Mid-Pliocene El Niño/Southern Oscillation suppressed by Pacific Inter-Tropical Convergence Zone shift

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Abstract

The El Niño-Southern Oscillation (ENSO), the dominant driver of year-to-year climate variability in the equatorial Pacific Ocean impacts climate pattern across the globe. However, the response of the ENSO system to past and potential future temperature increases is not fully understood. Here we investigate ENSO variability in the warmer climate of the mid-Pliocene (~3–3.3 Ma), when surface temperatures were ~2–3 ºC above modern values, in a large ensemble of climate models – the Pliocene Model Intercomparison Project. We show that the ensemble consistently suggests a weakening of ENSO variability, with a mean reduction of 25% (±16%). We further show that shifts in the equatorial Pacific mean state cannot fully explain these changes. Instead, ENSO was suppressed by a series of off-equatorial processes triggered by a northward displacement of the Pacific Inter-Tropical Convergence Zone: weakened convective feedback and intensified Southern Hemisphere circulation, which inhibits various processes that initiate ENSO. The connection between the climatological Inter-Tropical Convergence Zone position and El Niño/Southern Oscillation we find in the past is expected to operate in our warming world with important ramifications for ENSO variability.

Main Text

ENSO warm (El Niño) and cold (La Niña) events cause significant changes in weather patterns and ocean circulation, impacting agriculture, fisheries, coral bleaching, cyclogenesis, amongst a host of other impacts[1]. Given its pronounced socioeconomic impacts and potential predictability of a few seasons in advance, ENSO has been under intense investigation[2]. Whether and how ENSO changes in response to greenhouse gases and other external forcing may be studied by investigating past, present, and future climates with paleo-reconstructions, instrumental records, theory, and numerical simulations. There is a lack of consensus among climate models in general as to how ENSO variability will respond to future warming[3,4], although models that better capture ENSO nonlinearity tend to simulate enhanced variability in the eastern equatorial Pacific[5] and increased frequency of extreme events[6,7]. These changes in ENSO properties are linked to changes in the Pacific mean state marked by a weakened Walker Circulation, increased upper-ocean stratification, reduced zonal sea surface temperature (SST) gradient, and equatorially enhanced warming that causes the Inter-Tropical Convergence Zone (ITCZ) to be displaced equatorward[7–9].

Studies based on paleo-reconstructions have also suggested that ENSO activity is sensitive to the mean climate. A synthesis of mid-Holocene (~6 ka [thousand years]) records indicates a 33% reduction in ENSO amplitude in the eastern Pacific during this period[10]. ENSO activity over the last millennium was shown to be weaker when compared to the last half-century[11], potentially suggesting global warming-related changes. Furthermore, there is evidence of significantly reduced ENSO variability during the Last Glacial Maximum[12] (~21 ka). Proxy-data for the Pliocene (~5 to ~3 Ma [million years]) are controversial with regards tropical Pacific changes[13–16]. A Pliocene El Niño-like mean state has been hypothesized to reduce ENSO variability[17], although there is evidence of significant interannual variability during this period[18,19], whose magnitude could be comparable to the late Holecene[20]. As such, tropical Pacific mean state changes during the Pliocene and how they have impacted ENSO activity remain uncertain.

Paleoclimate studies have suggested that the mid-Pliocene Warm period (mPWP; ~3.3 Ma) can possibly be a useful analogue to the end-of-century climate based on the warming magnitude[21-23]. The mPWP was marked by warmer SSTs of up to 9 ºC and 4 ºC in the Northern and Southern Hemisphere, respectively, compared to pre-industrial times[22] (~1850), with orbital forcing and elevated atmospheric CO_2 concentrations similar to present day (~400 ppm) while polar ice was reduced[23]. Partly motivated by the similarities between the mPWP and scenarios of future projected warming, the Pliocene Model Intercomparison Project (PlioMIP)[24,25] initiative was developed. Here we examine the broad PlioMIP ensemble, including phases 1 and 2 with a total of 25 models (Extended Data Tables 1 and 2), to better understand how ENSO activity might change in warmer climates.

Reduced ENSO amplitude

The PlioMIP ensemble simulates significant reduction in the variability of SST anomalies across most of the global tropics in the mPWP compared to pre-industrial (Fig. 1a; see Extended Data Figure 1 for PlioMIP1). Although there are notable changes in the Indian and Atlantic Oceans[26], the most pronounced weakening occurs in the equatorial Pacific where reduced SST variability in the eastern basin (Niño3 region) is simulated by 21 out of 23 PlioMIP models (including PlioMIP1 and 2). Considering PlioMIP2 models only, there is a multi-model mean amplitude reduction of 25% (±16% standard deviation; Fig. 1b).

Separating the Niño3 variability change into interannual (<10yr) and longer timescale components shows that all but one model simulate reduced amplitude in the interannual band (Extended Data Figure 2), a timescale that is dominated by ENSO.

Additionally, 75% (17 out of 23) of the models suggest a shift towards lower frequencies as indicated by either an increased amplitude at low-frequency (>10 yr) or a more pronounced weakening at interannual than on longer timescales. Here due to data availability, our analysis is performed on the last 100 years of each model's simulation, making the decadal analysis more uncertain.

Role of Equatorial Pacific Ocean changes

ENSO dynamics is dominated by equatorial processes, which are influenced by the background state[27]. Although the PlioMIP models simulate an amplified eastern Pacific warming (Fig. 2a), there are large inter-model differences in this pattern, as indicated by not consistent changes in the zonal SST difference[28] (Extended Data Figure 3). Of particular importance for ENSO dynamics are changes in equatorial thermal gradients in the mixed-layer[5,6,29].

Firstly, we evaluate changes in the thermocline slope which plays an important role in ENSO dynamics. Stronger (weaker) westward equatorial currents are associated with increased (decreased) east-west thermocline slope[6]. The thermocline slope better represents the resultant effect of changes in zonal equatorial ocean dynamics than the zonal SST gradient in the PlioMIP models, as reflected in a higher inter-model correlation with ENSO amplitude change (Figure 2b; Extended Data Figure 3). Models with a steeper mean thermocline in the mPWP are typically associated with larger ENSO amplitude reductions, while a flatter mean thermocline is associated with either a slight increase or a weak decrease in ENSO variability (r_s=-0.43; Figure 2b). This indicates that an equatorial Pacific mean state with a steeper thermocline, which is associated with intensified trades and westward surface currents, is less favourable for strong ENSO variability. Under such a

"La Niña-like" mean state, stronger initial anomalies are required to weaken the climatological conditions sufficiently for El Niño development[6].

Another mean-state factor that can affect ENSO development is the equatorial upper-ocean stratification[5]. In particular, western-central equatorial Pacific stratification influences the variability of strong ENSO events, through changes in the dynamical ocean-atmosphere coupling. As such, we evaluate ocean stratification in the central-western Pacific, a region where wind anomalies trigger oceanic Kelvin and Rossby waves which influence ENSO genesis[30]. Models with decreased ocean stratification are typically associated with larger ENSO reductions, while weaker reductions occur in models where ocean stratification increases (Figure 2c). Given that over half of the models show increased stratification, this relationship cannot explain the consistent decrease in ENSO across the ensemble. Similarly, the fact that many models show a decrease in thermocline slope indicates that this is not the underlying cause for ENSO amplitude reduction. In summary, while changes in the thermocline and stratification help explain inter-model differences in ENSO amplitude changes, it appears that other processes that apply across models are required for the overall weakening of ENSO variability.

Off-Equatorial Pacific changes

Whilst ENSO development is closely related to zonal equatorial dynamics[27], ENSO events are also affected by a variety of other large-scale processes beyond the equatorial Pacific[7,31,32]. For instance, changes to the mean meridional SST gradient or processes in the extratropics can play an important role in triggering ENSO events. In particular, all PlioMIP models simulate a weaker equator-to-pole temperature gradient associated with polar amplified warming[33].

We first evaluate the role of meridional SST gradients through possible displacements of the ITCZ in the mPWP. Southward (northward) ITCZ displacements, due to reduced (increased) off-equatorial SST gradients, affect ENSO activity through increased (reduced) probability of occurrences of deep convection in the central-eastern equatorial Pacific[8,34]. Here we show that a mean northward ITCZ shift during austral spring-summer, developing and mature ENSO phases, is strongly related to the ENSO weakening across models (r_s=-0.64; Figure 3a). This scenario increases convergence throughout the tropical North Pacific that suppresses anomalous convergence feedback at the equator (Extended Data Figure 4). To further illustrate this effect, we evaluate models' performance in simulating the non-linear relationship between SST anomalies and precipitation events in the eastern Pacific (see Methods; Extended Data Figure 5). Six models correctly simulate this characteristic and indicate that the further north the mean ITCZ migrates the less probable are occurrences of deep convection events in the eastern Pacific associated with ENSO SST anomalies (Figure 3). The ITCZ shift can fully explain ENSO weakening across these 6 models (r_s=0.94; Extended Data Figure 6).

This PlioMIP result is analogous to the reduced ENSO activity in the past two decades, which corresponded with a more northward position of the ITCZ[35] (Figure 3a). The multi-decadal period pre-2000 was marked by enhanced ENSO variability, while post-2000 it has been reduced by 21%[36,37], resulting in weaker rainfall events in the eastern Pacific (Figure 3b). This reduction has been attributed to a negative phase of the Interdecadal Pacific Oscillation[38] with enhanced trade winds and surface ocean currents, and resembles a La Niña-like mean-state with the Pacific ITCZ displaced northward.

Consistently, the PlioMIP models indicate a larger reduction in ENSO activity when shifted towards a La Niña-like mean state (Figure 2b).

We also evaluate possible changes to other processes that are favourable for initiating ENSO events, such as the reversal of the easterly trade winds in the western Pacific[39]. In the PlioMIP models, the annual mean intensification of the western Pacific trade winds corresponds with weaker wind variability over this region (Figure 4a). Climatologically stronger easterly trades tend to inhibit: 1) the stochastic forcing of westerly wind bursts in the western Pacific[40] that triggers the positive thermocline feedback; 2) southward shifts of the ITCZ through positive wind-evaporation-SST feedback[34] which cools the equatorial Pacific Ocean, increasing the meridional SST gradient; and 3) eastward displacements of the Walker circulation.

Further, we evaluate patterns of variability that promote wind anomalies in the western Pacific and contribute to the development of El Niño events. Firstly, the South Pacific Meridional Mode (SPMM), analogue to the North Pacific Meridional Mode (NPMM), is initiated by the weakening of off-equatorial southeast trade winds in the eastern Pacific. This alters the latent heat flux, triggering a wind-evaporation-SST feedback that propagates wind anomalies into the tropics[32]. We find that all but two PlioMIP2 models simulate decreased SPMM variability in the mPWP (Figure 4b). Equivalent changes in the NPMM are not consistent across models and do not help explain ENSO changes (Extended Data Figure 7).

Finally, extreme El Niño events are amplified by an anomalous zonal pressure dipole in the Southern Hemisphere[31]. In such condition, an anomalous high pressure over Australia facilitates cold surges through the Coral Sea (the Southern Hemisphere Booster, SHB)[31], that promote westerly wind bursts in the western Pacific conducive for El Niño development. This meridional wind variability in the SHB region also decreases in 10 out of 12 PlioMIP2 models (Figure 4c). All these aforementioned changes are associated with reduced probability of El Niño initiation, which results in weaker ENSO activity. It is important noting that a northward ITCZ shift likely had a major effect on ENSO triggers from the Southern Hemisphere, due to changes in the large-scale atmospheric circulation, as we evaluate next.

Large-scale forcing

The Pacific ITCZ-ENSO relationship demonstrated in the previous section can either be a result of a large-scale global ITCZ shift modulating ENSO or a local response of the Pacific ITCZ to changes in ENSO activity. The PlioMIP models indicate that the northward ITCZ shift during the mPWP occurs in all basins, as indicated by anomalous meridional dipoles in rainfall across the global tropics (Figure 5a; see Extended Data Figure 8 for PlioMIP1). Additionally, the PlioMIP models systematically simulate asymmetric polar amplified warming in both hemispheres (Figure 5b), which can give rise to large-scale changes in the meridional temperature gradient and affect the ITCZ position through changes in atmospheric heat fluxes[41].

It is important noting that increased rainfall south of equator in the eastern Pacific may be a result of double-ITCZ bias in the PlioMIP models[9,42]. A more consistent northward ITCZ shift across the tropical North Pacific is evident through increased low-level wind convergence (Extended Data Figure 4), which indicates that increased precipitation in the eastern Pacific is likely a result of the thermodynamic effect over the double-ITCZ region[43].

The ITCZ northward shift is not consistent with the equatorial warming (Figure 2a) which would otherwise tend to shift the ITCZ southward. To assess the role of the large-scale SST warming patterns in the ITCZ shift, we performed sensitivity experiments using an Atmospheric General Circulation Model (AGCM; the NCAR Community Atmospheric Model version 4 [CAM4]). Here the AGCM is forced with PlioMIP climatological SSTs, which allow us to isolate changes in atmospheric circulation from changes in ocean-atmosphere variability, such as ENSO. It is worth noting the mPWP climatological-mean warming pattern, used to force the atmospheric model, may still contain some non-linear influence of ENSO changes, but this effect is negligible (see Methods).

In the present climate, during austral summer, increased insolation in the Southern Hemisphere results in intensification of the Northern Hemisphere Hadley circulation, northward energy flux across the equator (hereafter referred as energy-flux-equator), and southward ITCZ shift[41]. In the mPWP, the AGCM simulates decreased northward energy-flux-equator during the austral summer (Figure 5c). Due to the mutual relationship between changes in the energy-flux-equator and ITCZ position, a decreased northward energy-flux-equator is accompanied by a northward ITCZ shift in agreement with a recent PlioMIP2 study[44]. Higher rates of warming in the Northern Hemisphere drive an intensification and northward expansion of the Southern Hemisphere Hadley cell and weaker circulation in the Northern counterpart (Figure 5d; see Extended Data Figure 8 for PlioMIP1), which reduces the atmospheric energy input from the Southern to the Northern Hemisphere during the austral summer.

The AGCM experiments suggest that the meridional displacement of the ITCZ is a global feature of the PlioMIP simulations and occurs due to the extratropical warming. The experiments indicate an overall decrease in the northward atmospheric heat transport in the Northern Hemisphere and a slight increase in the southward heat transport in the Southern Hemisphere (Figure 5c), which initially points to changes in pole-to-pole temperature gradient. One of the most robust features of the mPWP simulations is the asymmetric polar amplified warming (Figure 5b), which increases the inter-hemispheric temperature gradient and was caused by reduced sea-ice volume[45]. However, whether the mPWP ITCZ shift was driven by sea-ice changes needs to be further investigated.

The large-scale changes in the meridional circulation likely induce changes in horizontal circulation. In the Pacific Ocean, the PlioMIP models indicate that a northward ITCZ shift is significantly related to intensified western Pacific trades (Figure 5d), which is analogous to synchronized shifts of the Walker and Hadley circulations during different ENSO phases[46]. An analysis of the low-level circulation indicates that the anomalously stronger western trades in the mPWP are sourced at the subtropical South Pacific due to an intensified circulation of the South Pacific Subtropical High system (Figure 5e,f; see Extended Data Figure 7 for PlioMIP1). These changes are not exclusive to the South Pacific but occur in all ocean basins (Figure 5f). The synchronized changes in the meridional and zonal atmospheric circulation are likely a result of global changes in atmospheric heat fluxes during the warmer mPWP. This illustrates a possible influence of changes in global atmospheric dynamics on ENSO in a warmer climate.

Implications for past and future climates

The results presented here suggest a link between reduced ENSO amplitude and the northward shift of the ITCZ in the mPWP, associated with stronger climatological circulation in the Southern Hemisphere (Figure 6). The northward shift of the ITCZ reduces the probability of ENSO-related rainfall events in the eastern Pacific. Northward ITCZ shift and intensified Southern Hemisphere Hadley and subtropical circulations are a response to enhanced Northern Hemisphere warming via energetic constraints for the ITCZ position[41] (Figure 6). This intensified Southern Hemisphere circulation reduces wind variability in the western Pacific, may suppress zonal sea-level pressure anomalies imposed by the South Pacific Meridional Mode and the Southern Hemisphere Booster and weakens and shifts the South Pacific Convergence Zone polewards[47], reducing its interaction with equatorial processes (Figure 6). As such, the climatological stability imposed by intensified tropical Southern Hemisphere circulation acts to increase ENSO stability, as ENSO, by definition, is a deviation from the mean climate, and thus stronger climatological circulations can be viewed as unfavourable to ENSO-induced changes[10].

In addition to the reduced ENSO amplitude, SST variability in other tropical basins also decreases (Figure 1a). This may also contribute to weakened ENSO variability via pan-tropical teleconnections related to a delayed and weaker negative feedback[48], although reduced variability in other tropical basins itself might also be a consequence of reduced ENSO variability. Pontes et al.[26] reported that all PlioMIP1 models simulate reduced tropical North Atlantic variability associated with a warming of this basin and a northward Atlantic ITCZ shift. Taken together, these results suggest that a northward shift of the global ITCZ may mute tropical Pacific and Atlantic SST variability.

Our results are subject to a number of uncertainties in the simulations tied to sparse and limited proxy data, which are used to constrain the PlioMIP experiments, and systematic climate model biases[49]. Changes in the inter-hemispheric SST gradient for example could be affected by uncertainties in the extension of the mPWP ice sheets[50], poor representation of certain polar feedbacks[51] (i.e. interactive land-ice), climate sensitivity[52], and biases in tropical convection and SST of the climate models, such as double-ITCZs[42] and an overly strong cold tongue. Despite different model biases, we show that the current generation of climate models simulate consistent changes to ENSO related to shifts in the ITCZ position in the mPWP.

Paleoclimate states may have particular relevance as analogues for the future climate. However, our findings indicate that, although the mPWP warming is comparable to that projected for the end of 21st century under a 'business as usual' scenario (~3 ºC)[21], the simulated mPWP ENSO response is the opposite to that projected[8,11]. An important factor in this difference is that the mPWP represents an equilibrium climate albeit with similar CO_2 levels as today. If equilibrium conditions are of particular importance, this suggests that a more Pliocene-like climate might be possible if present-day CO_2 concentrations were to be maintained constant and a steady-state is reached. However, the current rate of atmospheric CO_2 rise is unprecedented in Earth's history, resulting in warming trends that differ compared to past regimes. Thus, relating past and future warmings is not straightforward. Here evaluating the empirically-based mPWP warming we find that a northward ITCZ shift supresses ENSO activity. If this relationship can be applied to the 21st century projections where a southward shift of the Pacific ITCZ is projected[7], then an increase in ENSO variability[5] appears to be a potential outcome.

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Author contributions

GMP, AST, ASG and AS designed the study. GMP, AST, ASG, AS and IW contributed to the interpretation of the data and discussions. GMP conducted the analysis, prepared the figures, and wrote the original manuscript. ASG produced the schematic in Figure 6. AH,

WLC, AAO, CS, GL, SH, JCT, MAC, LES, WRP, DC, YK, KHN, ZZ, CC, NT, QZ, BOB, ECB, RF, ASH, MLJB performed the PlioMIP2 simulations. GMP and AST performed the CAM4 experiments. All authors commented and reviewed the manuscript.

Competing Interests

The authors declare no competing interests.

Figure Legends

Figure 1 | Simulated mid-Pliocene tropical variability changes. a multi-model mean change in the amplitude (standard deviation) of Sea Surface Temperature anomaly variability in the PlioMIP2 models (see Extended Data Figure 1 for PlioMIP1 models). Sea Surface Temperature anomaly is obtained through removing the mean seasonal cycle. Stippling indicates locations where there is a significant model agreement (at least 70%) in the sign of the change. **b** change in the amplitude (standard deviation) of the Niño3 time series in each PlioMIP model. Red box in the eastern Pacific in panel 'a' indicates the Niño3 region. Map created using the Basemap library for python.

Figure 2 | Equatorial Pacific Ocean changes. a PlioMIP2 multi-model mean change in surface tropical and sub-surface equatorial Pacific temperatures. The vertical profile is averaged between 5ºS and 5ºN. Stippling indicates significant change at the 95% level (in the SST panel the entire basin-wide warming is significant at the 95% level). **b** inter-model relationship between the change in the thermocline slope between the eastern and western Pacific (see Methods) and the change in the Niño3 amplitude. **c** inter-model relationship between the change in ocean stratification and in the Niño3 amplitude. Ocean stratification was measured as the difference between the average temperature in the top 75m (green box, panel **a)** and at 100m (blue line), between 150ºE-140ºE.

Figure 3 | Inter-Tropical Convergence Zone–El Niño/Southern Oscillation relationship. a PlioMIP2 inter-model relationship between the change in the Niño3 amplitude and mean ITCZ shift from October to February. Green star indicates values obtained from observations by comparing periods 1979-1999 and 2000-2020. The correlation coefficient was evaluated considering PlioMIP models only. **b** relationship between DJF Niño3 SST anomalies and DJF Niño3 rainfall for the period pre-2000 (red) and and post-2000 (green). **c** to **h** as in panel '**b**' but for selected PlioMIP models that correctly simulate non-linear ENSO characteristics (See Methods), pre-industrial simulation in blue and Pliocene in yellow.

Figure 4 | Changes to potential El Niño/Southern Oscillation triggers. a inter-model relationship between the change in the intensity of the western Pacific trade winds (10ºS-

10ºN; 160ºE-150ºW) and the amplitude (standard deviation) of its monthly variability. To ideally examine changes in the western wind bursts we would need high frequency output, which is not available for the PlioMIP models. **b** Change in the amplitude (standard deviation) of the South Pacific Meridional mode time series, defined as the mean SST anomaly between 15ºS-25ºS and 110ºW-120WºE. **c** Change in the amplitude (standard deviation) of the meridional wind variability over the Southern Hemisphere Booster region (10ºS-30ºS; 140º-170ºE). PlioMIP2 models in panels **b** and **c**: a – CCSM4-UofT; b – CCSM4-2deg; c – CESM2; d – COSMOS; e – EC-EARTH3.3; f – GISS-E2-1-G; g – HadCM3; h – IPSL-CM6A-LR; i – IPSL-CM5A; j – IPSL-CM5A2; k – MIROC4m; l – MRI-CGCM2.3; m – NorESM-L; n – NorESM1-F.

Figure 5 | Energetic constraints for the Inter-Tropical Convergence Zone position. a DJF precipitation change in the PlioMIP2 models (mPWP minus pre-industrial). Stippling indicates where the change is significant at the 95% level. **b** multi-model mean change zonally averaged SST for PlioMIP1 (magenta) and PlioMIP2 (red). Banding indicates standard deviation range. **c** Changes in DJF atmospheric energy flux, computed as the residual between the total top-of-the-atmosphere and surface energy fluxes, in the AGCM experiments forced with PlioMIP1 and 2 climatological SST and sea-ice (see Methods). Banding indicates standard deviation range of a 5-member ensemble. Negative anomalies in the Northern Hemisphere indicate weakening of the northward heat transport, while negative anomalies in the Southern Hemisphere indicate intensification of the southward heat transport. **d** Changes in the meridional streamfunction in the AGCM experiment forced with PlioMIP2 SST and sea-ice. Contours indicate pre-industrial streamfunction (zero contour in bold). Colours indicate change. **e** Inter-model relationship between changes in the intensity of the zonal western Pacific trades and ITCZ shift during austral summer. **f** Changes in low-level (850 hPa) winds and streamfunction in the PlioMIP2 models. Wind changes are only shown where changes are significant at the 95% level. Map created using the Basemap library for python.

Figure 6 | Schematic of the drivers of suppressed ENSO activity in the mPWP. A northward ITCZ shift reduces the probability of occurrence of deep convection in the central-eastern Pacific. Energetic constrains for the ITCZ position indicate that higher rates of warming in Northern Hemisphere drive a northward ITCZ shift and enhanced Southern Hemisphere Hadley circulation. These changes are also associated with intensified surface subtropical high and western Pacific trades. Enhanced trade winds suppress wind variability in the western Pacific, which is important for El Niño initiation. An intensified subtropical high is thought to impede zonal pressure anomalies across the tropical South Pacific and, thus, suppress the activity of the South Pacific Meridional Mode (SPMM) and Southern Hemisphere Booster (SHB) that are important for the development of strong El Niño events. Map created using the Basemap library for python.

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Methods

Data Availability. PlioMIP2 data (with exception of IPSLCM6A and GISS2.1G) is available upon request to Alan M. Haywood (a.m.haywood@leeds.ac.uk). PlioMIP2 data from CESM2, EC-Earth3.3, NorESM1-F, IPSLCM6A and GISS2.1G can be obtained directly through the Earth System Grid Federation repository (ESGF; https://esgf-node.llnl.gov/search/cmip6/). Observational SST and precipitation data can be found in the NOAA-USA (https://ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v5) and NCAR-USA (https://climatedataguide.ucar.edu/climate-data/gpcp-monthly-global-precipitation-climatology-project) online repositories, respectively.

Code Availability. Computer codes are available at https://github.com/gmpontes/Nature_Geoscience_ENSO_ITCZ_PlioMIP.git or upon request to Gabriel M. Pontes (gabrielpontes@usp.br).

Models and data. A total of 9 PlioMIP1 and 16 PlioMIP2 models were analysed. See Extended Data Table 1 for a list of the models included in our analysis. The number of models used in each analysis varying according to data availability in the PlioMIP1 and PlioMIP2 databases. The last 100 years of each model's simulation is used. We additionally use observational SST and precipitation from the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) and Global Precipitation Climatology Project (GPCP) datasets, respectively.

PlioMIP1 and 2 protocols. PlioMIP phases 1 and 2 apply rather similar boundary conditions (Extended Data Table 2). Nonetheless there were significant differences at some regional locations, which can potentially affect large-scale climate[24,25]. Both phases applied a mPWP land-sea mask, but PlioMIP2 land-sea mask accounts for glacial isostatic adjustments and changes dynamic topography. This resulted in a subaerial Canadian Archipelago, Bering Strait and emergence of Sunda and Sahul shelves in the Indonesia and Australia region. Phase 2 models also applied soils and lakes reconstructions and a newer reconstruction of the Greenland ice sheet that now accounts for a 70% retreat, instead of the 50% retreat applied in phase 1. These reconstructions were derived from the U.S. Geological Survey PRISM dataset, specifically the most recent and fourth iteration of the reconstructions (PRISM4)[53]. In PlioMIP2, modelling groups could choose from either using the vegetation reconstruction from Salzmann et al. (2008), same as PlioMIP1, or use dynamic model vegetation option. COSMOS was the only model among PlioMIP2 participants to use dynamic vegetation. CO_2 concentrations were set to 405 and 400 ppm in phases 1 and 2, respectively. For a detailed description of each model's implementation see[54–73] (Extended Data Table 1). Beyond differences in boundary conditions, there are also fundamental differences in the conception of PlioMIP2 vs. PlioMIP1. Although both phases have not applied changes in orbital parameters, phase 1 was designed to simulate a time averaged global SST reconstruction between 3 and 3.3 Ma BP, while phase 2 focuses on a narrower time slice (Marine Isotope Stage KM5c at 3.205 Ma BP) with almost identical orbital parameters to modern.

Statistical significance of the changes. This is measured through model agreement on the sign of the change. This method is based on a binomial distribution of equal probability (i.e. $p = q = 0.5$). Here, we consider that all models have an equal probability of simulating positive and negative changes in the mPWP simulation. As such, the cumulative probability distribution function of a binomial distribution of N=9 (PlioMIP1) and N=16 (PlioMIP2) models shows that the 95% probability level is reached when there is a model agreement on the sign of the change of 7 and 11 models, respectively. Additionally, we use the non-parametric Spearman rank-correlation test (r_s) to determine if there is a monotonic relation between two variables. It worth noting that the assumption of sample independence may not be completely satisfied, given that climate models share common components and physical equations. Also, the CESM family of models may be overrepresented in the PlioMIP ensemble; however, the differing results obtained among their simulations may allow us to consider these models independent. To illustrate that, we performed a sensitivity analysis where each model from the CESM family was considered at a time when computing the Spearman rank correlation for the relationship shown in Figure 3a. The coefficients ranged from -0.55 (p=0.01) to -0.63 (p=3e-3).

ENSO amplitude. The standard deviation of Niño3 index is used to represent ENSO amplitude. The Niño3 index is calculated from SST anomalies averaged over the eastern Pacific region between 5ºN-5ºS latitude and 150º-90ºW longitude. SST anomalies were computed by removing the mean annual cycle.

Frequency separation. The amplitude of low-frequency variability (>10yr) is evaluated through the variance of the 11-year running mean Niño3 time series in each model. The amplitude of the interannual period is estimated as the variance of the residual time series, i.e., original Niño3 timeseries subtracted from the Niño3 decadal timeseries.

Thermocline Slope. Difference between mean eastern (5ºS-5ºN; 150º-90ºW) and western Pacific thermocline depths (5ºS-5ºN; 160ºE-150ºW). The thermocline depths are computed from the mean temperature profile in each of the boxes indicated above. This is the weighted average depth, based on depths in which the temperature gradients are greater than 50% of its maximum.

Equatorial Pacific Ocean stratification. Difference between the mean temperature in the top 75 meters and the temperature at 100m from 150ºE to 140ºW (as indicated in Figure 2a).

Pacific ITCZ position[45]. The ITCZ position is taken as the average latitudes over which precipitation in the tropical Pacific Ocean (20ºS/N) is greater than 50% of the maximum zonally averaged precipitation over 120ºE-90ºW. This method may take into account the double-ITCZ bias[42] if the double-ITCZ associated precipitation is greater than 50% of the maximum. The double-ITCZ bias is an artificial feature produced by most climate models that overestimates the tropical precipitation south of the equator. Here we define the ITCZ bias as the difference between simulated pre-industrial Pacific ITCZ position and the observed position averaged from 1979 to 2020. Although the PlioMIP models suffer from double-ITCZ bias (mean bias: -4.1° ± 2.1° sd), we do not find a statistically significant relationship with ENSO amplitude changes (r_s=-0.16; p=0.45). It is worth noting that the ITCZ bias is evaluated by comparing the pre-industrial model simulations with modern climate, which is already under the influence of global warming.

Criteria for model selection[8]. Models were selected according to their ability to simulate ENSO non-linear characteristics. Models were required to be able to simulate DJF Niño3 precipitation greater than 5 mm per day, and Niño3 precipitation skewness greater than 1 in the pre-industrial control run. These criteria underscore the essential definition of an extreme El Niño[8] which is fundamental to the ENSO system in observations[74]. Out of 14 PlioMIP2 models, six models met these criteria (Extended Data Figure 5). The skewness criterion filters out models that systematically simulate overly wet and dry conditions in the eastern equatorial Pacific. Such biases tend to reduce rainfall skewness in the models as they simulate SSTs well below or above the convective threshold of 26-28ºC[75], affecting Niño3 precipitation variability.

Atmospheric Subtropical High systems. Quantifying the intensity of the subtropical highs is not a simple task when dealing with different climate backgrounds (+ 2–3K) as the global pressure weakens in a warmer atmosphere. To overcome this pressure issue, we compute the stream function at 850 hPa to identify the position and intensity of the Subtropical High systems. The stream function can be derived from the geostrophic balance:

$$f \times \vec{v} = -\frac{1}{\rho}\nabla_H \mathrm{p}$$

where $\vec{v} = (u_g, v_g)$, p, f and ρ are the velocity vector, pressure, Coriolis function, and density, respectively. Knowing that for a fluid of horizontally uniform density, the geostrophic flow in an f-plane is non-divergent, i.e.

$$\frac{\partial u_g}{\partial x} + \frac{\partial v_g}{\partial y} = 0 \quad \text{for} \quad \rho = \rho_0(g) \quad \text{and} \quad f = f_0 = 2\Omega sin\theta,$$

we can define a stream function which yields to

$$u_g = -\frac{\partial \psi}{\partial y} = -\frac{1}{\rho_0 f_0}\frac{\partial p}{\partial y} \quad \text{and} \quad v_g = \frac{\partial \psi}{\partial x} = \frac{1}{\rho_0 f_0}\frac{\partial p}{\partial x}$$

It is worth noting that in the Southern Hemisphere, increased pressure gradients over geostrophic flows result in intensified anticyclonic circulation (negative stream function).

South Pacific Meridional Mode amplitude. Computed as the amplitude (standard deviation) of mean SST anomalies from 15ºS to 25ºS and from 110ºW to 120ºW.

North Pacific Meridional Mode amplitude. Computed as the amplitude (standard deviation) of mean SST anomalies from 20ºS to 25ºS and from 142ºW to 138ºW.

Southern Hemisphere Booster amplitude. Computed as the amplitude (standard deviation) of meridional wind anomalies from 10ºS to 30ºS and from 140ºE to 170ºE.

CAM4 experiments. We undertook four experiments, with multiple ensemble members, using the NCAR Community Atmospheric Model version 4 (CAM4): 1) mean mid-Pliocene SST and sea-ice forcing from PlioMIP1. PlioMIP1 SST and sea-ice were time and ensemble averaged to force the CAM4 model; 2) mean pre-industrial SST and sea-ice as simulated by PlioMIP1 models for comparison; experiments 3 and 4 consisted in repeating experiments 1 and 2 but with PlioMIP2 SST and sea-ice. For each experiment 5 ensemble members were integrated with slightly different initial conditions: each ensemble member was initialised from a different day of the year. The CO_2 forcing was kept as pre-industrial at 280 ppm and no changes over continental areas were made in all experiments. Each experiment was run for 31 years. The first year of each simulation was discarded due to the atmospheric spin-up. To check if non-linearities in ENSO affected the mean SST change we compared the multi-model mean mPWP warming during all years and during non-ENSO years only. Differences in the tropical Pacific were approximately two orders of magnitude (<0.05 K) lower than the mean tropical Pacific warming (~2 K).

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