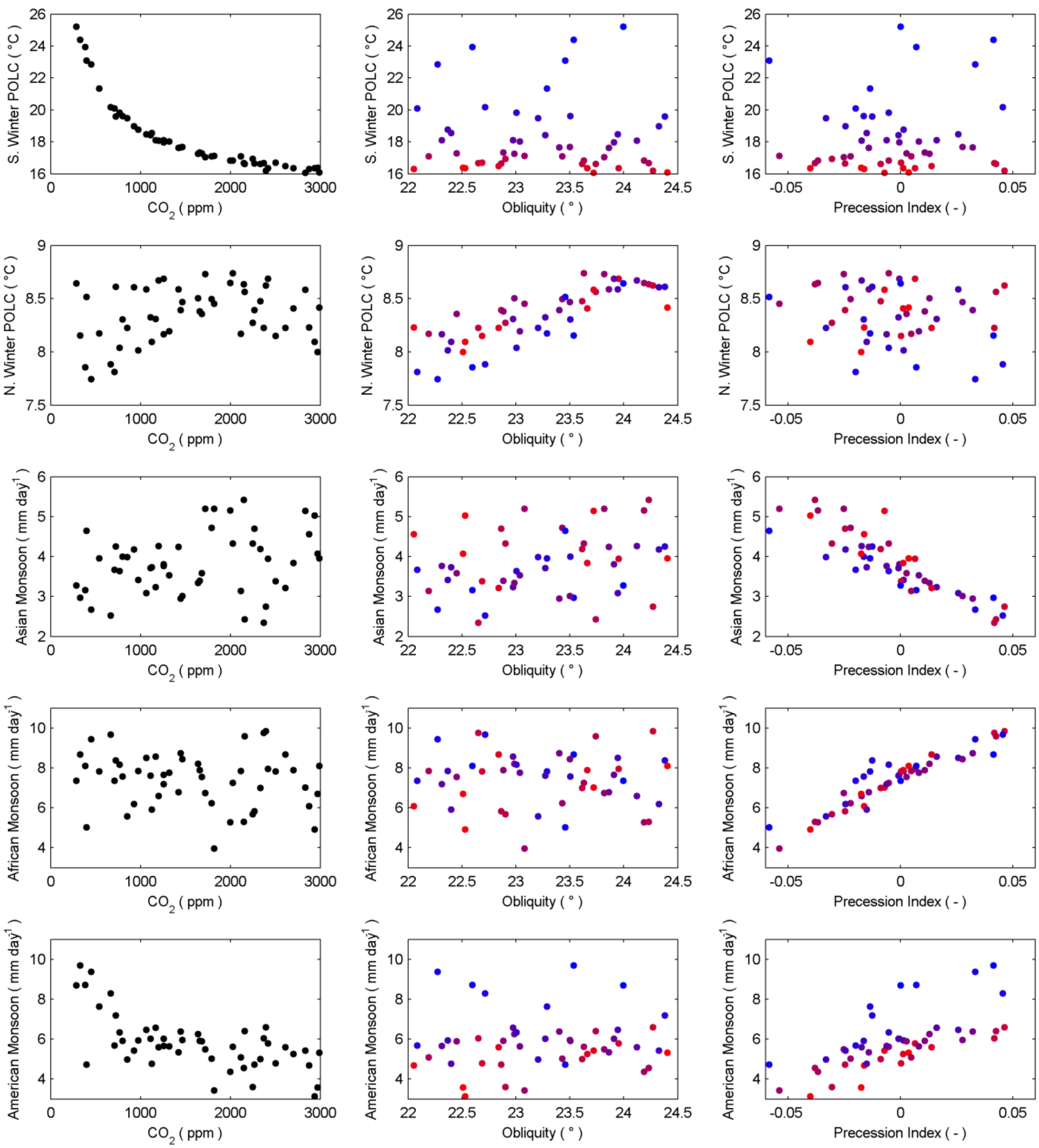

Figure 6 reworked with CO_2 plotted in colour in obliquity and precession plots (blue = low, red = high). Additional (bottom) row plots the forcing factors against the American monsoon index.

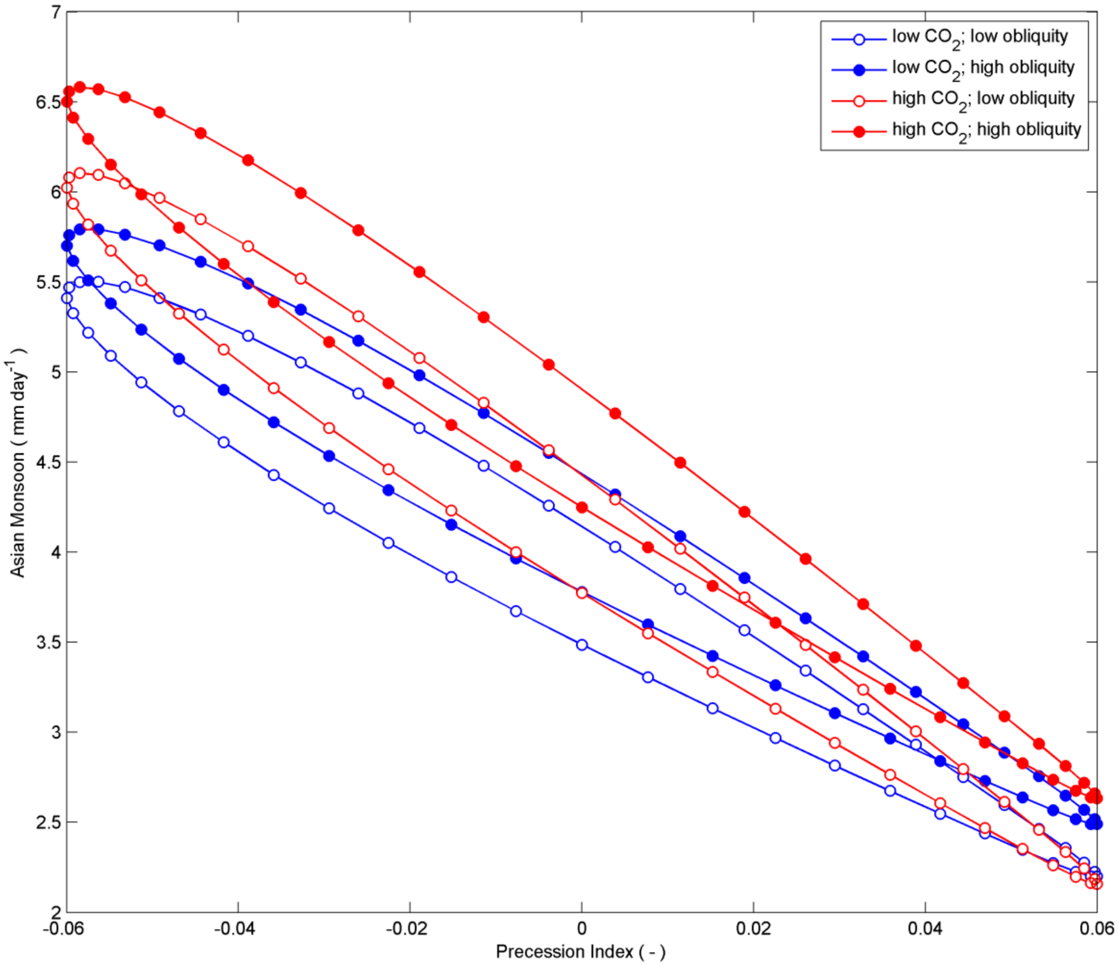

Figure 11: Emulated values of the Asian monsoon index, for the full range of the precession index ($e\sin\omega$), at low and high values of CO_2 and obliquity (ε).

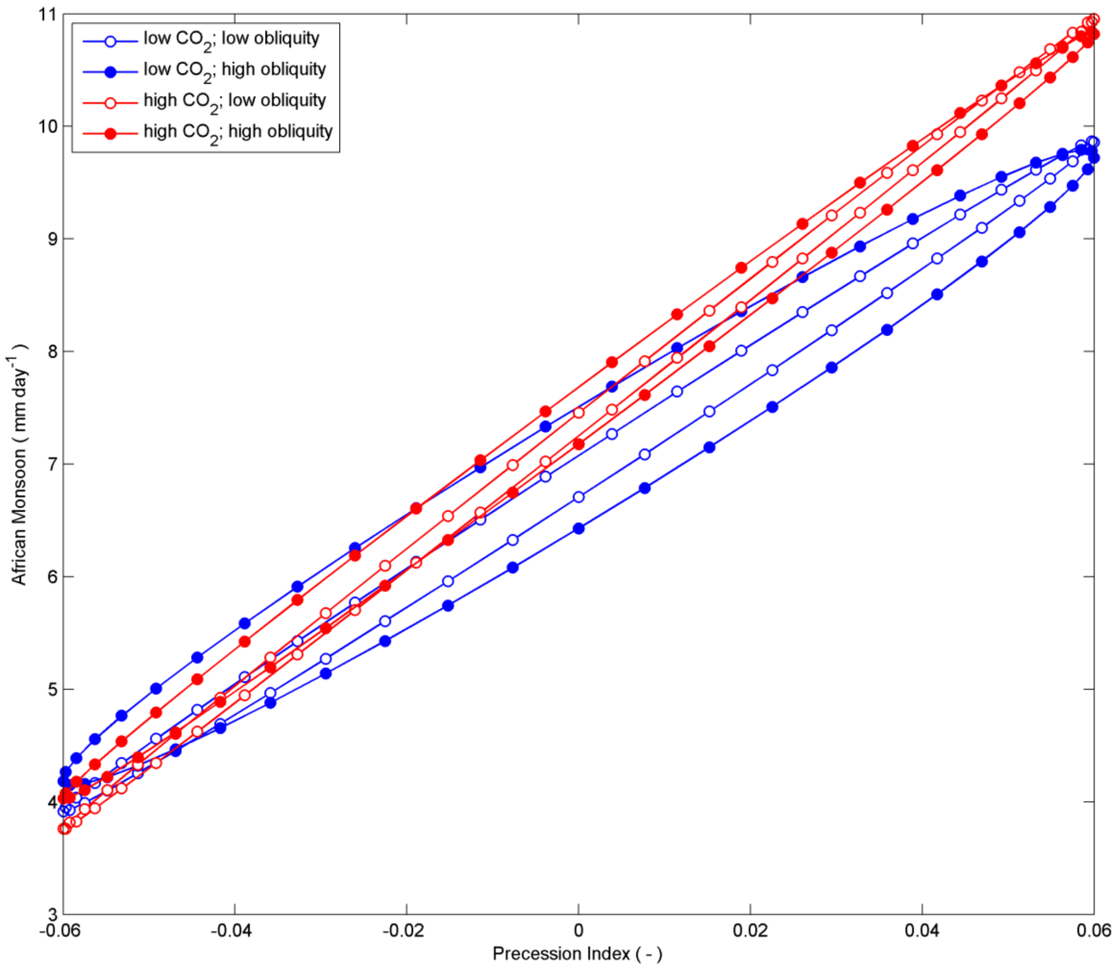

Figure 12: Emulated values of the African monsoon index, for the full range of the precession index ($e\sin\omega$), at low and high values of CO_2 and obliquity (ε).

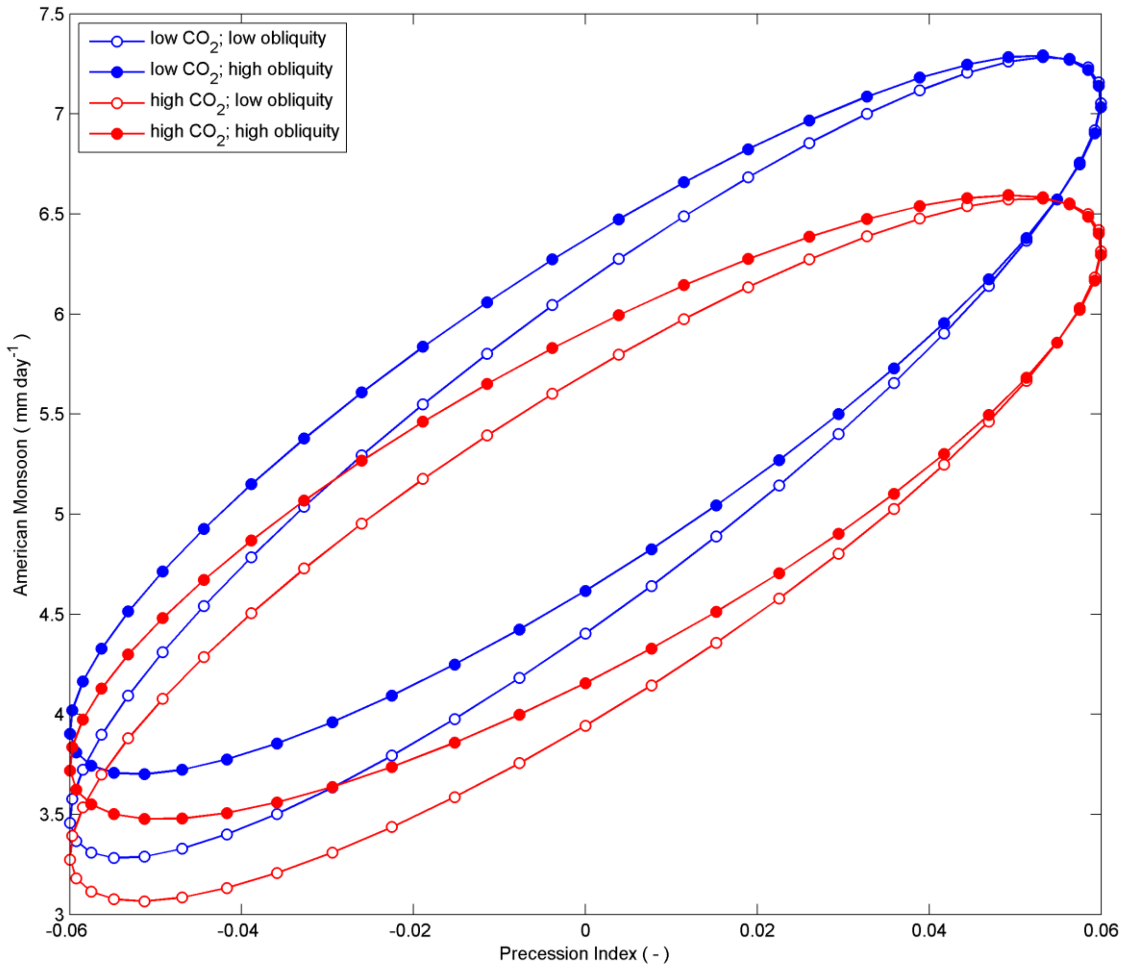

Figure 13: Emulated values of the American monsoon index, for the full range of the precession index ($e\sin\omega$), at low and high values of CO_2 and obliquity (ε).

2. The authors do not provide their 50-simulation experimental design. It is essential to have an overview of the parameter settings for each simulation that was run in the framework of this study. The details on the settings of the 50 simulations could be given either in the form of a Table, or in the form of a figure, or in both forms. For good examples, please check Figure 2 and Table 1 in Araya-Melo et al. (2015, cp-11-45-2015), Figure 2 and Table 2 in Lord et al. (2017, cp-2017-57), and Figure 1 in Bounceur et al. (2015, esd-6-205-2015).

We will include the values of the forcing factors and the dummy variable for the ensemble in a new table (Table 2).

We note that Araya-Melo et al. (2015) constrained their experiment to exclude non-physical combinations of CO_2 and sea ice, and their Figure 2 includes an informative subplot showing fairly strong inverse correlation between CO_2 and sea ice. In our study, however, we do not have a priori information with which to constrain any combinations of our forcing factors, each of which is sampled independently to maximise state space coverage and to minimise correlations between the forcing factors. We include in this response a new figure showing cross-plots and r coefficients of all of the forcing factors and the dummy parameter, which illustrate both the coverage of the state space, and the very low correlation between any of the factors. We do not consider that this figure, or a variation, could add significant information to that included in the text, which will be amended to include the statement:

> The absolute value of the correlation coefficient r did not exceed 0.1 for any pair of input (forcing and dummy) parameters.

Table 2 Forcing factors and dummy values for each member in the ensemble. Precession = ω, the angle between the moving vernal equinox and the longitude of perihelion.

Member (-)	CO_2 (ppm)	Eccentricity (-)	Precession (°)	Obliquity (°)	Dummy (-)
1	975.6	0.0022	142.5	22.37	0.822
2	2418.7	0.0256	165.2	23.95	0.907
3	1259.4	0.0007	307.1	23.91	0.323
4	801.3	0.0163	270.4	23.50	0.276
5	1720.1	0.0559	206.7	23.82	0.402
6	327.1	0.0595	135.9	23.53	0.681
7	2937.7	0.0418	287.1	22.53	0.650
8	1200.3	0.0237	313.2	24.12	0.978
9	1420.7	0.0158	297.1	23.86	0.931
10	2157.6	0.0432	100.6	23.74	0.661
11	1791.7	0.0241	247.2	23.43	0.429
12	2369.0	0.0425	78.9	22.65	0.167
13	2502.9	0.0296	0.5	22.69	0.122
14	2149.2	0.0405	249.9	24.23	0.347
15	1061.7	0.0394	40.9	23.94	0.189
16	711.3	0.0199	274.6	22.08	0.913
17	1817.1	0.0578	291.4	23.08	0.888
18	722.1	0.0463	195.8	24.38	0.865
19	2988.5	0.0039	110.1	24.40	0.049
20	539.4	0.0251	212.5	23.29	0.234
21	450.6	0.0335	96.1	22.28	0.674
22	2700.1	0.0049	165.9	23.66	0.630
23	2025.4	0.0320	189.4	23.63	0.087
24	2268.7	0.0308	233.3	22.86	0.461
25	1447.2	0.0364	62.0	23.40	0.541
26	1168.3	0.0300	147.4	22.97	0.947
27	1317.6	0.0377	12.4	23.04	0.714
28	1639.5	0.0265	150.9	22.98	0.524
29	399.0	0.0589	262.7	23.46	0.028
30	2876.3	0.0411	203.0	22.05	0.608
31	2611.1	0.0170	54.3	22.84	0.746
32	2831.7	0.0564	187.2	23.72	0.696
33	1998.5	0.0372	278.8	24.19	0.805
34	1465.0	0.0439	38.9	23.50	0.376
35	1660.0	0.0109	85.3	22.88	0.896
36	2393.7	0.0587	127.9	24.27	0.191
37	286.3	0.0004	27.1	23.99	0.391
38	667.4	0.0509	116.5	22.71	0.569
39	2246.8	0.0450	317.4	22.90	0.103
40	2334.2	0.0096	294.7	23.61	0.532
41	2968.2	0.0346	329.8	22.51	0.314
42	768.2	0.0085	218.3	23.00	0.000
43	925.8	0.0450	327.2	24.32	0.753
44	384.5	0.0081	60.6	22.59	0.436
45	850.7	0.0551	322.9	23.21	0.459
46	1112.8	0.0150	356.7	23.27	0.579
47	1255.8	0.0116	212.2	22.31	0.487
48	1124.1	0.0530	343.7	22.40	0.065
49	2113.9	0.0276	9.9	22.19	0.856
50	1681.0	0.0354	175.5	22.45	0.287

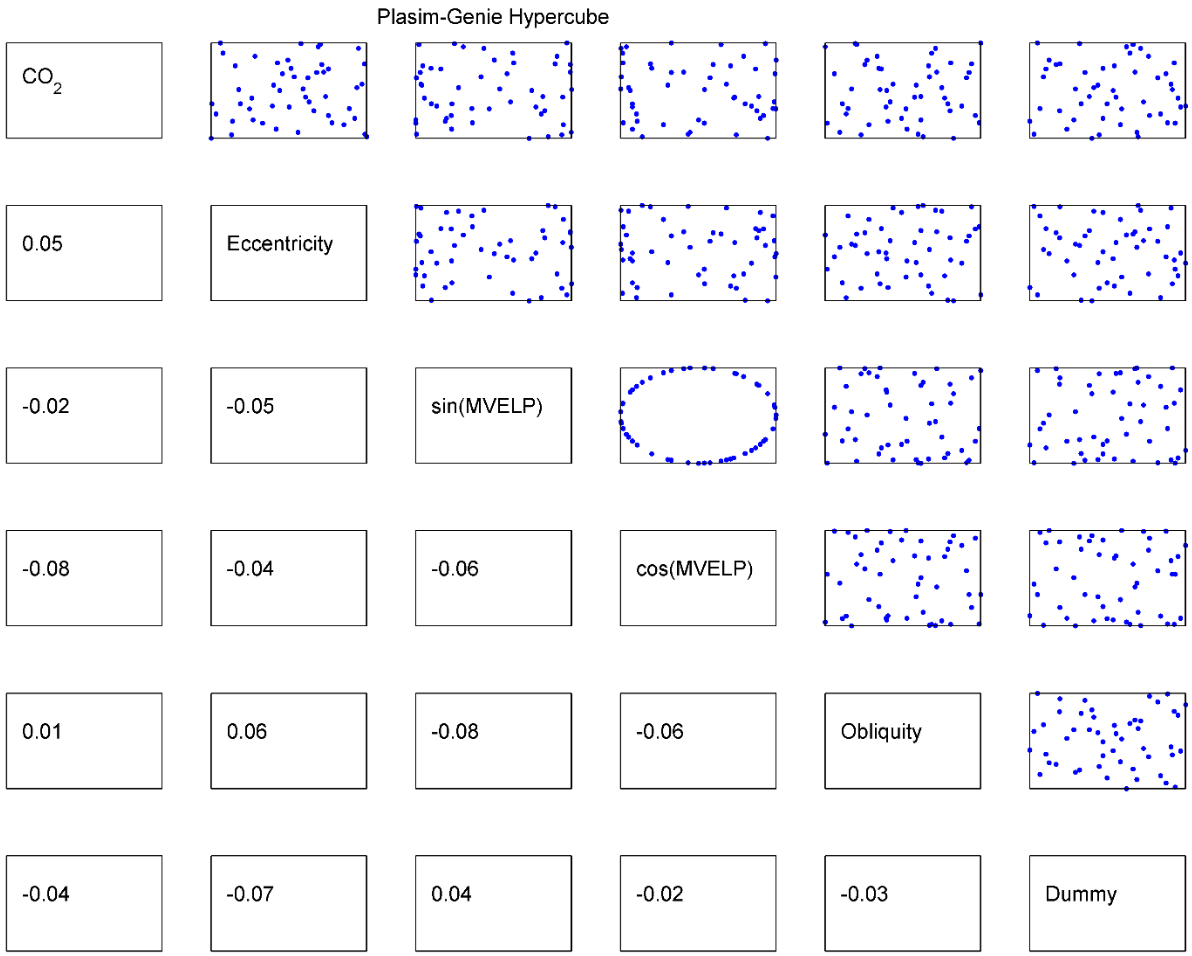

Figure R2 Correlation plots and r coefficients between all forcing factors.

3. From Figure 6, it is very clear that precession has an important influence on the Asian Monsoon intensity, with higher rainfall when the index is minimum (i.e. Earth in perihelion during JJA, maximum northern hemisphere summer insolation). However, if I interpret PC2 in JJA temperature and PC2 in JJA precipitation correctly (Table 5 and Figures 7 and 8), it seems that a precession-driven increase in monsoonal rainfall coincides with a decrease in JJA temperature in the Asian Monsoon region. Such a decrease in temperature is remarkable, given that it occurs when northern hemisphere JJA insolation is maximum. This observation can either be explained by the consumption of incoming solar radiation as latent heat, or by a negative influence of the increased cloud cover on the radiation balance. Indeed, the reflective character of clouds contributes to the planetary albedo. In the revised version of the manuscript, I would like to read more discussion of paleoclimate mechanisms like this one.

This temperature decrease is indeed observed in the model results for the Asian monsoon. We will augment the text to describe this effect more clearly:

> An increase in the second PC scores for JJA precipitation in the Asian monsoon region (Fig. 8) corresponds to a decrease in the second PC scores for JJA temperature (Fig. 7), and as already noted, the second PC scores for both temperature and precipitation in JJA are strongly correlated to the precession

> index. This temperature reduction during the Asian monsoon was also observed by Holden et al. (2014), and attributed to a reduction in incoming solar radiation due to increased cloud cover, and an increase in energy lost as latent heat with an increase in evaporation.

4. Page 7, lines 23-25 and Figure 6: When I was first interpreting Figure 6, I was confused by the fact that the Asian Monsoon and the African monsoon seemed to respond to precession in the same way, despite the fact that they are located on opposite sides of the equator. It took me quite a while to realize that both monsoonal systems are responding to precession in the expected way: with intensified wet-season precipitation in the Asian Monsoon system when the Earth reaches perihelion in JJA (negative precession index), and intensified wet-season precipitation in the African Monsoon system when the Earth reaches perihelion in DFF (positive precession index). I only understood this after reading lines 23-25 (page 7) several times. Indeed, the authors define their monsoon-related "simple scalar metric" by the difference in rainfall in DJF and JJA, regardless of whether DJF is the wet or the dry season in the monsoonal system considered. This also explains why the panel of Figure 6 that is related to the African Monsoon shows negative values, whereas the panel that is related to the Asian Monsoon exhibits positive values. I would strongly advise the authors to think about ways to illustrate the monsoonal response to precession in a more intuitive way. Maybe the paper by Tuenter et al (2003) could provide some inspiration as to how to best present the response of a summer monsoon to precessional (and obliquity?) forcing. Also, why is the South American monsoon system missing from Figure 6?

We have amended our monsoon indices so that each is now derived by subtracting winter precipitation from summer precipitation, as suggested. Figure 6 has been altered accordingly, and now also includes a row for the American monsoon index, an entry for which will be added to the table of total effects of forcing parameters on simple scalar metrics (presently Table 3; will be Table 4).

We will amend the text to reflect the changes to the monsoon indices:

> In this study, we derive simple scalar metrics to denote indices for monsoons for Asia, Africa and South America by subtracting winter rainfall from summer rainfall for defined geographical regions, denoted on Fig. 1, and selected for their similarity to monsoonal regions in the modern continental configuration.

We will amend our comments on Figures 5 and 6 in the Results section, following addition of the American monsoon index, and the use of colour in these Figures:

> In Figs. 5 and 6, CO_2, obliquity (ε) and precession index ($e\sin\omega$) are plotted against MAT, northern seasonality, northern winter TPTD and northern summer TPTD (Fig. 5), and southern winter polar OLC, northern winter polar OLC, Asian monsoon index, African monsoon index and American monsoon index (Fig. 6). Subplots for obliquity and precession index in Figures 5 and 6 denote the CO_2 level on a continuous colour scale.

and we will add the comment:

> The American monsoon index is fairly strongly correlated with the precession index at high levels of CO_2, and negatively correlated with CO_2 at low levels of CO_2.

We note that the study by Tuenter et al. (2003) included six experimental setups, with each one comprising either maximum or minimum values of obliquity, and maximum, minimum or zero values of precession. They were therefore able to illustrate their results in the form of spatial patterns of the differences in output values for pairs of experiments with contrasting values of one or both forcing factors. This approach is not appropriate for our 50 member ensemble, with uncorrelated forcing factor values, in which no pairs of experiments can be identified for this type of comparison.

Additional comments and recommendations

Abstract line 5 and p. 2 lines 1-3: I would recommend being a little bit more conservative on the possible analogy between the PETM and the ongoing anthropogenic disturbance of the global carbon cycle. Also cite Zeebe et al. (2016, Nature Geoscience) here.

We will amend the text to clarify the importance of the PETM, particularly its importance as the closest, if not perfect, analogue to anthropogenic climate change:

> Since the PETM is the most recent period in Earth's history for which estimated atmospheric GHG concentrations are similar in magnitude to those of the present-day, and expected to arise from fossil fuel burning, the PETM may provide a valuable analogue for anthropogenic climate change.

We will also cite Zeebe et al (2016) in the first paragraph of the introduction.

Abstract: The abstract reads too technical and vague. I find the following sentence particularly vague: "Two dimensional model output fields are reduced to scalar values through simple summarizing algorithms and by singular value decomposition." The reader gets very little information from this sentence. I would recommend rewriting the abstract, making it more results-oriented.

> We will delete this sentence, and make amendments to the abstract to make it less vague, with more focus on the results, including our additional work using the emulators.

Page 2, line 30: suggestion: "The Earth resided in a greenhouse state"

We don't understand the reason behind this suggestion. Our intention was to emphasise that the greenhouse state had been continuous since the early Cretaceous, so we will leave the sentence unchanged.

Page 3, line 4: What do you mean with "high levels of radiative forcing"? Only eccentricity influences the total amount of solar energy received by the Earth: : : but the amplitude of that variability is only 0.15

Huber & Caballero (2011) used CO_2 as a proxy for all changes to incoming and outgoing radiation. They commented "We have not addressed whether the enhanced radiative forcing was due to pCO_2, methane, other greenhouse gases, novel cloud feedbacks, or other "missing" factors. We have also not established whether large forcing is actually necessary, the alternative being high values of climate sensitivity as in the study of Heinemann et al. (2009) and only moderate increases in forcing."

We will amend the text to clarify this:

> Huber and Caballero (2011), hereafter HC11, have demonstrated that with sufficiently high levels of CO_2 (as a proxy for all forms of radiative forcing), climate models can generate global air temperature distributions in broad agreement with the proxy temperature measurements.

Page 2, line 9: Either you provide the reader with information on which kind of evidence exists. Or you rewrite like: "During the PETM, the emission of organic carbon was initially in the form of methane, which later oxidized to CO2".

We will amend the text (Page 3, line 9), to give brief details of the evidence, and we will include an additional citation:

> There is some evidence from analysis and modelling of the timing and duration of variations in $\delta^{13}C$ and $\delta^{13}O$ observed in nannoplankton fossils that some of the GHG emissions were initially in the form of CH_4 (Dickens, 2011; Lunt et al., 2011; Thomas et al., 2002), which is rapidly oxidised in the atmosphere to CO_2.

Page 2, line 23: "broadly similar" is quite a subjective, interpretative qualification. I find the Eocene paleogeography quite different from todays, given that the Tethys Ocean was still open. If you want to point to the similarity with the present-day, you could state that the majority of the continents were located in the northern hemisphere.

We have used the phrase "broadly similar" in the sense that the continental configuration is instantly recognisable, unlike for example, the Triassic period, with a single supercontinent just starting to break up into those that we're familiar with today. We will amend this paragraph:

> The arrangement of the continents and oceans in the Early Eocene was broadly similar to that of the present, with the Earth's land mass divided into the same major continents, and with most of the land mass in the northern hemisphere. India had not yet collided with the Eurasian continent, and the closure of the Tethys Ocean was not yet complete. Such tectonic movements may have effected some changes to the climate system. In particular, the configuration of ocean gateways strongly influences modes of ocean circulation, and hence affects energy transport throughout the climate system (Lunt et al., 2016; Sijp et al., 2014).

Page 4, line 10 and many other occurrences: "dominant periods of 100 kyr and 405 kyr". In an eccentricity power spectrum there are 4 peaks around 100 kyr, but only a single one at 405 kyr. Therefore, I would suggest the above notation.

We note that there are multiple peaks in the power spectra for eccentricity, equivalent to a single peak with a period of approximately 100 ka, together with an isolated peak for eccentricity with a period of 405 ka. There are similar clusters of peaks around 40 ka for obliquity, and around 20 ka for precession. We will amend the text to use the approximation symbol '~' in respect of the obliquity, precession and 100 ka eccentricity cycles, but not in respect of the 405 ka eccentricity cycle:

> The main oscillations are the eccentricity of the Earth's orbit around the Sun, with periods of ~100 ka and 405 ka, the obliquity or tilt of the Earth's axis of rotation, with a period of ~40 ka, and precession, the relative timing between perihelion and the seasons, with a period of ~20 ka (Berger et al., 1993).

Page 4, line 16: Jacques Laskar does not calculate time scales. He calculates astronomical solutions.

We will replace "astronomical time scale" with "astronomical solution".

Page 5: Why is Section 3 not a subsection of Section 4 "Methods"?

This section will be moved to the Methods as suggested by both reviewers.

Page 5, line 3: What is "T21"?

We will amend this sentence to clarify that T21 denotes the resolution obtained through spectral modelling:

> We apply the model at a spectral T21 atmospheric resolution, which corresponds to a triangular truncation applied at wave number 21 and a horizontal resolution of 5.625°, with 10 layers, and a matching ocean grid with 32 depth levels.

Page 6, lines 9-11: An injection of carbon into the atmosphere is measured in tons of C, whereas the concentration of CO2 in the atmosphere is measured in ppm. These are thus two different things, with two different units. You have to rephrase this sentence to correct for that.
We will amend the sentence as follows:

> Although the maximum mass of CO_2 injected into the atmosphere during CIEs, and in particular the PETM, remains uncertain, there is broad agreement that the atmospheric concentration of CO_2 did not exceed 3000 ppm (e.g. Gehler et al., 2016), and that it did not fall below the pre-industrial level of 280 ppm at any time during the early Eocene.

Page 6, lines 13-16: It’s not immediately clear to me how knowledge on the phase relationship between carbon isotope excursions and the astronomical parameters would influence the experimental design of your study. If you would know these phase relationships, would you then have designed your experiments differently?

If these relationships were known, we would have been able to concentrate our investigation on combinations of the orbital forcing parameters of particular interest, i.e. those considered to be important in respect of the CIEs. We will amend this paragraph:

> Since the absolute astronomical time scale for the early Eocene has an uncertainty which is greater than the periods of the obliquity and precession cycles, and there remains disagreement as to which phases of the eccentricity cycles are related to CIEs, there are no combinations of the orbital forcing parameters which can be known a priori to be of greater importance in their effects on the Eocene climate in general, and on their contributions to the initiation, duration and termination of the CIEs in particular. We therefore select values of orbital parameters independently, and from the full range of each parameter’s variation during the early Eocene.

Page 6, line 26: What do you mean with “quasi-steady state”?

We will add the phrase "a spin-up period of" to clarify that the "quasi-steady" state is the state of approximate equilibration of the model after the model has run for long enough such that the initial conditions have been 'forgotten'.

Page 7, line 7-8: The atmospheric circulation patterns during the Eocene were most definitely different from those in the modern world. I think you can remove the “are likely to”.

We agree, and we will replace “are likely to have differed” with “will have differed”.

Page 7 line 27: Spell out SVD
We will amend this sentence to accommodate suggestions from both reviewers:

> We perform a singular value decomposition to identify the PCs and empirical orthogonal functions (EOFs) of temperature and precipitation fields in the full ensemble.

Page 8 line 9: Please provide the appropriate references where these criteria are defined.

We will provide the appropriate references for the Akaike information criterion (Akaike, 1974), and Bayes information criterion (Schwarz, 1978), and since these are of a highly technical nature, we will add a reference to a much cited textbook on model selection:

> Burnham and Anderson (2003) provide a detailed discussion of the application of information criteria in model selection.

Page 8 lines 23-24: The Figure 3 that you are referring to, only contains global annual mean SST’s, not the Arctic winter SST’s you are discussing.

We will amend the text:

> We note that the Arctic winter median air temperature is below freezing over both land and sea in the PLASIM-GENIE ensemble, (see Fig 3) and the Arctic does not remain ice-free throughout the year in any of the 50 simulations in our study.

Page 9, line 1: It is unclear to me what exactly you mean with “parametric uncertainty”

We will amend the text for clarification:

> Quantification of model-related uncertainty is beyond the scope of the present study.

Page 10, line 17: JJA instead of JJF.

We will correct this error.

Page 10, line 15: Shouldn't this be Table 4?

We will correct this error – it will now be Table 5, following earlier insertion of an additional table.

The paper contains a few important shortcomings when it comes to appropriately referencing pre-existing work.
For example, the authors do not refer to the Deep-time Model Intercomparison Project (Deep-MIP, Lunt et al., 2017, gmd-10-889-2017). The authors do not frame their study within that project, nor do they differentiate their study from that project. A statement on this topic is indiscernible, given that both this study and the Deep-MIP project explicitly focus on simulating (early) Eocene warm climates and that both are using the same paleogeographic configuration from Herold et al. (2014).

This paper was at the final stages of preparation when Lunt et al. (2017) was published online (on 23 February 2017). We are pleased to note that their recommended palaeogeography is that of Herold et al. (2014) which we have used as the basis for the palaeogeography in our study. We will amend the first sentence in the description of our model configuration:

> This study was designed before Lunt et al. (2017) presented their 'DeepMIP' guidelines for model simulations of the latest Paleocene and early Eocene. However, our palaeogeography is based on the high-resolution digital reconstruction of the early Eocene published by Herold et al. (2014), and which Lunt et al. (2017) recommended should be used as the standard for all palaeoclimate simulations within the DeepMIP framework. We have used the dataset of Herold et al. (2014) as an initial configuration for the tectonic layout, topography and bathymetric boundary conditions in our study.

We will also add a comment on the solar constant:

> We note that Lunt et al. (2017) have recommended that a modern value of 1361.0 W m^{-2} should be applied to studies within the DeepMIP framework, in order to facilitate comparison between simulations with modern and pre-industrial levels of CO_2, and to offset the absence of elevated levels of CH_4.

The authors refer to Bounceur et al. (2015), who applied a "similar emulator approach" (p. 8 line 13). First of all, I am unsure whether that statement is technically correct. Secondly, this reference is missing from the reference list.

We will ensure that Bounceur et al. (2015) are included in the reference list, and we will amend the text to clarify our comparison with their approach:

> Our emulator approach uses linear regression, rather than a Gaussian process, and is therefore simpler than the methods applied by Bounceur et al. (2015) in a study of the response of the climate-vegetation system in interglacial conditions to astronomical forcing, and by Araya-Melo et al. (2015) in their study of the Indian monsoon in the Pleistocene.

On page 4, line 28, the authors give credit to Ruddiman (2006, cp-2-43-2006) for noting "a relationship between obliquity and the extent of northern ice sheets". First of all, this is a Pleistocene-focused paper, of which I don't really see the relevance when discussing orbital configurations during the Eocene and possible influence on climate. Moreover, the relationship between obliquity-induced minima in NH summer insolation and ice age cycles was already suggested by Milutin Milankovitch in 1941.

We agree that this is misleading, and adds little to the paper. We will delete it.

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