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

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Abstract. During the Mid-Pleistocene Transition (MPT), ca. 1250–800 kya, the Earth's glacial cycles changed from 41 kyr to 100 kyr 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 is 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.~~ Here we present results from a simple generalized least squares model that predicts atmospheric CO_2 out to 1.5 Myr. Our prediction utilises existing records of atmospheric carbon dioxide (CO_2) from Antarctic ice cores spanning the past 800 kyr along with the existing LR04 benthic $\delta^{18}O_{calcite}$ stack (Lisiecki & Raymo, 2005) from marine sediment cores. Our predictions assume that the relationship between CO_2 and benthic ~~$\delta^{18}O$~~ $\delta^{18}O_{calcite}$ over the past 800 thousand years can be extended over the last one and a half million years. The ~~implied~~ implicit null hypothesis is that there has been no fundamental change in ~~the global climate–carbon cycle–cryosphere feedback systems across the MPT~~. feedbacks between atmospheric CO_2 and the climate parameters represented by benthic $\delta^{18}O_{calcite}$, global ice volume and ocean temperature.

~~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.

We test the GLS-model predicted CO_2 concentrations against observed blue ice CO_2 concentrations, δ^{11}B-based CO_2 reconstructions from marine sediment cores and δ^{13}C of leaf-wax based CO_2 reconstructions (Higgins *et al*., Yan *et al*., 2019 and Yamamoto *et al*., 2022). We show that there is not clear evidence from the existing blue ice or proxy CO_2 data to reject our predictions nor our associated null-hypothesis. A definitive test and/or rejection of the null hypothesis may be provided following recovery and analysis of continuous oldest ice core records from Antarctica, which is still several years away. The record presented here should provide a useful comparison for the oldest ice core records and opportunity to provide further constraints on the processes involved in the MPT.

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 and is characterised by a change from regularly paced 40 thousand year (kyr)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). To resolve the forcings and feedbacks involved in this transition, multiple nations are targeting recovery of continuous ice cores spanning the MPT under the framework of the International Partnerships in Ice Core Science (IPICS) oldest ice core challenge (IPICS, 2020).

The purpose of the current study is to make a simple prediction of atmospheric CO_2 across the MPT. Cross-comparison of our and other predicted CO_2 records against observed MPT CO_2 data will aid in testing competing hypotheses on the cause of the transition, in particular the role of carbon cycle changes.

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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. A common element in many of these, is internal climate/earth system changes which allow for the development of thicker, more extensive ice sheets that could endure insolation peaks corresponding to the 23 kyr precession and 41 kyr obliquity cycles, i.e., an increase in the threshold for deglaciation and altered sensitivity to orbital forcings (Tzedakis *et al*., 2017; McClymont *et al.*, 2013). Among the prominent hypotheses are the following three.

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).

1) A long term decrease in radiative forcing due to a secular reduction in atmospheric CO_2 across the transition (e.g. Berger *et al.*, Hönisch *et al.*, 2009; 1999, Raymo *et al.*, 1988). According to this view, reduced radiative forcing drives the formation of larger and more stable ice sheets.
2) Progressive removal of sub-glacial regolith during the 41 kyr glacial cycles. Clark & Pollard (1998) proposed that ice sheet basal sliding prior to the MPT was enhanced by the presence of a low-friction sedimentary regolith layer between the Laurentide ice sheet and the crystalline bedrock. According to this view, progressive removal of this sedimentary layer then favored the development of larger and more persistent post-MPT ice sheets.
3) Phase-locking of the Northern and Southern Hemisphere ice sheets. In frequency spectra of the global marine benthic $\delta^{18}O$ record (Fig. 1) there is no evidence of the precession (23 kyr) component of northern hemisphere insolation prior to the MPT; the spectra is dominated by the obliquity (41 kyr) component (Fig. 1C). Emergence of significant precession and eccentricity 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 (Raymo & Huybers, 2008). According to this view, during the MPT the precession-paced changes to fall into phase between the two hemispheres, such that the precession signal emerges (Raymo *et al.*, 2006). In this view the global synchronization of ice volume drives the formation of larger and more stable ice sheets.

These hypotheses are not mutually exclusive. For a recent review on the cause of the MPT see Berends *et al.* (2021).

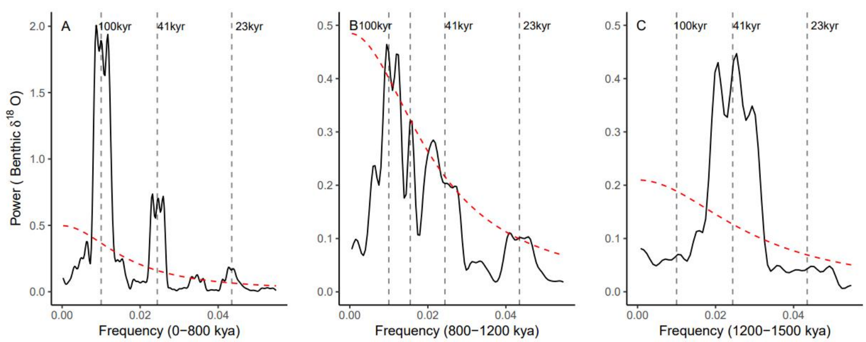


Figure 1: Thomson Multi–taper Method (MTM) spectral analysis representing relative power of signal periodicity for: A) Benthic $\delta^{18}O$ stack after (0–800 kya) the Mid–Pleistocene Transition (MPT); B) Benthic $\delta^{18}O$ across the MPT (800–1200 kya); C) Benthic $\delta^{18}O$ prior to the onset of the MPT (1200 kya–1500 kya). Each with a robust AR (1) 95 % Confidence interval (red dashed line). Benthic $\delta^{18}O$ stack data from Lisiecki and Raymo (2005).

~~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.

For a long term decrease in radiative forcing by atmospheric CO_2 to be the cause of the MPT, the reduction in CO_2 would be expected in both glacial and interglacial stages (Chalk *et al*., 2017). However, low resolution boron-isotope-based CO_2 reconstructions by Hönisch *et al*., (2009), and Chalk *et al*., (2017) suggest that glacial-stage CO_2 drawdown occurred over the MPT in the absence of interglacial CO_2 drawdown. Glacial-stage CO_2 draw-down across the MPT may be a positive climate–carbon cycle feedback to changes in ice sheet dynamics, including CO_2 drawdown by enhanced iron fertilisation of the Southern Ocean in response to exposed continental shelves due to lower sea level, as well as planetary drying associated with colder climate conditions (Chalk *et al*., 2017). Colder glacial temperatures that enhance the solubility of CO_2 in the oceans, and reduced abyssal ocean ventilation has also been implicated in enhanced glacial-stage ocean storage of CO_2 (McClymont *et al*., 2013; Hasenfratz *et al*., 2019).

Testing of hypotheses on the cause of the MPT is currently limited by the lack 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 key priority in ice core research (IPICS, 2020). Multiple national and international projects have commenced, or are soon to commence, drilling for 'oldest ice' (see e.g. Shugi, 2022). 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 800–400 kya based on the existing 400 kyr Vostok ice core record (Wolff *et al*., 2004). Here, we use a generalised least squares (GLS) model trained on continuous climate archives to predict a CO_2 record out to 1.5 Mya. We utilise two primary data sets for the GLS model: the existing 800 kyr ice core composite record of atmospheric CO_2 (Bereiter *et al.*, 2015) and the LR04 benthic stack of 52 globally-distributed records of the ^{18}O to ^{16}O ratio of fossil benthic foraminifera calcite (hereafter referred to as the LR04 $\delta^{18}O$ benthic stack). The $\delta^{18}O$ ratios in the LR04 benthic stack are governed by ocean temperature and global ice volume at the time the foraminifera lived, with higher values indicating both increased ice volume and a colder climate.

Fig. 2 shows a scatter-plot of the LR04 $\delta^{18}O$ benthic stack versus observed ice core CO_2 over the past 800 kyr. Both data sets are binned to equivalent 3-kyr time steps (Methods). The Pearson's correlation coefficient (r) between the data sets is -0.82 ($p < 0.05$) indicating that ~68% of the variance in observed CO_2 is shared with the LR04 $\delta^{18}O$ benthic stack. This strong relationship provides an initial rationale for using the LR04 $\delta^{18}O$ benthic stack as an input parameter to predict CO_2 beyond 800 kyr. Mechanistically, multiple processes are expected to contribute to the shared variance. A first order factor is the dependency of CO_2 solubility on ocean temperature (e.g. Millero, 1995). From the simple solubility perspective, colder climate states with increased ice volume and colder ocean temperatures will drive increased ocean uptake of CO_2 (Berends *et al*., 2021). However, the solubility effect only accounts for a portion of observed glacial CO_2 drawdown (Archer *et al*., 2000). Multiple additional contributors to the shared variance are proposed in the literature. These include (not exhaustively), direct radiative forcing of ice volume changes by CO_2 (e.g. Shackleton *et al*., 1985); the impact of ice volume/sea level changes on atmospheric CO_2 via ocean productivity and carbonate chemistry changes (e.g. Broecker, 1982; Archer *et al*., 2000; Ushie and Matsumoto, 2012); CO_2 drawdown during periods of high ice volume by increased iron fertilization (e.g. Rothlisberger *et al*., 2004; Martinez-Garcia *et al*., 2014) and enhanced sea ice extent during periods of high ice volume capping the ventilation of CO_2 from the ocean interior at high latitudes (Stephens and Keeling, 2000).

A quantitative separation and attribution of the processes linking global ice volume, ocean temperature and atmospheric CO_2 on millennial to orbital timescales is not currently available (e.g. Archer *et al*., 2000; Sigman *et al*., 2010; Gottschalk *et al*., 2019) and will not be attempted here. Rather, we make the simple assumption that the relationships between the LR04 benthic $\delta^{18}O$ stack and CO_2 can be extended beyond 800 kya and use regression modelling between benthic $\delta^{18}O$ and CO_2 to make a predictions of CO_2 spanning 800–1500 kya. The deliberately simple implicit assumption, and null hypothesis, is that there is no change to the feedback processes linking benthic $\delta^{18}O$ and CO_2 before and after the MPT.

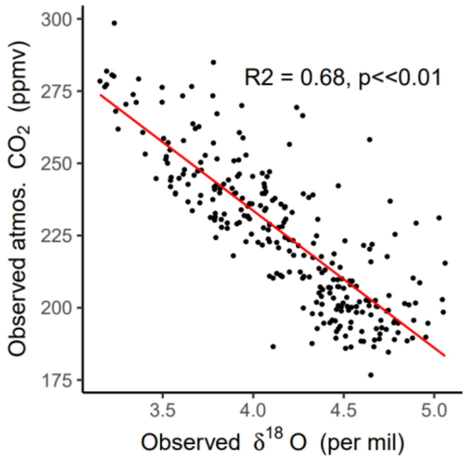


Figure 2: Scatter plot of the composite observed atmospheric CO_2 record (Bereiter *et al*., 2015) against the LR04 benthic stack of marine $\delta^{18}O$ records (Lisiecki & Raymo, 2005). Red line is a linear line of best fit (R^2 = 0.68; $p < 0.05$).

To test the null hypothesis, in advance of the recovery of a continuous ice core, we compare our predicted CO_2 record to two sets of low-resolution ice core data that exist outside the current 800 kyr observed CO_2. These data come from direct CO_2 measurements from ancient "blue ice" from the Allan Hills in East Antarctica (hereafter referred to as BI-CO_2) from ca. 1 Mya (Higgins *et al.*, 2015) and 1.5 Mya (Yan *et al.*, 2022). We use the term blue ice to describe deep, ancient glacial ice that has been brought nearer to the surface of an ice sheet by ice flow. Blue ice is sampled by cutting trenches or shallow drilling of up to several hundred meters (e.g. Higgins *et al*., 2015). The vertical migration of blue 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 records alone do not provide a continuous CO_2 record across the MPT. We also compare our predicted record to existing proxy-CO_2 reconstructions from boron-isotope analysis of benthic foraminfera in marine sediment records (Chalk, *et al*., 2017; Dyez *et al.*, 2018; Guillermic *et al.*, 2022), leaf wax $\delta^{13}C$ carbon isotope ratios (Yamamoto *et al*., 2022) and predictions from previous models of various complexities (van de Wal *et al*., 2011; Willeit *et al.* 2019). We conclude with discussion of the implications of our results and data-comparisons for the understanding MPT dynamics.

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.~~

We use a generalised least squares (GLS) model to predict atmospheric CO_2 from the LR04 benthic $\delta^{18}O$ stack (Fig. 3A and B). We apply an AR(1) correlation factor to account for autocorrelation in the data. The AR(1) correlation factor yielded the lowest Akaike information criterion (AIC) value from a test of multiple correlation factors. To obtain common time steps and resolution between the predictor (LR04 benthic $\delta^{18}O$ stack) and response (CO_2) variables, we re-grid the LR04 benthic stack and Bereiter *et al.*, (2015) CO_2 data into time bins with a resolution of 3-kyr. The GLS regression model was applied over the 0–800 kyr range of the predictor and response variables as follows:

$$CO_2 = 33.37 \times \delta^{18}O + 365.15, autoregressive\ (AR) factor: 1$$

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). To estimate the GLS model uncertainty and sensitivity we took a bootstrap approach, selecting a random 50% subset of our data and re-running the model 1000 times to determine 95% confidence intervals for the predictions.

Uncertainties in the independent age scales of both the LR04 stack and the compiled CO_2 record are inherited by our GLS model and its predictions. The LR04 stack includes 57 globally-distributed benthic $\delta^{18}O$ sediment core records. The age models for these cores are independently constructed from the average sedimentation rates of each core, assuming global sedimentation rates have remained relatively stable, and with tuning to a simple ice model based on 21 June insolation at 65°N (Lisiecki & Raymo, 2005). The authors estimate uncertainty of 6 kyr from 1.5 – 1.0 Mya and 4 kyr from 1 – 0 Mya (Lisiecki & Raymo, 2005). The observed CO_2 composite ice core record for the past 800 kya (Bereiter at al., 2015) uses six independent dating methods for various core locations both spatially across Antarctica, and stratigraphically for different sections of the same core. The age uncertainty in the gas timescale has a median over the 0 – 800 kya interval of 2 kyr, but individual uncertainties can reach up to 5 kyr (Veres *et al* 2013; Bazin *et al*., 2013). The relative age uncertainties between these input variables may diminish the regression or in some instances lead to spurious correlation. However, we expect any such effects are minor on the basis that our predictions show little sensitivity to the bootstrap analysis with 1000 iterations of re-computing the regression after removing 50% of data (see Fig. 3B, C and Discussion).

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.

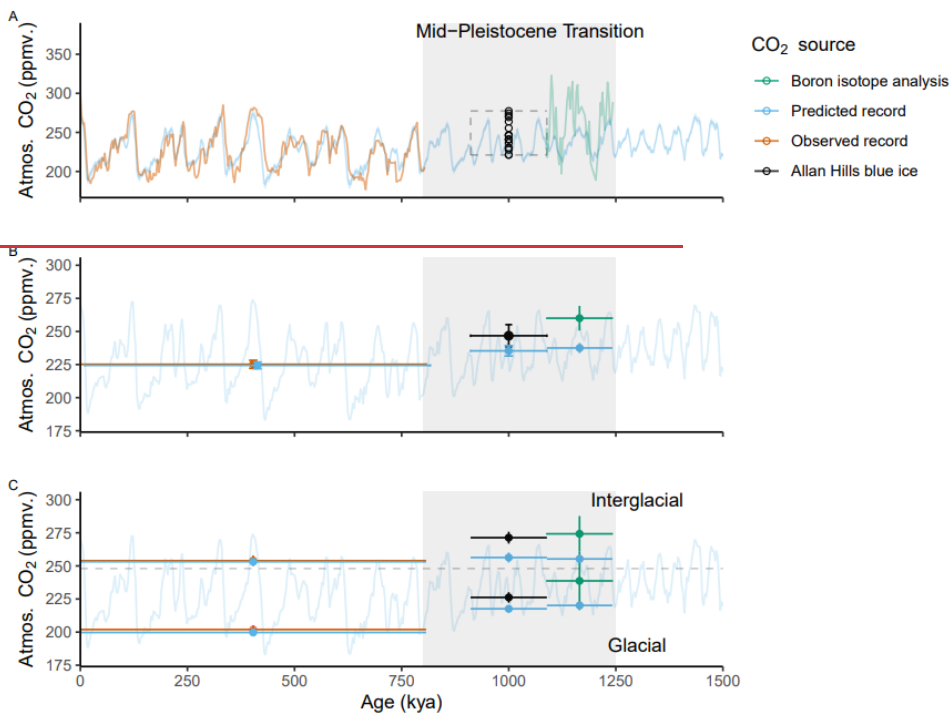


Figure 1: A) Comparison of our PRED-CO_2 (ppm) record to the current continuous composite record; CO_2 estimates from boron isotope analysis of benthic foraminifera shells (BOR-CO_2) (Chalk, et al., 2017), and direct CO_2 measurements from Allan Hills blue ice core data (BI-CO_2) (Higgins et al., 2015). 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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.

Fig. 3B shows the time series of our LR04 benthic $\delta^{18}O$ stack-based GLS model predictions of atmospheric CO_2 (PRED-CO_2) over the past 800 kyr, in comparison to the observed ice core CO_2 record from Bereiter at al., (2015). The correlation coefficient (r^2) between the predicted and observed records is 0.68 ($p \ll 0.01$). Our PRED-CO_2 record out to 1.5 Mya is also shown, overlain with observed Allan Hills blue ice CO_2 (BI-CO_2) datasets of age 1000 ± 89 kya (Higgins *et al.*, 2015) and 1.5 Mya ± 213 kyr (Yan *et al.*, 2022).

We evaluate the PRED-CO_2 record against the observed CO_2 data according to criteria of mean concentrations across the common intervals, and mean concentrations in the glacial and interglacial subsets of the data. First, the mean CO_2 concentration over the common intervals (Fig 3C). From 0–800 kya the mean concentration in observed (Bereiter at al., 2015) and PRED-CO_2 data are in close agreement (225.2 ± 3.03 ppm versus the predicted 225.1 ± 2.5 ppm respectively; uncertainties are 95% confidence intervals, i.e. 1.96σ). In the 1000 ± 89 kya interval (i.e. averaged across the age uncertainty of the Higgins (2015) blue ice data) the BI-CO_2 concentration is ~ 11ppm higher than PRED-CO2 (246.7 ± 8.4 ppm versus the predicted 235.5 ± 3.9 ppm), this difference is not significant at the 95% confidence level. For the 1.5 Mya ± 213 kyr interval, the mean BI-CO_2 concentration is ~10 ppm lower than PRED-CO2 (231.9 ± 5.6 ppm versus the predicted 241.7 ± 2.5 ppm), which is marginally significant at the 95% level. Comparisons of mean levels across intervals spanning multiple glacial and interglacial cycles may be biased if (as is likely) the blue ice data is not sampling glacial and interglacial values with the same uniformity as a continuous record.

To address this, we define the glacial and interglacial thresholds of PRED-CO_2 to be respectively the lower and upper 25th percentiles of the LR04 δ^{18}O predictor variable (following Chalk *et al.*, 2017). Filtering the observed (Bereiter at al., 2015) CO_2 record and our predicted CO_2 record according to these definitions we find a very close match for glacial (202.0 ± 3.2 versus the predicted 199.7 ± 1.7 ppm) and interglacial intervals (253.9 ± 4.1 ppm versus the predicted 253.1 ± 2.3 ppm), over the past 800 kya (see Fig. 3D). For blue ice (BI_CO_2) data, a corresponding LR04 isotope signal could not be confidently applied to the measured CO_2 concentration due to the uncertainties associated with blue ice aging; therefore, we defined the glacial and interglacial thresholds of blue ice data according to the top (interglacial) and bottom (glacial) 25th percentiles of actual CO_2. Applying this to the 1000 ± 89 kya interval finds that observed BI-CO_2 data is ~ 9 ppm higher than PRED-CO_2 during the glacial stages (226.2 ± 4.0 ppm versus the predicted 217.6 ± 2.3 ppm) and ~ 15 ppm higher than PRED-CO2 during the interglacial stages (271.3 ± 4.5 versus the predicted 256.3 ± 3.8 ppm). These differences are significant with respect to the constrained uncertainties. In contrast, during the 1.5 Mya ± 213 kyr interval, the mean BI- CO2 concentration is not significantly different to PRED-CO2 in either glacial (217.6 ± 2.3 versus the predicted 224.2 ± 6.6 ppm) or interglacial stages (256.3 ± 3.8 versus the predicted 261.1 ± 6.3 ppm). These comparisons, particularly the agreement at 1.5 Myr, indicate that PRED-CO_2 is not drifting systematically away from the existing observed BI-CO_2 data. In our view the disagreement at 1.0 Myr, where BI-CO_2 is elevated with respect to PRED-CO_2, does not give sufficient cause to reject the GLS model, it could of course be a failing in the model and/or could be due to potential biases in the blue ice data, for example elevated CO_2 concentrations due to in-situ CO_2 production in blue ice (see Discussion).

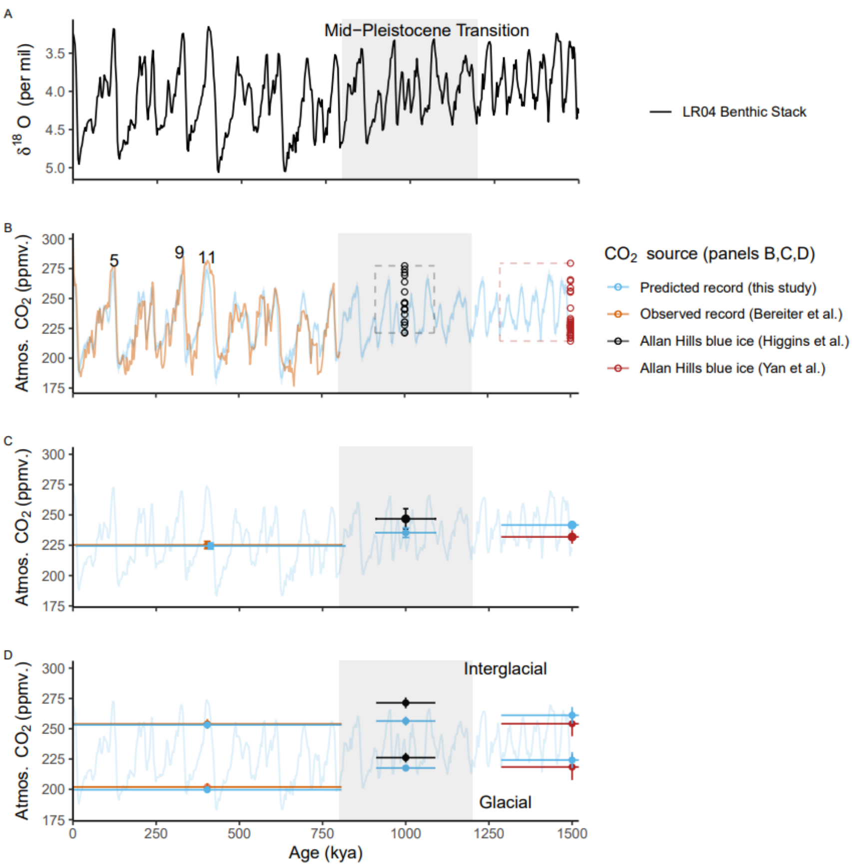


Figure 3: A) The LR04 Benthic Stack of 57 globally distributed $\delta^{18}O$ records (Lisiecki & Raymo, 2005). B) Comparison of our PRED-CO_2 (ppm) record to the current continuous composite record (0–800 kya); and to direct CO_2 measurements from Allan Hills blue ice cores (BI-CO_2) ca. 1 Mya (± 89 kyr) (Higgins *et al.*, 2015) and ca. 1.5 Mya (± 213 kyr) (Yan *et al.*, 2022). Age uncertainty boundaries for the BI-CO_2 data are represented by dashed box boundaries. Marine isotope stages 5, 9, and 11 are numbered on the plot according to Lisiecki & Raymo (2005). C) Mean concentrations of the PRED-CO_2 and observed composite CO_2 records over the range of the observed composite record (offset for clarity), and the mean concentrations of the PRED-CO_2 and BI-CO_2 data at 1 Mya and

again at 1.5 Mya averaged over the age uncertainty range of each BI-CO_2 data set. D) As for C) however filtered by the upper and lower 25th and 75th percentiles to estimate glacial and interglacial periods.

We now consider long-term trends in interglacial and (separately) glacial CO_2 levels across the past 1.5 Myr in PRED-CO_2 and in the existing ice core CO_2 data. For PRED-CO_2 there is no significant difference between CO_2 concentrations in the interglacial stages of the 1.5 Mya ± 213 kya, 1000 ± 89 kya and 0–800 kya windows (Fig 4 D, blue bars). In the ice core observations, interglacial levels at 1.5 Mya in BI-CO_2 are also within the uncertainties of those in the 0–800 kya interval. Notably, the BI-CO_2 concentrations in the 1000 ± 89 kya interval appear elevated with respect to the 0–800 kyr and 1.5 Mya ± 213 kya intervals, however this elevated (ca. 271 ppm) level is consistent with the observed interglacial CO_2 concentration during interglacials 5, 9 and 11 (Fig 3B). Overall, there is no indication in the observed ice core CO_2 data or in PRED-CO_2 for a long-term trend in *interglacial* CO_2 levels across the past 1.5 Myr.

In comparison, there are significant declines in glacial CO_2 levels across the MPT in PRED-CO_2 and the observed ice core data. For PRED-CO_2, glacial CO_2 concentrations are not significantly different during the 1.5 Mya ± 213 kya and 1000 ± 89 kya windows. However, across the MPT, PRED-CO_2 glacial concentrations drop by ~18 ppm. This pattern is consistent with the observed data, where glacial CO_2 levels are also not significantly different between the 1.5 Mya ± 213 kya and 1000 ± 89 kya windows (217.6 ± 2.3 and 226.2 ± 4.0 ppm, respectively) and then fall by 24 ppm to the 0–800 kyr observed glacial mean of 202.0 ± 3.2 ppm. Glacial-stage draw-down of CO_2 across the MPT in the absence of interglacial draw-down is consistent with previous observations based on the boron-isotope-based CO_2 reconstructions (e.g., Chalk *et al*., 2017; Hönisch *et al*., 2009 and see Discussion). In the following section we also compare PRED-CO_2 data to boron-isotope-based and other CO_2 proxy records covering the 0 to 1.5 Myr interval.

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 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.

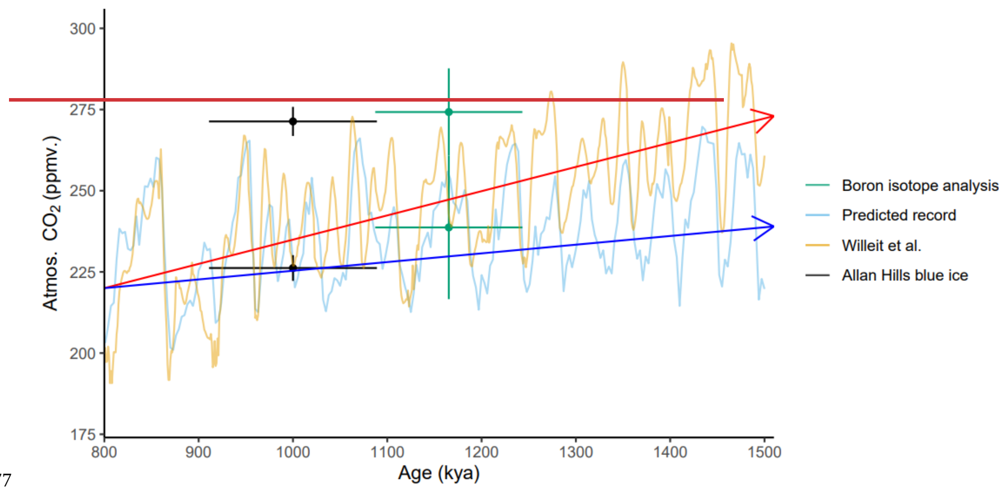


Figure 2: The modelled CO_2 record of Willeit *et al.*, (2019) overlayed on our predicted CO_2 record across and beyond the MPT (800 – 1500 kya). Arrows represent the trajectory of atmospheric CO_2 under two conditions: 1) CO_2 reconstructed under our null hypothesis that no change to the carbon – climate 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.

Our objective with this manuscript was to generate the simplest reasonable model to predict CO_2 from the LR04 $\delta^{18}O$ benthic stack and to test the predictions against available observations. It is possible that the fit between observed and our predicted CO_2 data could be further improved using a non-linear approach. However, we refrain from a non-linear approach for several key reasons. First, a scatter plot of the LR04 $\delta^{18}O$ benthic stack versus observed ice core CO_2 over the past 800 kyr yields a Pearson's correlation coefficient (R) of -0.82 (Fig. 2), indicating that ~68% of the variance in observed CO_2 is shared with the benthic stack. Importantly, there is no evidence in this scatter plot for departure from the linear relationship at high or low CO_2 or benthic $\delta^{18}O$ levels. Second, following the approach of Chalk *et al*., 2017 and interpreting the upper 25th percentile of CO_2 data as representing mean interglacial stage CO_2 and the lower 25th percentile of CO_2 data as representing mean glacial stages CO_2 levels, we see that our predicted interglacial mean value for the past 800 kyr (253.1 ± 2.3 ppm) closely overlaps with the observed interglacial mean value (253.9 ± 4.1 ppm) and similarly, the predicted glacial stage mean (199.7 ± 1.7 ppm) closely overlaps with the observed glacial stage mean (202.0 ± 3.2 ppm). Third, the predictions are remarkably insensitive to bootstrap analysis in which 50 % of that data are omitted with each iteration of the GLS model (Fig 1). Such insensitivity to the bootstrap analysis and accurate prediction of glacial *and* interglacial state CO_2 values would be unlikely in the case of major non-linear dependencies between the LR04 predictor and CO_2 response variables. Fourth, non-linear approaches would risk generating an improved fit due to statistical artefacts that do not meaningfully relate to any dependence between benthic $\delta^{18}O$ and CO_2. Finally, the specific causes and sources and sinks involved in glacial to interglacial and millennial-scale CO_2 variations still remain poorly constrained (e.g. Archer *et al*., 2000; Sigman *et al*., 2010; Gottschalk *et al*., 2019). Given this process-uncertainty, the GLS model fits our criteria of the simplest reasonable model. Further, the use of benthic $\delta^{18}O$ to predict atmospheric CO_2 has precedence; in response to the EPICA challenge (Wolff et al., 2004), N. Shackleton used this method to predict atmospheric CO_2 out to 800 kyr (Wolff, 2005). Furthermore, inverse modelling of CO_2 forced by the LR04 benthic stack has been undertaken by Berends et al. (2021a) and van de Wal et al. (2011).

There are several caveats with blue ice data that may affect its use to evaluate our GLS model predictions. The blue ice data may have been subject to diffusional smoothing of CO_2 (e.g. Yan *et al.*, 2019), which would act in the direction of elevating the (lower 25th percentile) assumed glacial concentrations above the glacial atmospheric values and reducing the (upper 25th percentile) assumed interglacial concentrations. There is also the potential for artificially elevated CO_2 concentrations in blue ice due in-situ respiration of CO_2 due to microbial activity in detrital matter. Respiration effects are screened for by measurements of $\delta^{13}C$ of CO_2, however it is difficult to demonstrate that all samples are unaffected (Yan *et al*., 2019). These uncertainties support our argument that the GLS-model predictions are not rejected by the available observed BI-CO_2 data.

We consider the BI-CO_2 date to provide the most reliable measurements of CO_2 concentration, in the absence of a continuous ice core record across the MPT. However, further comparison of our CO_2 predictions can also be made against CO_2 proxy data from non-ice core archives (Fig 4A). We consider here δ^{11}B-based atmospheric CO_2 reconstructions (Chalk *et al.*, 2017, Dyez *et al.* 2018 and Guillermic *et al.* 2022) and a recent atmospheric CO_2 reconstruction from δ^{13}C of leaf wax (Yamamoto *et al.*, 2022). The continuous δ^{11}B-based reconstructions of Dyez *et al.*, (2018) overlap PRED-CO_2 from ~1.38 – 1.5 Mya while the Chalk *et al*., (2017) reconstruction overlaps PRED-CO_2 from 1.09 – 1.43 Mya. Discrete reconstructions from Guillermic *et al.* (2022) are distributed non-uniformly across the 800 to 1.5 Mya interval. For the two continuous δ^{11}B-based reconstructions (Chalk *et al.*, (2017) and Dyez *et al.*, (2018)) the glacial CO_2 levels appear consistent with the PRED-CO_2 record, within their reported 30 – 60 ppm uncertainties. However, δ^{11}B-based interglacial stages in these reconstructions exceed those of the PRED-CO_2 record (Fig. 4A). The Guillermic *et al.* (2022) reconstructions suggest a larger range of CO_2 concentrations than the overlapping intervals of PRED-CO_2 and of the two continuous δ^{11}B-based reconstructions (Fig. 4A). The large range of the Guillermic *et al.* (2022) data and the high interglacial maxima in the Chalk *et al* (2017) and Dyez *et al*., (2018) data, all significantly exceed the range and interglacial maxima from the BI-CO_2 estimates. These discrepancies internally between different δ^{11}B-based CO_2 reconstructions and between the δ^{11}B-based reconstructions and the BI-CO_2 data, may be due to uncertainties associated with the δ^{11}B proxy transfer function. The δ^{11}B-based CO_2 reconstructions are dependent on assumptions about multiple components of the carbonate system, including local marine carbon chemistry and the CO_2 saturation state in the past and (Hönisch *et al*., 2009). Evidence that δ^{11}B-based reconstructions may overestimate interglacial stage CO_2 is also seen in data from Chalk *et al*., (2017) spanning ca. 0–250 kya, where the δ^{11}B-based interglacial CO_2 levels exceed the continuous ice core CO_2 record by ca. 30 ppm (not shown).

By comparison, the δ^{13}C of leaf wax data (Yamamoto *et al.*, 2022) has a similar glacial to interglacial range as PRED-CO_2, but a ca. 20ppm lower mean concentration than our predictions (Fig 4A). Hence, our PRED-CO_2 data fall lower than interglacial δ^{11}B-based interglacial levels but are higher than the δ^{13}C of leaf-wax based estimate. Given the evidence that δ^{11}B-based reconstructions are known to overestimate atmospheric CO_2 concentration in the continuous ice core record, we do not find cause from the existing CO_2 proxy data to reject our predictions nor our associated null-hypothesis.

We also compare our predictions to existing more complex model simulations (Fig 4B.). First, against a transient simulation using an intermediate-complexity earth system model (CLIMBER-2) by Willeit *et al.* (2019). This study suggests a combination of gradual regolith removal and atmospheric CO_2 decline can explain the long-term climate variability over the past 3Myr. Second, against a longer-term reconstruction by van de Wal *et al.* (2011) that utilises deep-sea benthic isotope records to reconstruct a continuous CO_2 record over the past 20 Myr. Our simple GLS model demonstrates a similar long-term trend and timing of glacial-interglacial signals and an atmospheric CO_2 level that sits approximately mid-way between the two more complex models.

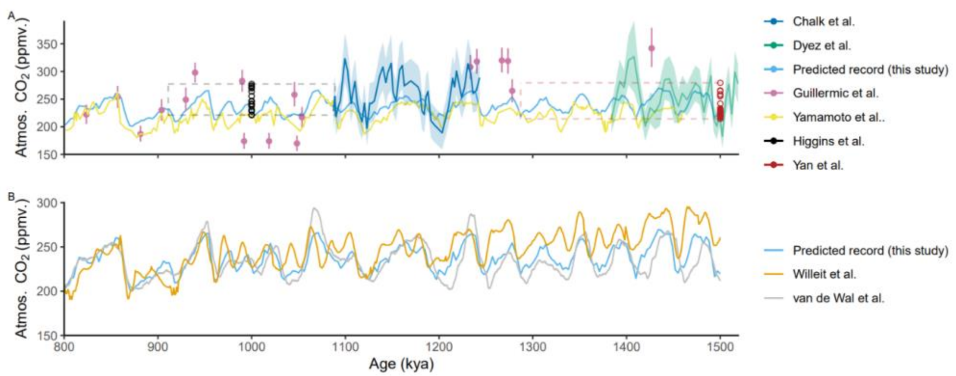


Figure 4: A) Predicted CO_2 (this work) compared to observed, proxy CO_2 estimates from a range of other sources: $\delta^{11}B$-based pCO_2 reconstructions and measurements by Dyez *et al.* (2018), Guillermic *et al.* (2022); Chalk *et al.*, (2017); blue ice CO_2 measurements by Yan *et al.* (2019) and Higgins *et al.* (2015); $\delta^{13}C$ leaf wax proxy reconstructions by Yamamoto *et al.* (2022). The dashed boxes indicate the dating uncertainty and range of the respective BI-CO_2 records. B) Our predicted record compared to various model simulations: a regolith removal hypothesis simulation by Willeit *et al.* (2019); and a high-resolution CO_2 reconstruction by van de Wal *et al.* (2011)

A complete and critical test of our and other CO_2 predictions awaits the upcoming analysis of the continuous oldest ice core records. We now discuss some potential applications of the PRED-CO2 record for hypothesis testing on the cause of the MPT.

PRED-CO_2 shows a long-term decline in glacial CO_2 across the MPT, but no long-term decrease in interglacial CO_2. This pattern is consistent with the boron-isotope-based CO_2 reconstructions shown earlier, where it is often described as an increase in the interglacial to glacial CO_2 difference (e.g., Chalk *et al*., 2017; Hönisch *et al*., 2009). Chalk *et al*, (2017) concludes that the MPT was initiated by a change in ice sheet dynamics and that longer and higher-ice volume post-MPT ice ages are sustained by carbon cycle feedbacks, in particular dust fertilization of the Southern Ocean. That fact that our LR04-based prediction of CO_2 captures this same trend, of declining glacial CO_2, reflects that LR04 benthic stack also features an increase in the interglacial to glacial benthic $\delta^{18}O$ difference across the MPT, which is dominated by the glacial decline (Fig 3A.). Here, a comparison of PRED-CO2 to a realised continuous oldest ice core record will be of value. The agreement or disagreement would inform on the proportionality of the CO_2 coupling with ice volume; if there were a major new or non-linear process across the MPT that changed the nature of coupling between CO_2 and ice volume the PRED-CO2 and observed CO_2 records would be expected to diverge.

Another avenue to use the PRED-CO2 record for hypothesis testing on the cause of the MPT concerns the phase locking hypothesis. The phase locking hypothesis is proposed to explain the absence of precession-related (23 kyr) periods in the LR04 benthic stack prior to the MPT (Fig 1), despite the strong precession cycle in insolation (Raymo *et al*., 2006, Morée *et al*., 2021). The key concept is that prior to the MPT the Northern Hemisphere and Antarctic ice sheets were responsive (in ice volume) to insolation changes in the precession band, but because precession forcing is out of phase between the hemispheres, the ice volume changes were opposing between the hemispheres and therefore cancelled in the benthic stack. This cancellation of the precession signal left insolation forcing in the 41 kyr obliquity band to dominate globally integrated ice volume changes expressed in the benthic stack. 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 precession forcing and to suppress ice sheet sensitivity to the obliquity band in favour of quasi-100kyr ice volume changes that are in phase between the hemispheres (Raymo *et al*., 2006).

Recently presented data from Yan *et al*. (2022), lend some support to the phase locking hypothesis, specifically with evidence that pre-MPT Antarctic temperature (and by extension ice volume) is positively correlated with a local precession-band insolation proxy based on the oxygen to nitrogen ratio of trapped air (Yan *et al*., 2022). Whereas the correlation becomes negative in the blue ice and continuous ice core data in the post-MPT record. If Yan *et al*., (2022) is correct and the phase locking hypothesis holds, then an implication is that prior to the MPT, Antarctic climate, Antarctic ice volume and by extension Southern Ocean climate conditions, would fall out of phase with the LR04 benthic stack. To now extend the argument to potential impacts on CO_2 exchange, if the phase locking hypothesis holds, then prior to the MPT the Antarctic and Southern Ocean climate conditions and by extension the Southern Ocean mechanisms of CO_2 exchange described earlier, would also be expected to fall out of phase with the benthic stack. Since our regression model assumes continuation of the in-phase relationship between the benthic stack and Antarctic and Southern Ocean climate conditions (as inherited from the post-MPT training data) we would expect to see major disagreement between our pre-MPT CO_2 predictions and a realised oldest ice continuous ice core CO_2 record.

Conclusions

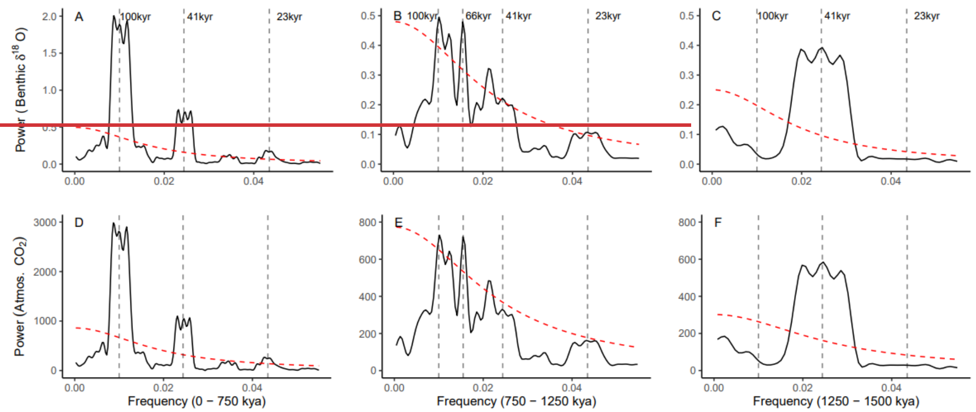
Here we have presented a predicted CO_2 record extending past the MPT. Our predictions are based on the relationships between CO_2, sea level, global ice volume and ocean temperature over the past 800 ky and therefore assume that these relationships have remained constant from 800–1500 kya; this has 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.

Summary and Conclusions

In this study we have used a simple generalised least squares (GLS) model to predict atmospheric CO_2 from the LR04 benthic $\delta^{18}O$ stack for the period spanning the mid-Pleistocene transition, 800–1500 kyr. Our CO_2 prediction is therefore based on the assumption that the physical processes linking CO_2, sea level, global ice volume and ocean temperature over the past 800 kyr do not fundamentally change across the 800–1500 kya time period. The null-hypothesis is deliberately simplistic on the basis that differences between our predictions and observed or proxy CO_2 records may be revealing of the physical processes involved in the mid-Pleistocene Transition.

We made initial tests of the null hypothesis by comparing our predicted CO_2 record to existing discrete blue ice CO_2 records and other non-ice-core proxy-CO_2 records from the 800–1500 kyr interval. Our predicted CO_2 concentrations do not show any systematic departure from observed blue ice CO_2 concentrations. The predictions are marginally lower (during glacial *and* interglacial stages) than those observed in blue ice from 1000 ± 89 kya and marginally higher than observed in blue ice data from 1.5 Mya ± 213 kyr. Our predictions were generally lower than interglacial $\delta^{11}B$-based-CO_2 reconstructions, but higher than recent $\delta^{13}C$ of leaf-wax based CO_2 reconstructions. Overall, we do not find clear evidence from the existing blue ice or proxy CO_2 data to reject our predictions nor our associated null-hypothesis. The definitive test of our and other CO_2 predictions therefore awaits the future analysis of the upcoming continuous oldest ice core records. The PRED-CO2 record presented here should provide a useful comparison to forthcoming oldest ice core records and opportunity to 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 δ^{18}O after the Mid-Pleistocene Transition (MPT); B) Benthic δ^{18}O across the MPT (800–1250 kya); C) Benthic δ^{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.~~

Project design by JRWM, JBP and TRV. Data analysis and writing led by JRWM with contributions from all authors.

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

PRED-CO2 data will be publicly archived at the Australian Antarctic Data Centre (https://data.aad.gov.au/ >>full link provided upon publication<<).

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

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