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A tropical Pacific role for the Mid-Pleistocene Transition

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ABSTRACT

The Mid-Pleistocene Transition (MPT), between ~1.5 and 0.9 million years ago, represents one of the most perplexing climate transitions yet discovered in oceanic benthic δ^{18}O records. It is characterized by the change in the frequency/amplitude of δ^{18}O, from 41,000-year cycles to 100,000-year cycles. Although the cause of this transition is still largely unsolved, there is an exceptionally strong bias in proposed explanations from high-latitude regions, possibly limiting a complete explanation of this puzzling climate phenomena. Here, I provide an alternative explanation of the MPT, with forcings originating from the tropical Pacific.

1. Introduction

When examining climate change over the past ~4.5 million years (Clark et al., 2024), one exceptionally notable climate shift jumps out prominently between ~1.5 and 0.9 million years ago (Fig. 1a and b). Commonly referred to as the Mid-Pleistocene Transition (MPT) (Berends et al., 2021) or Early Middle Pleistocene Transition (Head and Gibbard, 2015), it has been rigorously investigated since its discovery nearly 50 years ago in an attempt to explain global climate dynamics (Shackleton and Opdyke, 1976; Kaboth-Bahr and Mudelsee, 2022).

One of the most striking features of the MPT is the frequency/amplitude change identified in δ^{18}O records of benthic foraminifera (Shackleton and Opdyke, 1976), which resemble high-frequency 41,000 year orbital cycles prior to the MPT and low-frequency 100,000 year orbital cycles following the MPT (Pisias and Moore Jr, 1981). However, orbital cycles do not change across the MPT (Pisias and Moore Jr, 1981), implying that internal forcings must be a key factor in driving the transition. To add to the mystery, the MPT appears to have been a gradual transition, occurring over several orbital cycles (Clark et al., 2006). While numerous internal mechanisms to explain the MPT exist (Clark et al., 2006; Berends et al., 2021), it is still largely unknown what drove this important climate transition.

One critical question to address any mechanism related to the MPT is: where did the internal climate forcings that caused the MPT originate? Since the benthic δ^{18}O records that capture the MPT primarily reflect ice-volume changes (Clark et al., 2006), as well as the popularization of the Milankovitch hypothesis (Milankovitch, 1941), virtually all studies that attempt to explain the MPT exclusively focus on high-latitude forcings (Clark et al., 2006; Berends et al., 2021; An et al., 2024), possibly hindering a complete understanding of this global phenomena.

Although I have no doubt that high-latitude forcings are important for driving global change during the MPT, I propose that low-latitude forcings may be equally, if not more important, in driving the MPT. Here, I provide an example of how a low-latitude mechanism in the tropical Pacific could initiate the MPT.

2. Focusing on the tropical Pacific

I begin my explanation by focusing on El Niño Southern Oscillation (ENSO), which fluctuates between an El Niño phase and a La Niña phase in the tropical Pacific. The fluctuation between ENSO phases consists of both an oceanic and atmospheric component. The oceanic component is the dynamical interaction of zonal sea surface temperature (SST) gradients in the tropical Pacific, between the western and the eastern Pacific. The atmospheric component consists of the weakening or strengthening of the Walker circulation, which is essentially low-level easterly winds blowing across the tropical Pacific. These two components of ENSO are linked via the Bjerknes feedback (Bjerknes, 1969), whereby changes in the Walker Circulation alter sea surface temperatures gradients that, in turn, alter the Walker Circulation in a positive feedback loop. While this pattern is typically viewed on interannual timescales during the instrumental period, it can also be viewed on longer, century to millennial, timescales (Cane, 1998).

In thinking about the climate dynamics behind ENSO on century to millennial timescales, I like to imagine an “ENSO seesaw” (Fig. 1c), with ENSO tipping in either the El Niño or La Niña direction depending on the zonal SST gradient across the tropical Pacific. For example, if SSTs in the

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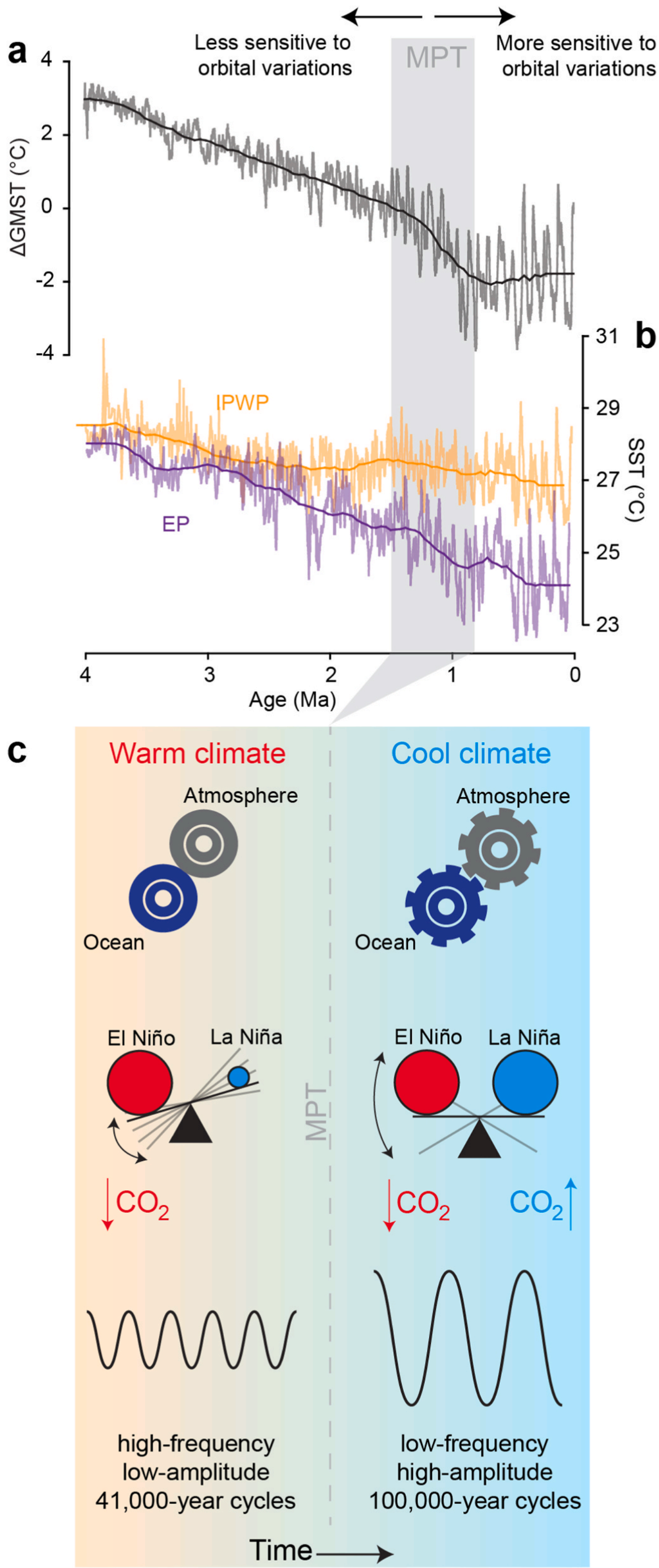

Fig. 1. Graphical illustration of the proposed orbital sensitivity shift forcing global climate changes during the MPT. **a**) Change in global mean surface temperature (Δ GMST) (Clark et al., 2024) **b**) Sea surface temperature (SST) changes between the eastern (EP) and western (IPWP) tropical Pacific (Clark et al., 2024). **c**) Schematic diagram showcasing the proposed mechanism. The ocean/atmosphere relates to the region over the tropical Pacific.

tropical eastern Pacific are similar to the tropical western Pacific, then the zonal temperature contrast between the tropical eastern and western Pacific will be weakened, causing the "ENSO seesaw" to tip in the direction of El Niño. This would lead to an El Niño mean state with a corresponding weakened Walker Circulation (Sadekov et al., 2013). On the other hand, if SSTs in the tropical eastern Pacific are cooler than the tropical western Pacific, then the zonal temperature contrast between the tropical eastern and western Pacific will be strengthened, causing the "ENSO seesaw" to tip in the direction of La Niña. This would lead to a La Niña mean state to develop with a corresponding strengthened Walker Circulation (Sadekov et al., 2013). Additionally, it has been identified that La Niña mean states correspond to increased atmospheric CO_2 concentrations, due to enhanced upwelling in the eastern Pacific and interactions with terrestrial vegetation (Chatterjee et al., 2017). Conversely, atmospheric CO_2 is subdued during El Niño mean states (Chatterjee et al., 2017). In this way, ENSO is one of the primary regulators of climate on the planet. But, what actually controls ENSO on century (or longer) timescales?

3. Influence from the Sun

Solar forcing, which is simply a measure of energy from the Sun without fully accounting for Earth's position from the Sun (otherwise known as insolation), has been identified as the key external source that controls changes in ENSO on century timescales (Wilcox et al., 2023a). That is, increased solar forcing corresponds to strengthened zonal SST gradient between the tropical eastern and western Pacific (i.e. La Niña mean state and strengthened Walker circulation) while decreased solar forcing corresponds to a weakened zonal SST gradient between the tropical eastern and western Pacific (i.e. El Niño mean state and weakened Walker circulation) (Wilcox et al., 2023a). However, peculiar things happen to ENSO and the Walker Circulation during different levels of insolation on millennial timescales that deviate from this straightforward pattern.

Recently, it was found that if insolation increases beyond a certain threshold, there is a thermodynamic de-coupling between the atmosphere and ocean in the tropical Pacific, possibly due to increased humidity, muting ENSO's response and ultimately affecting global climate change (Wilcox et al., 2023b). In other words, the "ENSO seesaw" tips in the direction of El Niño during increased insolation, weakening the Walker Circulation while simultaneously creating conditions that allow a reduction of atmospheric CO_2. This would be analogous to two smooth wheels (i.e. lower coupling potential than gears) rotating against each other, with one wheel representing the tropical Pacific atmosphere and the other wheel representing the tropical Pacific ocean (Fig. 1c). On the other hand, when insolation decreases beyond a certain threshold, the thermodynamic coupling between the atmosphere and ocean is strengthened in the tropical Pacific, amplifying ENSO's response (Wilcox et al., 2023b). This creates ideal conditions for the "ENSO seesaw" to tip more efficiently back-and-forth between El Niño and La Niña modes, even with subtle changes in insolation. This would be analogous to two gears (i.e. higher coupling potential than smooth wheels) rotating against each other, with one gear representing the tropical Pacific atmosphere and the other gear representing the tropical Pacific ocean (Fig. 1c). In this way, Earth's climate sensitivity to insolation is regulated by ENSO.

4. An orbital sensitivity shift to account for the MPT

When discussing the MPT, certain components of the insolation mechanism (Wilcox et al., 2023b) can be applied to account for the benthic $\delta^{18}O$ frequency/amplitude changes. Although, since orbital forcings do not change across the MPT, insolation (Wilcox et al., 2023b) cannot fully explain the benthic $\delta^{18}O$ frequency/amplitude changes. Instead, global mean surface temperatures (Clark et al., 2024), which is the combined influence of all forcings (both external and internal), may serve as the catalyst for changes in the tropical Pacific on orbital timescales. Therefore, by examining global mean surface temperature (Clark et al., 2024), rather than simply insolation (Wilcox et al., 2023b), it is apparent that global mean surface temperatures (relative to post-MPT temperatures) were quite warm (Fig. 1a). These warm temperatures may have caused a thermodynamic de-coupling between the atmosphere and ocean, analogous to increased insolation (Wilcox et al., 2023b), resulting in ENSO being less sensitive to orbital cycles. This would severely weaken the SST gradient in the tropical Pacific (Fig. 1b), causing the "ENSO seesaw" to tip in the direction of El Niño. In turn, the El Niño mean state, possibly equivalent to a "permanent El Niño" (Fedorov et al., 2010), drove a reduction of atmospheric CO_2, leading to decreased global mean surface temperatures over time. Eventually, during the MPT, global mean surface temperatures decreased enough (Fig. 1a) to cross the critical threshold that may have caused a thermodynamic coupling between the atmosphere and ocean, analogous to reduced insolation (Wilcox et al., 2023b), resulting in ENSO being more sensitive to orbital cycles. This would cause the "ENSO seesaw" to tip more efficiently back-and-forth between El Niño and La Niña mean states on orbital timescales, driving both intense glacial and interglacial periods following the MPT. Importantly, any change in ENSO dynamics would influence ice-sheet behavior in polar regions (Zhang et al., 2021), greatly impacting benthic $\delta^{18}O$ records.

Based on the aforementioned reasoning, I hypothesize that benthic $\delta^{18}O$ would only respond to the strong 41,000-year obliquity cycles prior to the MPT, due to ENSO's lack of orbital sensitivity. However, following the MPT, benthic $\delta^{18}O$ would be ultra-responsive to obliquity, precession, or even eccentricity cycles, due to ENSO's increased sensitivity to orbital variations. In other words, Earth's sensitivity to orbital cycles changed during the MPT in response to thermodynamic changes in the tropical Pacific, causing the benthic $\delta^{18}O$ frequency/amplitude changes.

While several aspects of the orbital sensitivity shift will need further testing and analyses, its sole intention is to highlight a new explanation of the MPT by incorporating low-latitude forcings. I suspect that high-latitude forcings, such as Southern Ocean sea-ice extent (Clark et al., 2024), work in tandem with the tropical Pacific to amplify or mute the response of orbital variations. Further, the proposed mechanism does not intend to counter previous studies exploring the orbital contribution to benthic $\delta^{18}O$ (e.g. Sun et al., 2019; Morée et al., 2021). Rather, it is meant to serve as a new way to examine these datasets. I conclude with a hypothetical question related to modern-day climate change: has human-induced warming caused Earth to cross the critical threshold proposed here, possibly causing Earth to be less sensitive to orbital forcings, thereby re-entering a pre-MPT world?

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data and/or code is contained within the submission.

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