Review response – Lorraine Lisiecki

Dear Erin,

The series of reviews have greatly strengthened this manuscript, and we appreciate the additional constructive comments from Lorraine Lisiecki. The requested corrections/clarifications to references to previous work along with all other suggestions have been taken up in full. Please refer to the line-by-line response below to each review point and to the tracked changes version of the manuscript attached to see these implemented changes.

In response to comment 5. from this review we have extended the model run from 1.5 Myr to 1.8 Myr. This allows us to make a comparison between corresponding time windows for PRED-CO2 and the full dating uncertainty of the Yan et al., 2019 blue ice data. This extension will also enhance the value of the PRED-CO2 data set for comparison with upcoming oldest ice records, which new geophysical data is indicating may extend to 1.8 Myr.

All code has been reviewed and prepared for upload as has the PRED-CO_2 data set. In reviewing the code we identified a couple of rounding errors and typos that have a minor effect on some quoted numbers in the text. Importantly, none of these changes affect the significance of comparisons between observed and predicted data or any conclusions. The corrected numbers are all noted in the tracked changes version and are summarised in a table at the end of the review response for full clarity.

Line numbers refer to the tracked changes version of the manuscript.

Sincere thanks for the extensions received to address earlier reviews while the authors managed other commitments.

Best regards, Jordan, Joel and Tess

1. Line 81: Use (Raymo et al., 2006) citation throughout text for hypothesis #3. Raymo & Huybers (2008) was a short review of several existing hypotheses. It didn't present any new details about the antiphase hypothesis.

Accepted and revised @ line 74-78

> *"Emergence of significant precession and 100 kyr signals occurs across the MPT (Fig. 1B), and all three components are clearly present after the MPT (Fig. 1A). Raymo et al. (2006) suggested that precession-paced changes in northern and southern hemisphere ice volumes may have occurred prior to the MPT, but are cancelled due to out-of-phase ice volume changes between the two hemispheres"*

2. Line 97: Whether a decrease in CO2 is expected during both glacials and interglacials depends on assumptions about the causes and effects of CO2 change as demonstrated by the authors' later explanation of why CO2 might decrease only during glacial stages (lines 99-105). Therefore, I recommend changing the wording here to say "reduction in CO2 might be expected in both" or "reduction in CO2 has been proposed in both…"

Accepted and revised @ line 93-94:

"For a long-term decrease in radiative forcing by atmospheric CO2 to be the cause of the MPT, the reduction in CO2 might be expected in both glacial and interglacial stages..."

3. Line 216: This description of the LR04 age model development is unclear because it suggests that each individual core's age model was based on that core's sedimentation rate. I recommend revising it to "The age models for these cores are constructed by alignment of their d18O signals, followed by tuning of the stack to a simple ice model based on 21 June insolation at 65°N in a way which maintains relatively stable global mean sedimentation rates."

Accepted and revised @ line 211-213:

> *"The LR04 stack includes 57 globally-distributed benthic δ18O sediment core records. The age models for these cores are constructed by alignment of their δ18O signals, followed by tuning of the stack to a simple ice model based on 21 June insolation at 65°N in a way which maintains relatively stable global mean sedimentation rates."*

4. Line 225: Please clarify the meaning of "(median, 2 sigma, 5.78 ppm)." I think this is supposed to indicate that the 2-sigma value for all bootstrap analyses has a median of 5.78 ppm, but it isn't clear from the current notation.

Strictly, what we get from the 1000 iterations of the model is a 95% confidence interval in the uncertainty of PRED_CO2 at each timestep. These uncertainties are provided in the PRED-CO2 data file. The median of the bootstrap 95% CI from 0 to 1.8 Mya is 5.78 ppm. We rephrase to (line 222-224)

> *"However, we expect any such effects are minor on the basis that our predictions show little sensitivity to the bootstrap analysis, which has a median 95% confidence interval of 5.8 ppm from 0 to 1.8 Mya (see Fig. 3B, C and Discussion)."*

5. Line 243-244 (and throughout the results section): It's not clear to me how the blue ice time window of 1.5 Mya +/- 213 kya is compared to the PRED-CO2 values which appear to only extend to 1.5 Mya. Do the authors only use the PRED-CO2 values from 1.287 to 1.5 Mya? That wouldn't be a completely fair comparison because the blue ice may be affected by higher or lower atmospheric CO2 levels during the older half of the time window (1.5 to 1.713 Mya). The authors should clarify whether they analyze PRED-CO2 older than 1.5 Mya without showing it in their figures or use different time windows for calculating the average CO2 values from the blue ice and predicted CO2. If they use different time windows, the text should include a caveat that this presents a potential source of bias in the comparison.

This is a good point. It is correct that the comparison to PREDCO2 is up to 1.5 Myr, whereas the Yan et al., blue ice data has an uncertainty range spanning 1.287 to 1.713 Mya. This reflects legacy of the Yan data being introduced for comparison during the review process, without updating the length of the model run. Note that this is not a time range covered by the blue ice data but the dating uncertainty range of the data.

To remove any concern about a potential source of bias and fully address this point, we have now extended the model prediction to 1.8 Myr and the extended PRED-CO_2 time series is now shown in Fig. 2 and 3.

The model extension allows a direct comparison of the Yan et al., and PRED-CO_2 data over the identical 1.5 Mya +/- 213 kya window. The impact on the comparison on the mean values is small <4 ppm. For clarity we show below (Table R1) the previous values and the values after extending PRED-CO_2. Notably the extension of the time widow (more data points) lowers the standard error in the uncertainty bound for PRED-CO_2. There remains no difference between the interglacial BI-CO_2 and interglacial PRED-CO_2 over the extended time window (as seen in Fig 3D). The central values for the glacial BI-CO2 and PRED-CO2 barely change (<1 ppm), but the reduced uncertainty bound translates to a 2.9 ppm difference between the upper estimate of BI-CO_2 and the lower estimate of PRED-CO_2 (see R1 below). We regard this difference as marginal, particularly given caveats associated with the blue ice dating and concentrations, that are covered in the Discussion. We update the text to reflect the extension of the time interval and revised comparison as follows (Line 265-273):

> *During the 1.5 Mya ± 213 kyr interval, the mean BI-CO_2 concentration did not show any significant difference to PRED-CO_2 in interglacial stages (254.1 ± 10.3 versus the predicted 257.2 ± 1.7 ppm. During glacial stages there is a small (2.9 ppm) difference between the upper estimate of BI-CO_2 and the lower estimate of PRED-CO_2 (218.4 ± 1.3 and 224 ± 1.4 ppm respectively, see Fig 3D). In our view these results, notwithstanding the 2.9 ppm difference at 1.5 Mya, do not give any cause to reject the GLS model. Furthermore, the comparison indicates that PRED-CO_2 is not drifting systematically away from the existing observed BI-CO_2 data (Fig 3D). The differences could of course be a failing in the model, potential biases in the blue ice data, dating uncertainty and/or unconstrained uncertainties (see Discussion for blue ice caveats).*

Throughout the manuscript references to a 1.5 Myr prediction of CO_2 are changed to 1.8 Myr.

Table R1 changes in numbers due to the extension of the model from 1.5 Mya to 1.8 Mya

Line	Data	Stage	i.e.	Period	Original	New	Reason
268/303	Yan blue ice	Glacial	Fig 3d	1.5 Mya ± 213 kyr	217.6 ± 2.3	218.4 ± 1.3	Review
267	Yan blue ice	Interglacial	Fig 3d	1.5 Mya ± 213 kyr	256.3 ± 3.8	254.1 ± 10.3	Review
268	Predictions	Glacial	Fig 3d	1.5 Mya ± 213 kyr	224.2 ± 6.6	224 ± 1.4	Model ext.
267	Predictions	Interglacial	Fig 3d	1.5 Mya ± 213 kyr	261.1 ± 6.3	257.2 ± 1.7	Model ext.

6. Line 295: How do the authors conclude that glacial CO2 levels of 217.6 +/- 2.3 and 226.2 +/- 4.0 ppm are NOT significantly different from each other? The 95% confidence intervals for the two estimates do not overlap (if the uncertainties quoted are 95% confidence intervals as described on line 240). Perhaps there is a typo here?

Thank you for catching this. The difference is small but significant at the quoted CI. However, this is in the direction of a marginal *increase* in CO_2 between the 1.5 Mya ± 213 kya (Yan et al., 2019) and 1000 ± 89 kya (Higgins et al., 2015) blue ice data sets. The main point the manuscript makes here is that there is not a decline in glacial CO_2 with time between these intervals, wheareas there is a very clear (ca. 24ppm) decline in glacial stage CO_2 between the 1.0 Myr and 0 – 800 kyr interval that follows (see Fig 3D). We adjust as follows. (Line 301-304):

"This pattern is similar to the observed BI-CO_2 data, where glacial CO_2 levels show no decline between the 1.5 Mya ± 213 kya and 1000 ± 89 kya windows (indeed there is a marginal increase from 218.4 ± 2.3 to 226.2 ± 4.0 ppm, respectively), before falling by 24 ppm to the 0–800 kyr observed glacial mean of 202.0 ± 3.2 ppm (Fig 3D)."

7. Line 421-422: There is an issue here with how the authors describe the antiphase hypothesis proposed by Raymo et al (2006). That publication did not propose an explanation for decreased obliquity sensitivity specifically, rather a change from local (insolation) forcing for a terrestrial ice margin to global (sea level/ice volume) forcing for a marine ice margin. Less total Antarctic ice volume change after the MPT resulted in less Antarctic ice volume sensitivity to all orbital cycles because Late Pleistocene Antarctic temperatures were consistently too cold for significant ice melt in East Antarctic. Therefore, I recommend changing this sentence to "is then proposed to remove sensitivity of Antarctic ice volume to local precession forcing in favor of quasi-100 kyr ice volume changes that are in phase between the hemispheres (Raymo et al., 2006)."

Accepted and revised @ line 427-430:

"A transition from a smaller and more dynamic terrestrial-terminating Antarctic ice sheet to a larger and more stable marine-terminating ice sheet with cooling climate across the MPT (e.g. Elderfield et al., 2012) is then proposed to remove sensitivity of Antarctic ice volume to local precession forcing in favour of quasi-100 kyr ice volume changes that are in phase between the hemispheres (Raymo et al., 2006)."

8. Line 56: Change comma to semicolon "forcing; therefore, the mechanisms"

Accepted and revised @ line 53:

9. Line 58: Omit comma "A common element in many of these is internal…"

Accepted and revised @ line 55:

10. Line 82: Omit "to" so that the text says "changes fall into phase"

Accepted and revised @ line 79:

11. Line 116: "52" should instead be "57 globally-distributed records…" in the LR04 stack

Accepted and revised @ line 113:

12. Line 204: A negative sign appears to be missing in front of the slope of 33.37 because CO2 is lower when d18O is high (as shown in Fig. 2).

Thanks for catching this. Accepted and revised @ line 199:

13. Figure 3: The 95% confidence interval shading is very hard to see. I recommend making both the line color and shading color darker.

Accepted and revised @ line 274 – Figure 3

14. Line 338: I think "date" should be "data"

Accepted and revised @ line 345

15. Line 356: Remove extra "and" at the end of the sentence.

Accepted and revised @ line 356:

16. Line 402: Change "That fact that..." to "The fact that..."

Accepted and revised @ line 410:

17. Line 404: Insert "the" to say "that the LR04 benthic stack"

Accepted and revised @ line 412:

Correction of rounding errors and typos following review of code and data provision

We uncovered, two minor rounding errors, one typo manuscript. Each error was in the decimal range, i.e. 0.1 ppm. and does not affect significance of any comparisons or conclusions. Below we present a table outlining the locations in our manuscript of these small changes. Apologies for these!

Table R2: Summary of minor changes to concentrations and uncertainties following review of code.

Line	*Data*	*Stage*	*i.e.*	*Period*	*Original*	*New*	*Reason*
238	Predictions	Undefined	Fig 3c	0-800 ky	225.1	225.2	Rounding
240	Predictions	Undefined	Fig 3c	1 Mya ± 89 kyr	235.5	235.3	Typo
250	Predictions	Glacial	Fig 3d	0-800 ky	± 1.7	± 1.6	Rounding

Data will be provided at the AAD data centre upon publication:
https://data.aad.gov.au/metadata/AAS_4632_Martin_etal_CP_2024