# Regional benthic $\delta^{18}O$ stacks for the "41-kyr world" - an Atlantic-Pacific divergence between 1.8-1.9 Ma

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## Key points

- New Atlantic and Pacific benthic $\delta^{18}O$ stacks show different patterns between 1.8-1.9 Ma.
- The Atlantic-Pacific difference in this portion of the 41-kyr world may be caused by regional sensitivity to relatively strong precession.
- Regional benthic $\delta^{18}O$ stacks are preferable to global stacks for stratigraphic alignment.

## Abstract

Benthic $\delta^{18}O$ stacks are the benchmarks by which paleoceanographic data are stratigraphically aligned and compared. However, a recent study found that between 1.8-1.9 million years ago (Ma) several Ceara Rise records differed substantially from the widely used LR04 global stack. Here, we use new Bayesian stacking software to construct regional stacks and demonstrate a geographical divergence in benthic $\delta^{18}O$ features from 1.8-1.9 Ma. The pattern of isotopic stage features observed in the Ceara Rise is widespread throughout the Atlantic and differs notably from Pacific records. We propose that this regional difference in isotopic stages may be the result of relatively strong precession forcing and weaker obliquity forcing between 1.8-1.9 Ma. In accordance with the Antiphase Hypothesis, our results highlight a period of apparent sensitivity to regional precession forcing that is masked during most of the 41-kyr world due to the amplitude modulation of obliquity forcing.

## Plain language summary

To determine the age of deep-sea sediments, often the oxygen isotope ratios of microfossils are measured and compared to a previously compiled global benchmark. Recently, one of the most widely used oxygen isotope benchmarks has been challenged based on a comparison with several Atlantic records. In this study we assess several lines of evidence including utilizing newly available data and software. We confirm the challenge to the global oxygen isotope benchmark and find that it is more widespread than originally realized. Particularly, we find that oxygen isotope records display different patterns between the Atlantic and Pacific Oceans from 1.8-1.9 million years ago (Ma). We propose that this difference is the result of the opposing seasonal solar radiation anomalies received by the northern and southern hemispheres, which exhibited particularly large amplitudes during this time. Our study adds supporting evidence to a hypothesis that explains the dominant frequency of climatic cycles from 1.2-2.6 Ma.

## Introduction

Benthic $\delta^{18}O$ stacks set benchmarks for comparison of paleoceanographic data (e.g., Ahn et al., 2017; Lisiecki & Raymo, 2005; Martinson et al., 1987) and are used to evaluate ice sheet evolution and climate responses to orbital forcing (e.g., Liautaud et al., 2020; Raymo et al., 2006; Tzedakis et al., 2017). The global "LR04" Plio-Pleistocene stack is one of the most commonly

used benthic $\delta^{18}O$ stacks (Lisiecki & Raymo, 2005). Given its wide use, the accuracy of LR04, even in relatively minor details, has important implications for a broad range of paleoceanographic applications.

Wilkens et al. (2017) identified 1.8-1.9 Ma as a period where the LR04 stack differs significantly from a benthic $\delta^{18}O$ stack of five Ceara Rise cores. The Ceara Rise stack exhibits fewer glacial cycles compared to LR04 during 1.8-1.9 Ma, casting doubt on how globally representative LR04 was during the early Pleistocene. Wilkens et al. (2017) attributed the discrepancy to LR04's choice of the initial alignment target records, ODP (Ocean Discovery Program) sites 677 and 849. Sites 677 and 849 use splicing to construct continuous records from adjacent drill holes, a common practice for achieving complete recovery at ODP sites. Problems with splicing, Wilkens et al. contended, might have made sites 677 and 849 records inaccurate.

Several recent advances provide us with an opportunity to place in a broader context the discrepancy with LR04 found by Wilkens et al. (2017). First, newly developed software for stacking benthic $\delta^{18}O$ records requires fewer input records and enables us to efficiently construct regional stacks (Lee and Rand et al., 2023), which can reveal spatial variability that is otherwise masked in global stacks (Lisiecki & Raymo, 2009; Lisiecki & Stern, 2016; Skinner & Shackleton, 2005; Stern & Lisiecki, 2014). We can thus assess whether the pattern seen in the Ceara Rise stack is representative of regional or global changes. Second, the subsequent publication of higher-resolution Atlantic records, e.g., Hodell and Channell (2016), allows an investigation into the 1.8-1.9 Ma period with less ambiguity. Third, the observation of a Laurentide meltwater event during the 1.8-1.9 Ma period (Shakun et al., 2016) points to a potential mechanistic explanation for the Ceara Rise $\delta^{18}O$ signal identified by Wilkens et al. Here, we apply these new data and techniques to demonstrate that the 1.8-1.9 Ma period stands out as an unusual instance of regional divergence in Pleistocene benthic $\delta^{18}O$. We discuss the mechanisms that could have caused this divergence and implications for the LR04 stack.

## Methods

We construct new Pleistocene regional Atlantic and Pacific Pleistocene stacks using 209 benthic $\delta^{18}O$ records, including 55 records from LR04 (Lisiecki & Raymo, 2005), 132 additional records from the ProbStack (Ahn et al., 2017), and 22 recently published records identified by this study (Table S1; Fig. S1-2). Many of the newly added records have relatively high resolutions, resulting in a 48% increase in data points compared to the ProbStack (Figs. S1-2). Over the Pleistocene, the Pacific stack includes data from 80 cores while the Atlantic stack includes data from 119 cores. To evaluate the hypothesis of Wilkens et al. (2017), we also construct shorter regional stacks for the Atlantic and the Pacific from 1.5 to 2.1 Ma. Between 1.8-1.9 Ma, there are 14 Pacific cores and 25 Atlantic cores. An Indian Ocean stack was not constructed because only one record is available from the Indian Ocean during 1.8-1.9 Ma.

The new stacks are created using Bayesian Inference Gaussian Process regression and Multiproxy Alignment for Continuous Stacks (BIGMACS), which is a newly developed software package for probabilistically stacking ocean sediment core data and constructing multiproxy age models (Lee and Rand et al., 2023). Unlike other probabilistic benthic $\delta^{18}O$ alignment software (Ahn et al., 2017; Lin et al., 2014), BIGMACS can reliably construct benthic $\delta^{18}O$ stacks using a smaller number of cores because it estimates a time-continuous signal using Gaussian process

regression (Rasmussen & Williams, 2005). This enhances our ability to create and compare benthic $\delta^{18}O$ stacks for the Atlantic and the Pacific back to the early Pleistocene (see below). Another advancement of BIGMACS is that it probabilistically integrates additional depth-age estimates provided by the user.

BIGMACS stack construction requires an initial alignment target, for which we used the LR04 global stack (Lisiecki & Raymo, 2005). However, because the LR04 stack may not be a good representation of $\delta^{18}O$ variability from 1.8-1.9 Ma, its use as an initial alignment target could be problematic. For the 1.5-2.1 Ma stacks, we assigned additional age control points in BIGMACS for records that have sufficient resolution by visually identifying the glacial maxima associated

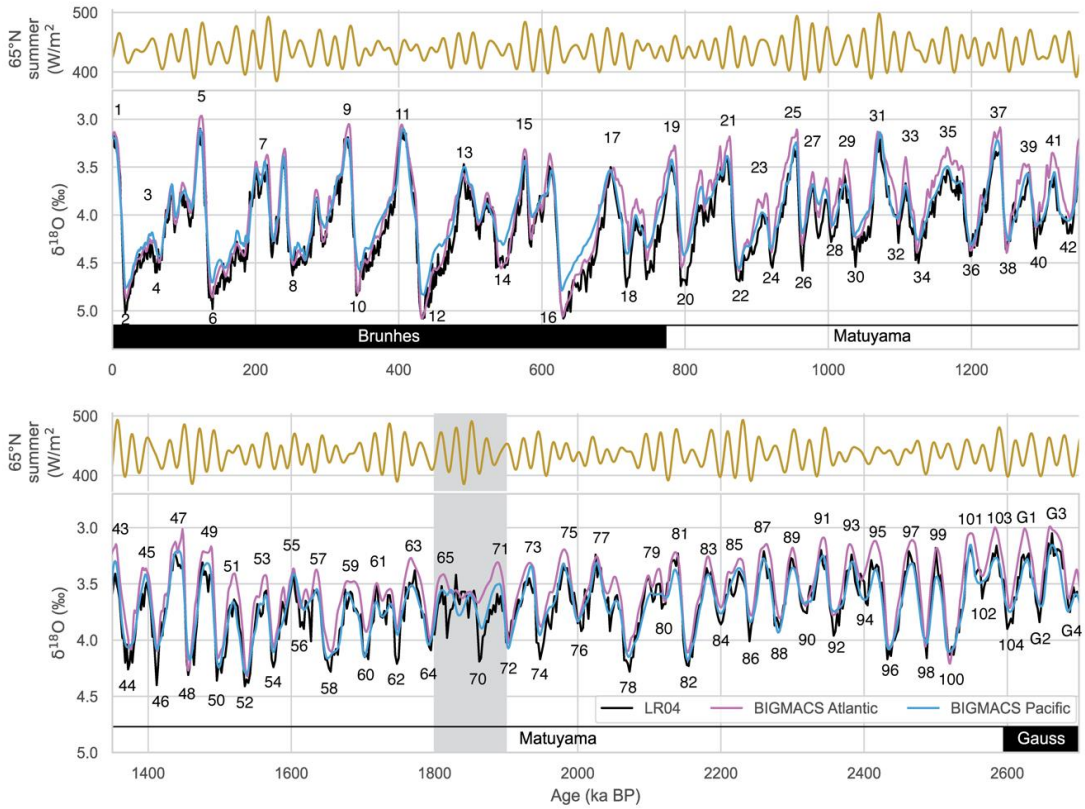


**Figure 1.** BIGMACS regional Pleistocene stacks for the Pacific (blue) and Atlantic (purple) without added tie points. The results presented are the stack means. Also shown is the LR04 global stack (black). The gray area is the 1.8-1.9 Ma period when the two BIGMACS regional stacks diverge. Also shown on top is the summer insolation at 65 °N. The numbers mark the Marine Isotope Stages. The black and white rectangles denote the geomagnetic chrons.

with MIS 64 and 74 and assigning them ages based on the respective obliquity minima (1.793 and 1.958 Ma). Because of the disagreement particularly between the LR04 global stack and

Atlantic records, we additionally identified the glacial maxima associated with MIS 68 and 70 in the Atlantic records that have sufficient resolution and assigned them as "additional ages" in BIGMACS based on the respective Northern Hemisphere (NH) insolation minima (1.841 and 1.864 Ma) with a 1-kyr standard deviation. (MIS 66 was not used because it was poorly defined in most high-resolution records.) In selecting these age constraints, we are guided by the average normalized sedimentation rate to ensure it is relatively steady and with no large deviations between tie points (Text S1, Fig. S3). We do not propose that these age assignments are necessarily appropriate corrections to the MIS ages of the LR04 stack; we merely use them to ensure consistent alignments in BIGMACS where fit to the original LR04 stack is poor. The discrepancies in the regional stacks between 1.8-1.9 Ma can also be seen in the full Pleistocene stacks for which we did not set any additional age controls (Text S2 and Fig. 1); however, the assigned age control points do affect the glacial-interglacial features of the regional stacks from 1.8-1.9 Ma (Fig. 2). Further details on the settings and parameters we used in BIGMACS are available (Text S2).

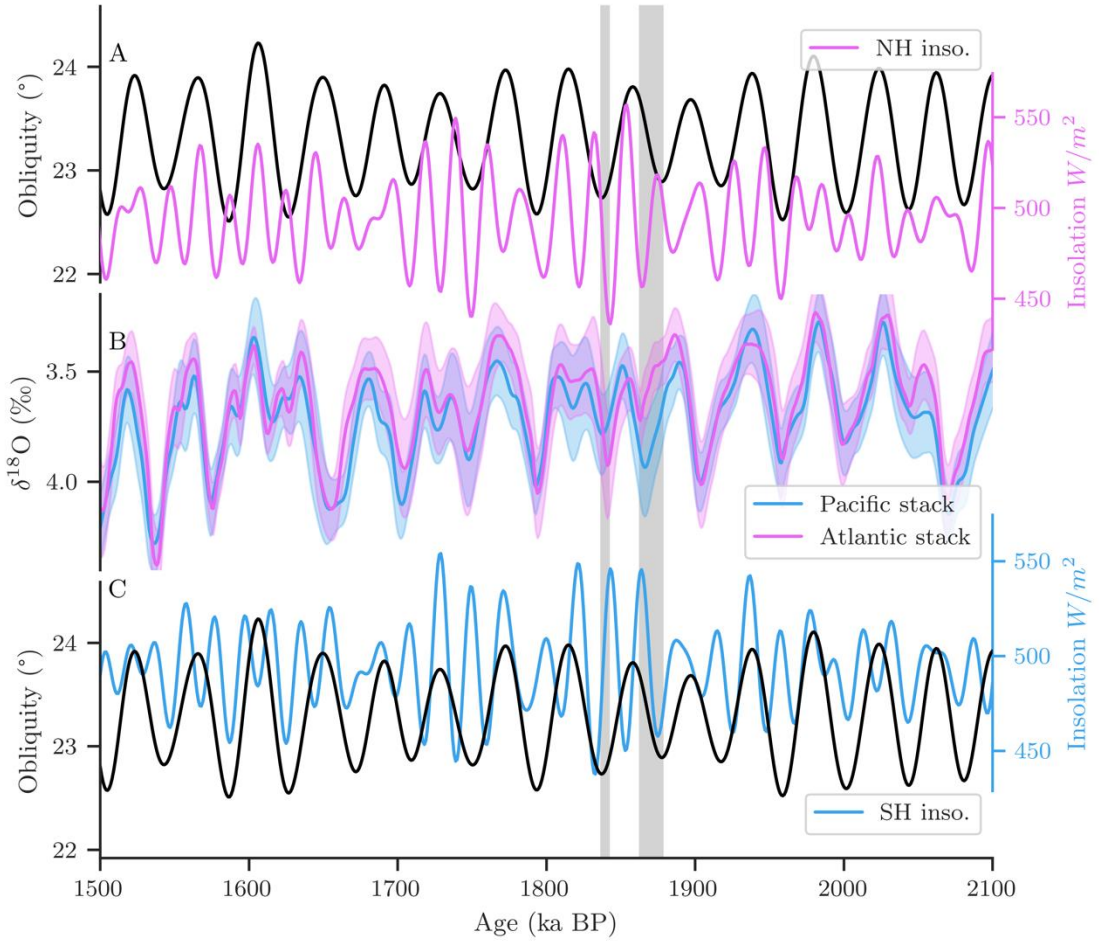


**Figure 2.** BIGMACS Atlantic and Pacific regional stacks compared to orbital parameters. (A) Obliquity (black) and summer insolation at 65°N (purple). The results presented are the stack means. (B) BIGMACS Atlantic (purple) and Pacific (blue) regional stacks. Shading denotes the 1σ uncertainty of the stack $\delta^{18}O$ values. (C) Obliquity (black) and summer insolation at 65°S (blue). The vertical gray shades associate glacial periods in the regional benthic $\delta^{18}O$ stacks with the corresponding orbital parameters.

Can we detect the same Atlantic-Pacific difference in the classic LR04 stack (Lisiecki & Raymo, 2005)? We separated the input records of LR04 based on ocean basins using the same $\delta^{18}O$ data on the age models used to construct the LR04 stack and binned at the same 2.5-kyr resolution used for the LR04 stack from 1.5-3 Ma. We refer to these results as the LR04 Atlantic/Pacific binned stacks.

## Results

The new Pleistocene Atlantic and Pacific stacks, for the most part, closely follow each other except at a few places, notably during 1.8-1.9 Ma (Fig. 1). In the 1.5-2.1 Ma stacks with tie-point-guided alignments (Fig. 2), the glacial maximum at ~1.863 Ma (MIS 70) is much stronger

in the Pacific than the Atlantic. In comparison to other glacial maxima from 1.5-2.1 Ma, the Atlantic benthic $\delta^{18}O$ response at MIS 70 more closely resembles a cold isotopic substage within a long interglacial than a glacial maximum. In contrast, the Atlantic stack's glacial maximum at ~1.841 Ma (MIS 68) is stronger than in the Pacific stack. The 1.5-2.1 Ma Atlantic stack differs substantially from both LR04 and ProbStack (Ahn et al., 2017) from 1.8-1.9 Ma, more closely resembling the Ceara Rise stack incorporated in CENOGRID (Wilkens et al., 2017; Westerhold et al., 2020) (Fig. S4). LR04 shows two poorly resolved glacial intervals (MIS 66 and 68) between two relatively normal glacial maxima (MIS 64 and 70); in contrast, the new Atlantic stack has a very weak MIS 70 while MIS 68 is similar in magnitude to MIS 64 and 72. However, marine isotope stages of the Pacific stack are similar to those in ProbStack from 1.8-1.9 Ma but with substantially smaller 95% confidence intervals. Another Atlantic-Pacific difference appears at ~2.05 Ma during the transition from glacial MIS 78 to interglacial MIS 77, during which the Atlantic stack shows a stronger interglacial substage (similar to LR04) than the Pacific stack.

Like the regional BIGMACS stacks, the LR04 Atlantic and Pacific binned stacks differ from one another between 1.8-1.9 Ma (Fig. S5). MIS 66 and 68 are absent in the LR04 Atlantic binned stack, whereas the Pacific binned stack matches LR04 well. Discrepancies in the relative amplitudes of MIS 68 and 70 between the Atlantic stacks produced by BIGMACS and LR04 binning may be caused by alignment errors during LR04 construction associated with relatively low-resolution Atlantic records. The new BIGMACS Atlantic stack contains more than double the $\delta^{18}O$ measurements of the LR04 Atlantic binned stack from 1.8-1.9 Ma.

## Discussion

### Stratigraphic implications

In all versions of the regional stacks we evaluated (with and without tie points), Atlantic benthic $\delta^{18}O$ exhibits a different pattern of variability than the Pacific between 1.8-1.9 Ma. Differences between regional stacks and the LR04 global stack at this time also provide a potential explanation for previous studies, including Wilkens et al. (2021), that found discrepancies with the LR04 stack between 1.8-1.9 Ma. For example, modeled ice volume differed more than normal from a benthic $\delta^{18}O$ record aligned to LR04 during 1.8-1.9 Ma (Liautaud et al., 2020 and Fig. 4b therein), probably because of distorted glacial cycles in the LR04 stack. A problem with the LR04 stack is also suggested by a divergence of ~30 kyr between tuned and untuned (depth-derived) age estimates for the LR04 stack from 1.8-1.9 Ma (Lisiecki, 2010 and Fig. S1 therein).

Regardless of the cause of the Atlantic-Pacific divergence, our results demonstrate that regional benthic $\delta^{18}O$ stacks are preferable to global stacks for age model development by stratigraphic alignment. The LR04 stack was created by performing pairwise alignment on all benthic $\delta^{18}O$ records to a target record. The targets were picked because of their relatively high resolution, low noise, and lack of apparent hiatuses. During 1.8-1.9 Ma, LR04 used two sites, ODP 677 and 849, to construct two stacks and observed that the resulting stack was largely independent of the target used. However, both sites 677 and 849 are from the Pacific, which our analysis show are quite dissimilar to Atlantic $\delta^{18}O$ records between 1.8-1.9 Ma. The poor fit between Atlantic records and the Pacific targets likely resulted in localized alignment errors for the Atlantic records.

The delicate task of choosing the right target cores for alignment is alleviated by the algorithmic approaches of HMM-Stack and BIGMACS (Ahn et al., 2017; Lee and Rand et al., 2023). These software packages align records to a target but iteratively update the alignment target to incorporate information from all other cores, thus reducing the reliance on the user-specified target. However, Atlantic and Pacific records were not analyzed separately when HMM-Stack was used to construct ProbStack. The iterative approach of BIGMACS was sufficient to identify a difference between the Atlantic and Pacific stacks without tie points (Fig. 1), but using the LR04 stack as our initial guess for the regional stacks resulted in ambiguous alignments and distortion of the glacial cycle features from 1.8-1.9 Ma. Ultimately, we bypassed this issue by manually defining several tie points for glacial maxima between 1.79-1.96 Ma for the benthic $\delta^{18}O$ records in which the glacial maxima could be confidently identified (Fig. S6).

**Mechanisms for generating benthic $\delta^{18}O$ gradients in the 41-kyr world**

Although benthic $\delta^{18}O$ is often considered a well-mixed proxy for global ice volume, one possible explanation for the regional difference in benthic $\delta^{18}O$ from 1.8-1.9 Ma may be differences in the deep water temperature or salinity of the two ocean basins. The modern global ocean mixing time of oxygen isotopes is about 1500 years (Broecker & Peng, 1983; Rohling, 2013), which is too short to explain gradients in seawater $\delta^{18}O$ that persist on orbital timescales (Morée et al., 2021). In contrast, regional variations in benthic $\delta^{18}O$ values associated with differences in deep water temperature or salinity may persist over tens of thousands of years. For example, regional differences observed in the amplitude of benthic $\delta^{18}O$ change during the last interglacial period (MIS 5) are most easily interpreted as temperature or salinity gradients between deep water masses (Lisiecki & Stern, 2016). During the 41-kyr world, the amplitude of global ice volume change is smaller in magnitude such that potential regional gradients in deep water temperature or salinity might constitute a larger percentage of the benthic $\delta^{18}O$ signal.

Benthic $\delta^{18}O$ values recorded for Pacific Deep Water (PDW) and North Atlantic Deep Water (NADW) could differ if the temperature or salinity the two water masses exhibited sensitivity to different forcings. For example, Raymo et al. (2006) asserted that the temperature/salinity of the Southern Ocean likely co-varied with the changes in the Antarctic ice volume; such Southern Ocean changes would also be expected to affect Antarctic Bottom Water (AABW) and PDW. At the same time, the NADW temperature or salinity signal would likely have changed concurrently with NH ice sheet dynamics (Marcott et al., 2011).

Circulation reconstructions for the 41-kyr world are consistent with deep water in the Atlantic and Pacific responding to different hemispheric insolation forcing between 1.8-1.9 Ma. The 41-kyr world Atlantic was primarily under the influence of the northern-sourced water, which filled most of the mid-depth to deep Atlantic, while southern-sourced water occasionally occupied the bottom depths (Cronin et al., 1996; Jakob et al., 2021; Lang et al., 2016; Zhang et al., 2013). Although the 41-kyr world Pacific might have seen deep water formation in the subarctic North Pacific (Burls et al., 2017; Ford et al., 2022), this northern-sourced Pacific deep water was limited to depths shallower than 3000 m. Antarctic-sourced bottom water is thought to have filled the deep Pacific below 3000 m (Burls et al., 2017; Ford et al., 2022), the depths from which most high-resolution Pacific cores in our compilation were recovered. The only two high-

resolution Pacific cores in our compilation retrieved from sites shallower than 3000 m, ODP 1143 and 1241, display different benthic $\delta^{18}O$ patterns than the deeper cores (Figs. S6 and S8), possibly due to the influence of NPDW.

We tentatively attribute the regional benthic $\delta^{18}O$ divergence to the effects of deep water temperature and/or salinity because we are unable to differentiate the impacts of temperature and salinity using only benthic $\delta^{18}O$. One bottom water temperature record from the Atlantic suggests that deep water temperature and benthic $\delta^{18}O$ co-vary during 1.8-1.9 Ma (Sosdian & Rosenthal, 2009), possibly hinting at the important influence of bottom water temperature on Atlantic benthic $\delta^{18}O$ during this period. As far as we are aware, there is not a commensurate Pacific deep water temperature record that can resolve glacial-interglacial cycles during 1.8-1.9 Ma. Such a record could shed more light on the role deep water temperature played in the Atlantic-Pacific divergence in benthic $\delta^{18}O$ records.

**Antiphased Precession Effects between 1.8-1.9 Ma**

Although orbital insolation is consistently dominated by precession (Fig. 3), benthic $\delta^{18}O$ records exhibit strong 41-kyr obliquity cycles during the late Pliocene/early Pleistocene. This mismatch between the substantial role that precession played in modulating the NH summer insolation and the apparent lack of a precessional imprint in geological records is termed the "41-kyr problem" (Raymo & Nisancioglu, 2003; Watanabe et al., 2023). Many researchers have put forward theories on why the 41-kyr world is dominated by obliquity. Among them, the Antiphase Hypothesis has particular appeal to explain our observations (Morée et al., 2021; Raymo et al., 2006). The Antiphase Hypothesis proposes that opposing responses of the northern and southern hemisphere ice sheets on precessional time scales canceled each other out in the global ice volume signal. For example, while cool NH summers lead to northern ice growth, coeval warm Southern Hemisphere (SH) summers act to shrink the Antarctic Ice Sheet. Obliquity, which exerts a symmetric effect on both hemispheres, is left as the governing cyclicity of global ice volume during this period.

The Antiphase Hypothesis provides a framework to explain the Atlantic-Pacific difference in benthic $\delta^{18}O$ records during 1.8-1.9 Ma (Fig. 2). While obliquity still paces the glacial-interglacial cycles in global ice volume, the opposite phase of the northern and southern hemisphere insolation on precession time scales could have influenced the magnitudes of glacial benthic $\delta^{18}O$ change in the Atlantic and the Pacific. In particular, the 1.8-1.9 Ma time interval experienced uniquely strong precession and weak obliquity relative to the rest of the 41-kyr world (Fig. 3). While high-latitude summer insolation is always dominated by precession (Raymo & Nisancioglu, 2003), the contrast between the strong precession and weak obliquity during 1.8-1.9 Ma stands out. Other times of similar relative power of obliquity and precession forcing are not directly comparable because they occur before or after the 41-kyr world, e.g., 0.9-1 Ma and 3-3.1 Ma. Before the 41-kyr world, the northern hemisphere was largely ice-free (Sosdian & Rosenthal, 2009). After the 41-kyr world, the Laurentide ice sheet expanded in size and the glacial cycles transitioned to 100-kyr pacing (Lisiecki & Raymo, 2007). The 1.8-1.9 Ma period is, thus, a unique window of time when more precession response might be expected compared to the rest of the 41-kyr world.

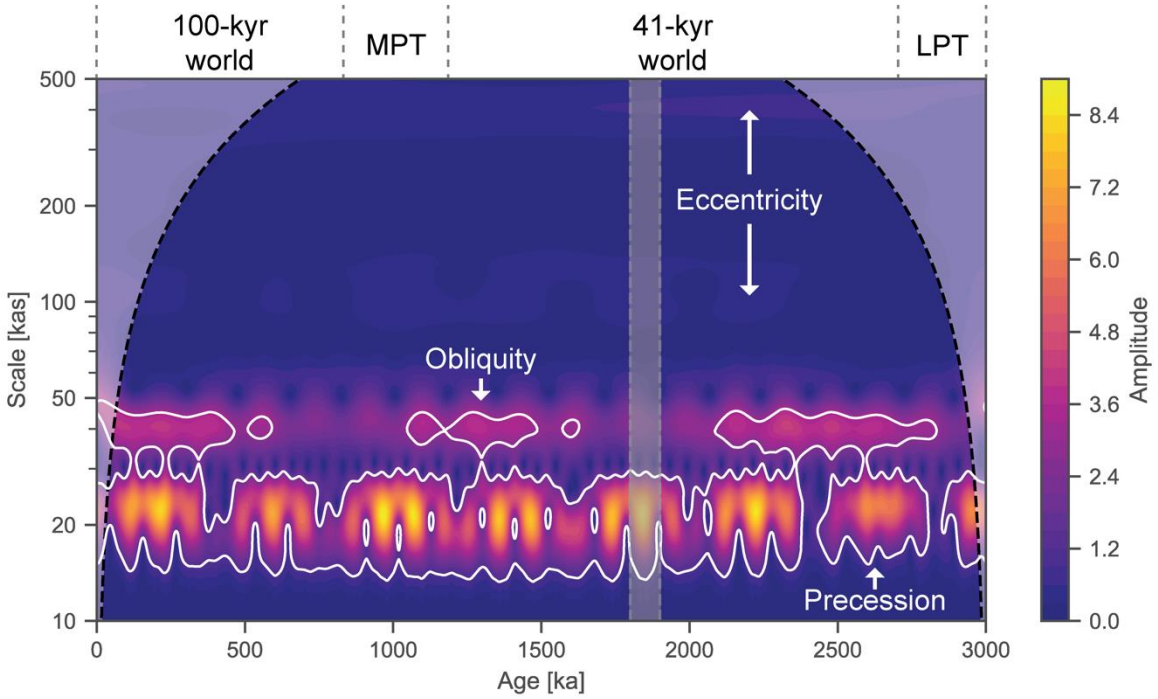


**Figure 3.** Wavelet spectrum of insolation at 65° N for the Plio-Pleistocene generated with Wavelet Continuous Transform using the Morlet wavelet (Torrence and Compo, 1998). The white lines delineate regions of the spectrum that are significant against a random AR(1) benchmark. The dashed lines denote the 1.8-1.9 Ma period where the Atlantic and Pacific records records diverge. LPT: Late Pliocene Transition (Sosdian and Rosenthal, 2009). MPT: Mid-Pleistocene Transition. This figure was generated with Pyleoclim (Khider et al., 2022).

Examining the northern and southern summer insolation forcing from 1.8-1.9 Ma (Fig. 2), we find that the magnitudes of the Atlantic and Pacific glacial responses are likely caused by the hemispheric insolation differences during the obliquity minima. The obliquity minimum at 1.878 Ma coincided with a maximum in NH summer insolation and minimum SH summer insolation due to the opposite hemispheric effects of precession on seasonal insolation. The Southern Ocean and PDW would be expected to cool strongly during MIS 70 because SH insolation is low during the obliquity minimum. In contrast, moderately high NH insolation would produce a weaker and delayed glacial response for MIS 70 in northern hemisphere climate and NADW. By the time NH summer insolation reaches its minimum, obliquity is relatively high and would quickly reverse the NH cooling trend. Hemispheric circumstances are reversed during MIS 68 with NH summer insolation low early during the obliquity minimum (amplifying NH/NADW cooling) while Southern Ocean/PDW cooling is delayed by a SH insolation peak, which would initially suppress SH cooling. However, because the SH insolation minimum was not as far offset from the obliquity minimum during MIS 68 as the NH insolation was during MIS 70, the antiphase insolation effect is weaker for MIS 68.

Notably, Atlantic $\delta^{18}O$ responses are similar for MIS 70 and MIS 56 at ~1.6 Ma (Fig. 2). They are similarly weak glacials and both have NH precession maxima that coincide with obliquity minima. The interesting difference between the two glacials is that the Pacific $\delta^{18}O$ response matches the Atlantic during MIS 56, in contrast to the strong Pacific glacial maximum during MIS 70. The discrepancy in Atlantic-Pacific divergence could be because MIS 70 has stronger precession forcing and weaker obliquity than MIS 56. Thus, the relatively strong power of precession forcing from 1.8-1.9 Ma may account for the greater regional benthic $\delta^{18}O$ difference during this time compared to the rest of the 41-kyr world, leaving vestiges of precession-driven regional temperature/salinity signals in the otherwise obliquity-dominated global ice volume component of benthic $\delta^{18}O$.

Another potential impact of strong precession forcing during the 1.8-1.9 Ma period is a Laurentide meltwater event in the Gulf of Mexico similar to or even larger in magnitude than those in the late Pleistocene (Shakun et al., 2016). Alignment of the Gulf of Mexico core which records this meltwater event to our Atlantic stack (Fig. S6, bottom panel) suggests that the event occurred during MIS 71, immediately before the very weak glacial maximum in the Atlantic. Terrestrial deposits along the Mississippi River dated to 1.8-2.0 Ma additionally substantiate the size and timing of this Gulf of Mexico meltwater drainage event (Rovey II & Spoering, 2020), indicating a rapid loss of Laurentide ice similar to meltwater events during the last deglaciation (Barber et al., 1999; Tarasov & Peltier, 2005). As this early Pleistocene meltwater event coincides with one of the weakest obliquity maxima of the 41-kyr world, it suggests sensitivity of the Laurentide ice sheet to the strong precession forcing at this time. Additionally, the meltwater event may have directly or indirectly contributed to the weaker Atlantic benthic $\delta^{18}O$ response during MIS 70. For example, the large meltwater input to the North Atlantic could have slowed deep water mixing times between the Atlantic and Pacific relative to their average for the 41-kyr world, prolonging the Atlantic-Pacific benthic $\delta^{18}O$ contrast. The weak Atlantic benthic $\delta^{18}O$ response during MIS 70 could also be accentuated by dissolution of benthic foraminiferal calcite in the Atlantic if the preceding meltwater event prolonged the residence time of North Atlantic Deep Water; however, dissolution is unlikely to fully account for the Atlantic-Pacific discrepancy (Text S3).

Our assertion that precession, in addition to obliquity, affects the 41-kyr world glacial cycles joins an array of previous studies reaching similar conclusions. An early study observed an increased response to precession in benthic $\delta^{18}O$ beginning at ~2.5 Ma (Lisiecki & Raymo, 2007). Another study detected a nontrivial precession contribution to benthic $\delta^{18}O$ variability from 1-3 Ma using Empirical Nonlinear Orbital Fitting (Liautaud et al., 2020). More recently, precession influence during the 41-kyr world has been shown in sedimentary elemental records (Sun et al., 2021), sea level (Vaucher et al., 2021), ice-rafted debris (Barker et al., 2022), and ice sheet modeling (Watanabe et al., 2023). Compared to the existing evidence, our finding suggests that between 1.8-1.9 Ma benthic $\delta^{18}O$ – the data originally used to demonstrate the "41-kyr problem" (Raymo & Nisancioglu, 2003) – responds to precession forcing differently depending on geographical locations, likely due to the different source regions of deep water masses.

## Conclusion

Benthic $\delta^{18}O$ from five Ceara Rise sites was previously shown to differ from the LR04 global benthic $\delta^{18}O$ stack between 1.8-1.9 Ma (Wilkens et al., 2017). Our investigation reveals that

discrepancy with the LR04 stack is widespread over this time interval; most Atlantic $\delta^{18}O$ records show a different pattern of Marine Isotope Stages than Pacific $\delta^{18}O$ records during 1.8-1.9 Ma. The largest difference between the Atlantic and Pacific benthic $\delta^{18}O$ stacks occurs during MIS 70 at ~1.878 Ma, and 1.8-1.9 Ma is the only portion of the Pleistocene for which glacial cycles in the regional stacks differ substantially from LR04 (Fig. 1). The next largest regional difference is an isotopic substage between MIS 77 and 78 at ~2.05 Ma that is isotopically lighter (or warmer) in the Atlantic than the Pacific. Throughout the rest of the Pleistocene, the Atlantic and Pacific regional stacks agree with LR04 and ProbStack (Fig. 1).

A re-examination of the Pacific alignment targets used in the LR04 construction process from 1.8-1.9 Ma explains why the LR04 stack more closely resembles the Pacific records and produced misalignments of the Atlantic records. This example demonstrates why regional benthic $\delta^{18}O$ stacks are preferable to global stacks for age model development by stratigraphic alignment. The new stacking software BIGMACS facilitates construction of regional stacks by requiring fewer records to generate a stack, but it still has some sensitivity to the choice of initial alignment target. The regional stacks presented here have largely inherited the orbitally tuned age model of the LR04 stack, and updated regional age models, particularly from 1.8-1.9 Ma, should be developed based on analysis of the regional stacks.

We propose that the cause of the Atlantic-Pacific divergence from 1.8-1.9 Ma is hemispheric sensitivity to antiphased precession forcing, specifically that Atlantic benthic $\delta^{18}O$ at this time was more sensitive to NH summer insolation while deep Pacific benthic $\delta^{18}O$ was more sensitive to SH summer insolation. This benthic $\delta^{18}O$ discrepancy could be caused by variations in the temperature or salinity of northern- versus southern-source deep water rather than requiring uneven mixing of meltwater inputs. The unusually strong precession power and weak obliquity power of orbital cycles from 1.8-1.9 Ma and a contemporaneous meltwater event in the Gulf of Mexico lend support to the Antiphase Hypothesis as a possible mechanism to explain spatial variability in benthic $\delta^{18}O$ during this portion of the 41-kyr world. Our study joins a variety of others (Barker et al., 2022; Liautaud et al., 2020; Lisiecki & Raymo, 2007; Sun et al., 2021; Vaucher et al., 2021; Watanabe et al., 2023) suggesting that precession, in addition to obliquity, plays a role in pacing climate signals during the 41-kyr world.

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**Availability Statement**

The BIGMACS stacking software is available at https://github.com/eilion/BIGMACS. The compiled benthic $\delta^{18}O$ records and the resulting regional stacks will be available upon publication in a Figshare repository or upon request during the review process.

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