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Predicting trends in atmospheric CO_2 across the Mid-Pleistocene Transition using existing climate archives

Jordan R.W. Martin[1], Joel Pedro[2,3], Tessa R. Vance[3]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, 7004, Australia
[2]Australian Antarctic Division, Kingston, 7050, Australia
[3]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, 7004, Australia

Correspondence to: Jordan R.W. Martin (jrmartin@utas.edu.au)

Abstract. During the Mid-Pleistocene Transition (MPT), ca. 1250–800 kya, the Earth's glacial cycles changed from 41 ky to 100 ky periodicity. The emergence of this longer ice-age periodicity was accompanied by higher global ice volume in glacial periods and lower global ice volume in interglacial periods. Since there is no known change in external orbital forcing across the MPT, it is generally agreed that the cause of this transition is internal to the earth system. Resolving the climate–carbon cycle–cryosphere dynamics processes responsible for the MPT remains a major challenge in ice core and climate science. To address this challenge, the international ice core community has prioritized recovery of an ice core record spanning the MPT interval. The results from such 'oldest ice' projects are still several years away. Our objective here it to make an advanced prediction of atmospheric CO_2 out to 1.5 my. Our prediction utilizes existing records of atmospheric carbon dioxide (CO_2) from Antarctic ice cores spanning the past 800 ky along with the existing benthic water stable isotope ($\delta^{18}O$) record from marine sediment cores. Our predictions assume that the relationship between CO_2 and benthic $\delta^{18}O$ over the past 800 thousand years can be extended over the last one and a half million years. The implied null hypothesis is that there has been no fundamental change in the global climate–carbon cycle–cryosphere feedback systems across the MPT. We find that our predicted CO_2 record is significantly lower during glacial intervals than the existing blue-ice and boron isotope-based estimates of CO_2 that pre-date the continuous 800 ky CO_2 record. Our predicted glacial CO_2 concentrations are ~9 ppm below glacial CO_2 concentrations observed in blue ice data at ca. 1 mya and ~19 ppm below glacial CO_2 concentrations reconstructed from boron isotopic data over ca ~1.1–1.25 mya. These results support rejection of our null hypothesis and provide quantitative evidence of a fundamental shift in the global climate–carbon cycle–cryosphere feedback systems across the MPT. However, the definitive test of the various theories explaining the MPT will be comparison of our predicted records with the forthcoming oldest ice core records.

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1 Introduction

Ice core records from Antarctica provide comprehensive and continuous records of many climate parameters over the last 800 thousand years, e.g., the Vostok (Petit *et al.*,1999) and European Project for Ice Coring in Antarctica's Dome-C (EDC) ice cores (Jouzel *et al.*, 2007). One of the major challenges in climate science lies beyond the current threshold of the ice core record: The Mid-Pleistocene Transition (MPT), which spanned from ca. 1250–800 thousand years ago (kya) (Chalk *et al.*, 2017). The MPT is characterised by a change from regularly paced 40 ky glacial cycles with thinner glacial ice sheets to quasi-periodic 100 ky glacial cycles in which ice sheets are more persistent and thicker (Clark *et al.*, 2006).

The MPT occurred in the absence of any changes to orbital insolation forcing, therefore, the mechanisms behind the MPT must be internal to the earth's carbon cycle–climate system (Raymo, 1997; Ruddiman *et al.*, 1989). Multiple hypotheses have been put forward to explain the transition. Three of the more prominent include: 1) A long term decrease in radiative forcing, e.g., due to a reduction in atmospheric CO_2 across the transition (e.g., Hönisch *et al.*, 2009; Raymo *et al.*, 1988; Berger *et al.*, 1999); 2) Removal of sub-glacial regolith and the subsequent transition from sliding to non-sliding Northern Hemisphere ice sheets (Clark & Pollard, 1998); and 3) Phase-locking of the Northern and Southern Hemisphere ice sheet changes at the orbital precession frequency (Raymo *et al.*, 2006; Raymo & Huybers, 2008). Key to all these hypotheses is a shift toward conditions favorable to building thicker, more persistent, and more globally extensive ice sheets that can skip insolation peaks corresponding to the 23 ky precession and 41 ky obliquity cycles, i.e., an increase in the threshold for deglaciation (Tzedakis *et al.*, 2017).

The key to testing hypotheses on the cause of the MPT is the recovery of a continuous ice core that spans its duration. The International Partnership in Ice Core Sciences (IPICS) has nominated recovery of such a record as a grand challenge in ice core research (IPICS, 2020). Multiple national and international projects have commenced or are soon to commence drilling for 'oldest ice'. In this project, we take inspiration from the "EPICA Challenge" in which the paleoclimate and modeling community was challenged to predict the global atmospheric carbon dioxide and methane concentrations from 400–800 kya based on the existing 400 ky Vostok ice core record (Wolff *et al.*, 2004). Here, we will use a statistical model on continuous climate archives to predict a CO_2 record for the upcoming 1.5 my ice core and compare these predictions to the discontinuous data available. We utilise two primary data sets: The existing 800 ky ice core composite record of atmospheric CO_2 (Bereiter *et al.*, 2015); and the LR04 benthic stack of 52 globally distributed records of $\delta^{18}O$ which are a proxy for global ice volume and ocean temperature (Lisiecki & Raymo, 2005). Regression modelling between CO_2 and $\delta^{18}O$ (sea level and global ice volume proxy) is then used to make predictions of CO_2 spanning 800–1500 kya, spanning the MPT. The regression makes the simple assumption that the relationships between the CO_2 and benthic $\delta^{18}O$ records can be extended beyond 800 ka; the implicit null hypothesis is that there is no change to the carbon–climate feedback systems outside of the current existing records.

To test the null hypothesis, we compare our predicted CO_2 record to two sets of low resolution/imprecisely dated data that exist within the predicted range: 1) CO_2 estimates from the analysis of boron isotope ratios in benthic sediment cores which present a proxy for ocean pH to which a transfer function is applied to reconstruct atmospheric CO_2 (hereafter referred to as BOR-CO_2) (Chalk, *et al*., 2017; Henehan *et al.*, 2013) and 2) direct CO_2 measurements from 1 million year old "blue ice" from the Allan Hills in East Antarctica (hereafter referred to as BI-CO_2) (Higgins *et al.*, 2015). Here we use the term blue ice to describe deep, ancient glacial ice that has been brought to the near surface of an ice sheet by ice flow processes. This makes it some of the oldest, easily accessible ice. However, the vertical migration of the ice is associated with high deformation making the ice samples stratigraphically complex and hard to date (Higgins *et al.*, 2015). As a result, blue ice is not adequate in itself to provide a continuous CO_2 record across the MPT.

2 Methods

We calculated the mean of the Bereiter *et al.*, (2015) CO_2 record at 3 ky resolution time bins. To obtain constant resolution between the predictor and response variables to run the model, we also binned the LR04 Benthic Stack to this resolution. To account for autocorrelation in the data, which would lead in inaccurate predictions in an ordinary least squares model, we utilized generalized least squares (GLS) regression models with a correlation factor for the model. The factor used yielded the lowest Akaike information criterion (AIC) value from a test of multiple correlation factors. Ultimately, we chose an AR(1) correlation factor for the model. The GLS regression model was performed over the 0–800 ky range of the predictor variable (LR04 Benthic Stack) and the response variable (CO_2). Based on the regression model the $\delta^{18}O$ values of the LR04 Benthic Stack from 800–1500 kya were used to predict CO_2 concentration over this range (hereafter referred to as PRED-CO_2). We took a bootstrap approach, selecting a random 50% subset of our data and running the model 1000 times to determine 95% confidence intervals for the predictions. Finally, we compared our PRED-CO_2 record to some sparse and discrete data that exists outside of the current continuous ice-core data from 800–1500 kya.

3 Results

Our model skillfully predicts atmospheric CO_2 over the past 800 ky (Fig. 1A) ($r(226) = .86$, $p = <<0.01$). However, across the MPT the PRED-CO_2 data is systematically lower when averaged over its common intervals with the Allan Hills BI-CO_2 and BOR-CO_2 beyond 800 kya (Fig. 1B). The average BI-CO_2 concentration (at 1000 ± 89 kya) is ~11 ppm higher than our predicted value (averaged over the age uncertainty of the BI-CO_2) and the 95% confidence interval (1.96 σ) overlap by 0.88 ppm; see blue and black bars in Fig. 1B. Similarly, the average BOR-CO_2 data from the early MPT (ca. ~1.1–1.15 mya) is ~22 ppm higher than our predicted value (green and blue bars in Fig. 1B). Our model appears to underpredict CO_2 increasingly with time, although the rate of this change may not be uniform.

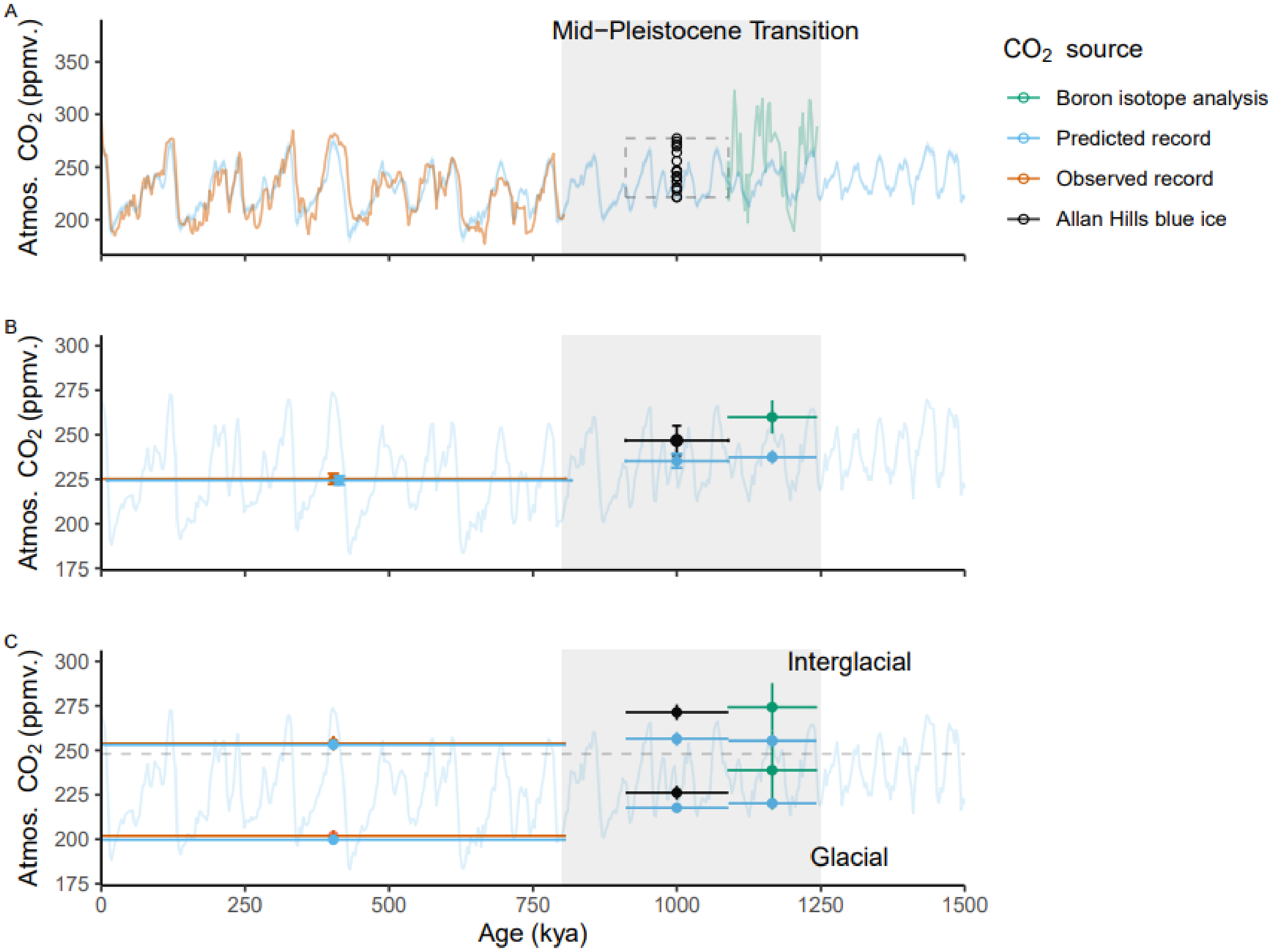

Figure 1: A) Comparison of our PRED-CO$_2$ (ppm) record to the current continuous composite record; CO$_2$ estimates from boron isotope analysis of benthic foraminifera shells (BOR-CO$_2$) (Chalk, et al., 2017), and direct CO$_2$ measurements from Allan Hills blue ice core data (BI-CO$_2$) (Higgins et al., 2015). Indicators for age uncertainty boundaries (± 89 ky) of the blue ice represented by dashed boundaries. B) The mean CO$_2$ concentration of the predicted record over the range of the observed composite record (offset for clarity) and the age uncertainty range of the BI-CO$_2$ data; mean concentrations of the observed composite CO$_2$ record; mean concentration of BI-CO$_2$ over its age uncertainty range; and the average BOR-CO$_2$ concentration. C) The same as B) but filtered by the highest and lowest 25th percentile of δ^{18}O to represent glacial and interglacial periods; but BI-CO$_2$ data filtered by highest and lowest 25th percentile of CO$_2$.

We define the interglacial and glacial thresholds of CO$_2$ to be the top and bottom 25th percentile of the δ^{18}O signal, respectively (following Chalk *et al.*, 2017). Applying this filtering to the predicted record and the observed composite CO$_2$ record for the post MPT (0–800 kya) interval demonstrates a close match (Fig. 1C). Applying the same filtering to our predicted record across the MPT (800–1500 kya) indicates a significant lowering of glacial stage CO_2 concentration; while no significant change in the interglacial stage CO_2 concentration was detected (ANOVA, $F_{1, 57} = 25.49$, $p = 4.86e^{-06}$; ANOVA, $F_{1, 57} = 1.47$ $p = 0.23$ respectively). As a change in radiative forcing (ΔRF) is a direct conversion of CO_2 concentration (IPCC, 2001), the PRED-CO_2 data would translate to a significant decline in ΔRF in glacial, but not interglacial stages across the MPT (as was suggested by Chalk *et al.*, 2007; Hönisch *et al.*, 2009).

Filtering BOR-CO_2, and BI-CO_2 by the same definition and averaging over their respective range ($\delta^{18}O$ linearly interpolated for BOR-CO_2 data) indicates that the model underpredicts relative to both the BI-CO_2 and BOR-CO_2 data for *both* glacial and interglacial stages during the MPT interval (800–1250 kya) (Fig. 1C). Overall, we see increasing difference between our predicted data and the sparse estimates over the MPT (BOR-CO_2 and BI-CO_2) going further back in time.

Various studies conclude that glacial stage draw-down of CO_2 occurs across the MPT in the absence of interglacial draw-down (e.g., Chalk et al., 2017; Hönisch *et al.*, 2009). This trend is seen in our predicted record, and in the filtered BI-CO_2 and BOR-CO_2 data (Fig. 1C). Importantly, the periodicity is consistent between our predicted record and the BOR-CO_2 data (i.e., the glacial and interglacial peaks and troughs coincide). Hence, the BOR-CO_2 and BI-CO_2 challenge the amplitude but not the periodicity of our predicted data. These results support rejection of our null hypothesis and provide quantitative evidence of a fundamental change in the carbon–climate feedback system having occurred across the Mid-Pleistocene Transition.

4 Discussion

In 2004, the community of Earth System modelers were issued a challenge: to predict what an 800 ky carbon dioxide record may look like prior to the final analysis of the EPICA Dome-C (EDC) ice core (Wolff *et al.*, 2004). Here we have adapted the EPICA Challenge to examine the MPT problem of the currently unknown mechanisms behind the transition from the 41 ky to 100 ky glacial cycle. However, unlike the EPICA challenge, we had the opportunity to compare our predictions to discrete data outside of the range of the continuous training data sets prior to the recovery of a continuous ice-core spanning the MPT. These data were direct CO_2 measurements from ~1 my old blue ice, and CO_2 estimates from the analysis of boron ratios in deep sea sediments (ca. ~1.1–1.25 mya). This has allowed us to preemptively examine differences in climate responses over the last 1.5 my. We now consider the implications of our results for hypotheses on the cause of the MPT.

4.1 Predicted changes to the climate–carbon cycle–cryosphere feedback system

The BOR-CO_2 and BI-CO_2 data supports the conclusion that an increase in the glacial to interglacial CO_2 difference has occurred across the MPT and that this difference is dominated by glacial stage CO_2 drawdown. We estimate the CO_2 glacial to

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interglacial difference has increased from ~36 ppm in the early MPT (ca. ~1.1–1.25 mya, BOR-CO_2) to ~52 ppm (observed composite CO_2 record) after the MPT (0–800 kya). Our PRED-CO_2 record also presents significant glacial-stage reduction over the MPT, although to a lesser extent to than BOR/BI-CO_2 (FIG. 1C). The reduction in only glacial stage CO_2 across the MPT is inconsistent with the theory that a long term decline in radiative forcing exerted by CO_2 (in both glacial and interglacial stages) was the main cause of the climate transition from the 40 ky world to the 100 ky world. This conclusion is consistent with results from Chalk *et al.* (2017) and Hönisch *et al.*, (2009) who associate the *glacial*-stage CO_2 draw-down to a change in the global carbon cycle across the MPT.

Glacial-stage CO_2 draw-down across the MPT may itself be a positive climate–carbon cycle–cryosphere feedback response to changes in ice sheet dynamics that favours enhanced glacial persistence over time (Chalk *et al.*, 2017). Potential processes allowing for the stabilization and persistence of ice sheets include the removal of sub-glacial regolith (Clark & Pollard, 1998), or Northern and Southern Hemisphere phase locking (Raymo *et al.* 2006; Raymo & Huybers, 2008). Either (or both) processes could allow for the persistence of ice sheets through obliquity (and potentially precession) dominated orbital cycles, i.e., a gradual rise in the threshold for deglaciation (Tzedakis *et al*., 2017). This persistence would promote glacial stage CO_2 decline, potentially through iron fertilisation of the Southern Ocean in response to increased ice volume and the planetary drying associated with colder climate conditions (Chalk *et al.*, 2017). In turn, further glacial stage build–up of ice sheets would be favoured by the reduced radiative forcing (Chalk *et al.*, 2017). Colder glacial temperatures that enhance the solubility of CO_2 in the oceans, and changes to ocean circulation have also been implicated in enhanced ocean storage of glacial-stage CO_2 (Hasenfratz *et al.*, 2019). Furthermore, relative sea level (SL) changes in the Mediterranean Sea (derived from a reconstruction through local benthic $\delta^{18}O$) (Rohling *et al*, 2014) between the early MPT and late Pleistocene reveal increased sensitivity to radiative forcing. That is, 1 Wm^{-2} reduction in radiative forcing (RF) by $CO_{2,}$ results in a more pronounced lowering of SL in the late Pleistocene than at the early MPT (Chalk *et al.*, 2017).

The clear offset between our PRED-CO_2 data and the sparse data pre-dating this record provides further evidence of a fundamental shift in the climate–carbon cycle–cryosphere feedbacks across the MPT. However, BOR-CO_2 and BI-CO_2 both have large concentration and timing uncertainties respectively, so the definitive test awaits a continuous ice core across the MPT. One modelling study that captures enhanced atmospheric CO_2 draw-down during glacial stages across the MPT is that of Willeit *et al.*, (2019). These investigators reconstructed atmospheric CO_2 over the past three million years under a regolith removal scenario, which can be compared to our modelled data (Fig. 2). Note the increasing difference with time between our predicted CO_2 level and that of Willeit *et al.*, (2019). Our simple model underpredicts CO_2 levels compared to the sparse observations (BOR/BI-CO_2) and Willeit *et al*., (2019). The implication is that addition physics, not captured in our LR04 stack-based predictions, is required to explain the divergence. These additional physics could include the gradual removal of sub-glacial regolith, allowing for increased "stickiness" of Northern Hemisphere ice sheets (as described by Clark and Pollard (1998), and the scenario for the model by Willeit *et al.*, (2019)); and/or the phase locking of the Northern and Southern

Hemisphere ice sheets at the precession frequency due to a transition to marine-based ice sheet margins in Antarctica (as described by Raymo *et al.*, (2006)). Both scenarios would have enabled the northern hemisphere ice sheets to persist past the obliquity paced threshold for deglaciation prior to the onset of the MPT.

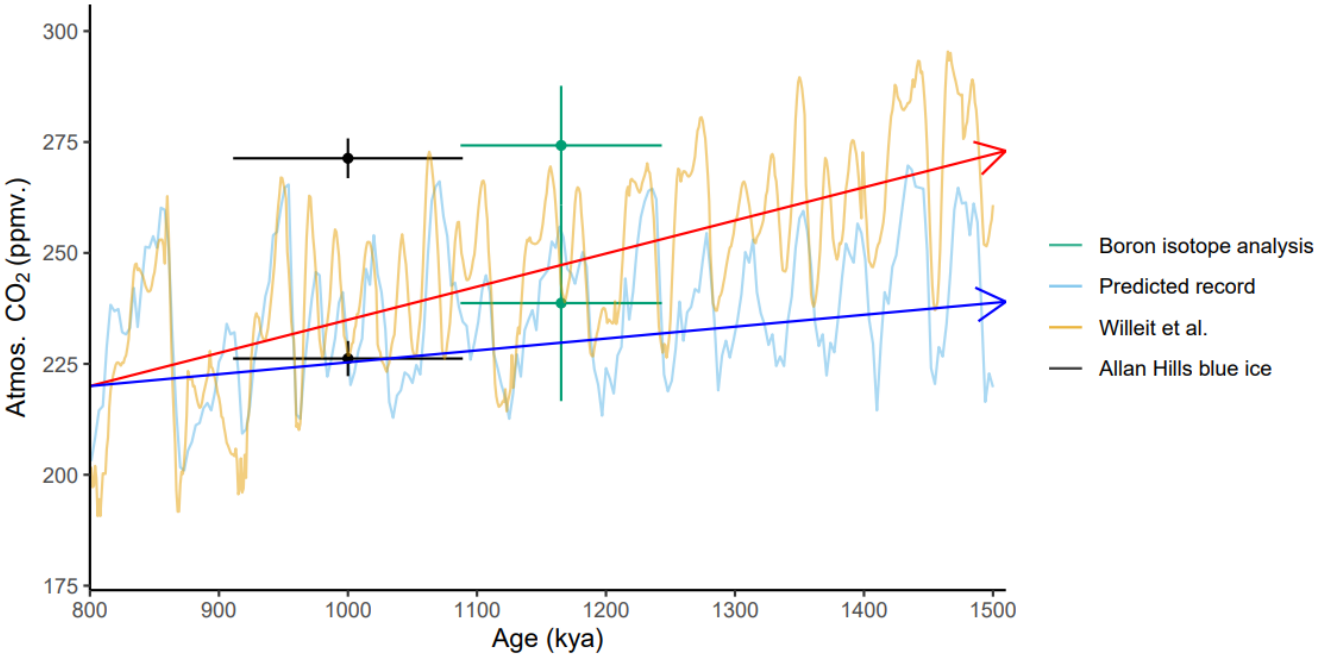

Figure 2: The modelled CO_2 record of Willeit *et al.*, (2019) overlayed on our predicted CO_2 record across and beyond the MPT (800 – 1500 kya). Arrows represent the trajectory of atmospheric CO_2 under two conditions: 1) CO_2 reconstructed under our null hypothesis that no change to the carbon – climate feedback system has occurred before and across the MPT (blue). 2) The trajectory of atmospheric CO_2 that more accurately represents the discrete measurements/estimates we have across the MPT (red).

4.2 Our model with respect to the phase-locking hypothesis

The predicted CO_2 record presented in this study cannot decisively test the phase locking hypothesis for the MPT until continuous oldest ice records have been recovered. Being entirely based on the LR04 Benthic Stack, our predictions inherit all the observed power spectra in the training data (Fig. A). Our predictions also inherit the climate–carbon cycle–cryosphere relationships over the past 800 ky during which time the Northern and Southern Hemisphere ice sheets have been in phase with each other on orbital timescales (Raymo *et al.*, 2006). For this reason, differences between the observed oldest ice records and our predicted data will shed light on the phase locking hypothesis. If the Northern and Southern hemisphere ice sheets did vary out of phase in the "40 ky world" then we would expect to see large discrepancies between the PRED-CO_2 record presented here and the realised data.

Conclusions

Here we have presented a predicted CO_2 record extending past the MPT. Our predictions are based on the relationships between CO_2, sea level, global ice volume and ocean temperature over the past 800 ky and therefore assume that these relationships have remained constant from 800–1500 kya; this has defined our null hypothesis. The departure of our predicted CO_2 record across the MPT from existing sparse data outside of the current continuous record reveals that climate–carbon cycle–cryosphere relationships over the last 800 ky do not apply across and prior to the MPT. Our results provide quantitative support of a fundamental change in the internal carbon–climate feedback systems of the earth over the Mid-Pleistocene Transition. Comparison of the predictions from our simple model to real data, once gathered, from 1.5 my old ice will provide further constraints on the processes involved in the MPT.

Appendices

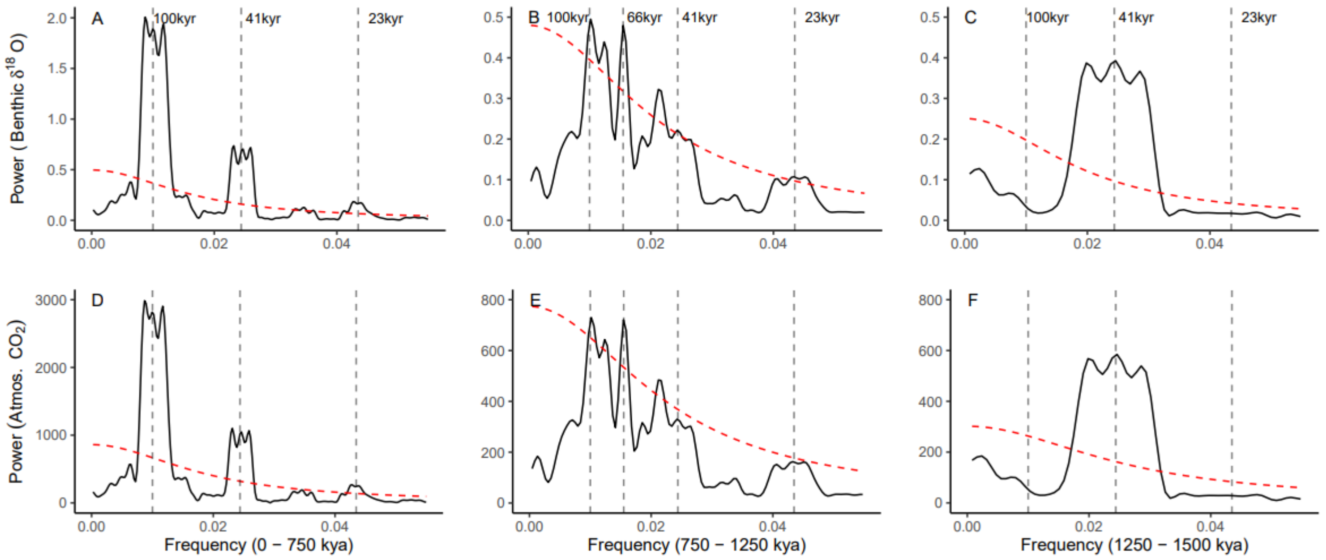

Figure A: Thomson Multi–taper Method (MTM) spectral analysis representing relative power of signal periodicity for: A) Benthic $\delta^{18}O$ after the Mid–Pleistocene Transition (MPT); B) Benthic $\delta^{18}O$ across the MPT (800–1250 kya); C) Benthic $\delta^{18}O$ prior to the onset of the MPT (1250 kya–1500 kya); D) CO_2 after the MPT; E) CO_2 across the MPT; F) CO_2 prior to the onset of the MPT. Each with a robust AR (1) 95 % Confidence interval (red dashed line).

Author contributions

Project design by Jordan R.W. Martin, Joel Pedro, Tessa R. Vance. Data analysis and writing led by Jordan Martin with contributions from Joel Pedro and Tessa R. Vance.

Competing interests

The authors declare that they have no competing interests.

Disclaimer

This study, to the best of the author(s) knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text of the study.

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Data availability

Data will be publicly archived during the review process and by publication.

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