

Title

Pacific Warm Pool sub-surface heat sequestration modulated Walker Circulation and ENSO activity during the Holocene

One-sentence summaries

Orbital-driven Warm Pool upper-water heating regulates the equatorial Pacific climate change in the last 25000 years

Authors

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Abstract

The dynamics driving the El Niño Southern Oscillation (ENSO) over longer-than-interannual time-scales is poorly understood. A compilation of new and published records of thermal evolution in the Indo-Pacific Warm Pool thermocline over the past 25,000 years reveals a clear pattern characterized by a major warming in the Early Holocene and a secondary warming in the Middle Holocene. The first thermocline warming is likely related to the precession minimum and associated intensification of the southern Pacific shallow overturning circulation. The second thermocline warming is likely related to the September insolation maximum, which may have caused a steeper west-east thermal gradient in the equatorial Pacific upper-ocean and an intensified Walker Circulation. The Early- to Middle-Holocene thermocline warming in the Warm Pool is proposed to have ultimately reduced the inter-annual ENSO activity. Thus, a substantially increased oceanic heat content of the Warm Pool likely plays a role as a negative feedback for ENSO, particularly in the ongoing global warming.

Introduction

The equatorial eastern Indian and western Pacific Oceans with a persistent sea surface temperature (SST) above 28°C (termed the Indo-Pacific Warm Pool, IPWP) represent a major oceanic heat source for the atmosphere, characterized by deep atmospheric convection accompanied with heavy rainfall (1). The heat storage in the IPWP is essentially formed by the accumulation of warm surface waters driven by the equatorial trade winds (2) and modulated by the convergence of sub-surface ocean heat anomalies from North and South subtropical and eastern Pacific (3) (Fig. 1A). The west-east thermal asymmetry across the tropical Pacific and associated Walker Circulation play a key role in both the inter-annual variability of El Niño Southern Oscillation (ENSO) (2, 4) and the decadal to multi-decadal Pacific climate changes (3, 4, 5). In association with the greenhouse warming over the 20th century, the equatorial Pacific west-east thermal gradient was possibly reduced, the Walker Circulation slowed down (6), and ENSO variability increased (4, 7). More recently, the slowdown of surface air warming between A.D. ~2000 and 2014 (aka “global warming hiatus”) was featured by substantial cooling of equatorial Pacific SST, strengthening of the zonal thermal gradient and the Walker Circulation (3, 5), which has been attributed to enhanced heat storage in the equatorial Pacific thermocline (8, 9). It is not well understood, however, over decadal and even longer time-scales, how the upper ocean heat anomalies will vary with changes in the Walker Circulation, ENSO activity and the shallow overturning circulation from the sub-tropics, which can greatly improve our understanding and prediction of the future climate change.

On longer time-scales, from the last glacial maximum (LGM) to the Early Holocene, a warming of up to 4°C has been observed in the thermocline temperature records over the IPWP (10, 11, 12), possibly leading to a reduction of ENSO activity in the Early- to Middle-Holocene (13, 14). Additionally, stalagmite records from Borneo suggest that Walker Circulation was relatively weak during the last deglacial and strengthened in the Middle Holocene (15) when ENSO activity was suppressed (16). However, while the Borneo stalagmite record suggests similar-to-modern ENSO activity during the Early Holocene (16), other proxy records of ENSO activity from eastern equatorial Pacific indicate little or no ENSO activity during this period (17, 18). Such a discrepancy is largely caused by the sparsity of sediment core records and thus leads to an incomplete understanding of past changes in the upper ocean heat structure of the IPWP.

Here we present a compilation of over 30 sedimentary proxy-records (8 from this work) from the equatorial Pacific (Fig. 1A, Supplementary Table S1) to comprehensively examine changes in the upper-water (thermocline and above) temperature of the IPWP over the last ~25,000 years. We excluded five records (e.g., those from southwest Sumatra, 19) which are predominately influenced by local processes such as upwelling and do not reflect the general characteristics of IPWP’s sub-surface (Supplementary Table S1). The records with an average temporal resolution of ~150 years constrained by a total of 217 radiocarbon dates (Methods, Table S2) covering the course of the LGM through the Holocene. The thermal structure of IPWP is examined by reconstructing temperatures of the thermocline water (TWT) and sea surface (SST) using shell Mg/Ca of two planktic foraminifera, the upper-thermocline dweller *Pulleniatina obliquiloculata* (20, 21) and the mixed-layer dweller *Globigerinoides ruber* (21) (Methods). In order to minimize the possible inter-laboratory and inter-calibration biases and the effect of different cleaning protocols (Supplementary Information), we calculated the SST and TWT anomalies relative to the average value of each temperature record over 6-10 ka (denoted as SSTA and TWTA, Fig. 1B, D). The records of *G. ruber* $\delta^{18}\text{O}$ from 22 cores are processed in the same way to acquire the mean

$\delta^{18}\text{O}_{G. ruber}$ anomaly ($\delta^{18}\text{O}_{G-A}$, Fig. 1F), and are calculated for seawater $\delta^{18}\text{O}$ by subtracting the amount related to changes in local temperature and global ice-volume (22, Supplementary Information). Three deep thermocline temperature records of the eastern equatorial Pacific (EEP), estimated by shell Mg/Ca of *Neogloboquadrina dutertrei* are also analyzed (Supplementary Table S1).

Results

Mean TWTa and SSTa variations

The mean SSTa continuously warms by $\sim 2.8 \pm 0.6^\circ\text{C}$ since ~ 19 ka to ~ 10 ka, and cools by $\sim 0.3 \pm 0.5^\circ\text{C}$ from ~ 9 ka to 0 ka (ka: kilo annum, thousand years before AD1950, Fig. 1E), consistent with previous estimates (23, 24). The deglacial onset of positive SSTa occurs at ~ 18 ka with site-specific differences (25), which is generally synchronous with the onsets of the atmospheric pCO_2 rise (Fig. 1D), global mean sea-surface temperature warming (Fig. 1E), and decreases in the IPWP mean *G. ruber* $\delta^{18}\text{O}$ and the global benthic $\delta^{18}\text{O}$ stack (Fig. 1F).

The mean TWTa warms by $3.0 \pm 0.6^\circ\text{C}$ from ~ 22 ka to 11-9 ka and cools by $1.0 \pm 0.7^\circ\text{C}$ from 9 ka to 0 ka (Fig. 1B). The TWTa at 11-9 ka is highest and synchronous with the precession minimum and obliquity maximum (Fig. 1C). The onset of deglacial warming occurs at ~ 22 ka in TWTa, in-phase with the turning point of precession parameter (Fig. 1C) and precedes the deglacial pCO_2 rise (26) by ~ 4000 years (Fig. 1D). The deglacial mean TWTa warming mainly occurs in two phases: a first warming between 22 and 19 ka, coeval with the initial decrease of precession parameter, and a second warming between 13 and 11 ka, coinciding with the minima of precession parameter (Fig. 1B). The later warming phase is also synchronous with the final-phase in the deglacial rise of the atmospheric pCO_2 (Fig. 1D). The overall trend and the timing of the deglacial warming illustrate that orbital-driven insolation forcing controls the TWT change in the IPWP.

Besides the warm TWTa peak at ~ 11 ka, a second peak is found around 7-6 ka (Fig. 1B). In fact, TWT features observed in sites from open ocean differ from those within the Maritime Continent waters. The TWTa from open-ocean sites gradually warms from 22 ka and peaks at 11-10 ka (Fig. 2A), which we define as the Early-Holocene peak type (EH-peak). The near-equator TWTa records from the Maritime Continent waters are characterized by a rise after 15 ka and a Middle Holocene warm peak around 7 ka (Fig. 2B), defined as the Middle-Holocene peak type (MH-peak). The principal component analysis confirms the distinction, with a first principal component (Fig. 2C) yielding positive loadings for all records (Fig. 2D), and a second principal component (Fig. 2C) yielding different signs of loadings among the sites (Fig. 2E). The linear combinations of the first and second principal components resembles the two types of TWTa change (Fig. 2F), suggesting that “PC1-PC2” represents the feature of EH-peak type TWTa, and “PC1+PC2” the MH-peak type.

The Early-Holocene TWTa peak

The Early-Holocene peak type, consistent with the mean TWTa trend (Fig. 1B), is in-phase with the changes in Earth’s orbital configuration of precession and obliquity (Fig. 3A). The relationship between precession/obliquity and IPWP’s thermocline change has been discovered before (10-12, 27, 28), and was explained by some regional oceanographic processes. Such a common Early-Holocene peak, however, implies a common driving mechanism over the entire IPWP thermocline. The western equatorial Pacific thermocline water originates from the basin-wide shallow overturning circulation of the Pacific Ocean

(1, 29), which is fed by the subduction of relatively salty, warm surface waters in the subtropical North and South Pacific (1), and is primarily regulated by the surface wind stress curls determined by the meridional SST gradients (30). Over the last 25 ka, the gradient between the southwestern Pacific SSTA (from 45.5°S, 174.9°E) (31, 32) and the IPWP mean SSTA (Fig. 3B) resembles the Early-Holocene peak type TWTA, possibly reflecting relatively warmer mid-latitude and thereby enhanced warm water transport of shallow overturning circulation in the Early Holocene. In addition, foraminifera $\delta^{13}\text{C}$ records of the equatorial Pacific also suggest an Early-Holocene intensification in the advection of southern-sourced sub-surface waters (33, 34). An Early-Holocene peak also appears in the southern Pacific and Antarctic temperature records due to the June (austral winter) insolation maximum at precession minimum (Supplementary Fig. S3). In modern observations (35), the northern Pacific shallow overturning circulation also contributes to the IPWP thermocline water, but the northwestern Pacific SSTA record shows no direct linkage to the Early-Holocene peak in IPWP thermocline (Supplementary Fig. S3). Therefore, we can only propose that the overall trend of IPWP's thermocline evolution over the LGM-Holocene may be dominated by the southern Pacific shallow overturning circulation, under the control of changing meridional insolation gradient induced by orbital forcing (i.e. precession and obliquity, 36).

Our hypothesized mechanism for the Pacific sub-surface temperature change is verified by a transient simulation of the Community Earth system model (CESM1.0.4, 37), forced by the orbital insolation and greenhouse gas changes of the past 300,000 years (38) (detailed in Methods). The responses of the Pacific upper-ocean thermal structure point out the key role played by precession in forming the Early-Holocene peak of TWT in the IPWP. At precession minimum during the Early Holocene, an intrusion of southern Pacific warm waters resulted in a drastic thermocline warming in the 30-200 m water depth of the open-ocean equatorial Pacific (140°E-140°W, Fig. 3C, D, E) and in the relatively deeper (below 120 m water depth) Maritime Continent waters (39) (100°E-140°E, Fig. 3F). Noteworthy, the precession minimum also induces significant cooling anomalies in the shallower Maritime Continent waters above 120 m depth in our simulation (Fig. 3F), in contrast to the paleo-proxy-based Early Holocene TWTA warming off the Philippines and in the Timor Sea. Therefore, the Early Holocene TWT warming in the IPWP may be a result of the precession-forced warming of deeper thermocline waters (Fig. 3D), which cannot be explained by the obliquity maximum with a cooling effect instead (Supplementary Fig. S4). Of course, the Early-Holocene warming may also be induced by the influence of increased atmosphere pCO_2 , which results in a universal warming at all latitudes (Supplementary Fig. S4). In addition, the deglacial sea-level rise can also deepen the thermocline and result in thermocline warming in the Maritime Continent waters (40). Thus, the Early Holocene warming of the IPWP sub-surface water could have been caused by the combined effect of precession minimum, atmosphere pCO_2 maximum and sea-level high-stand.

The Middle-Holocene TWTA peak

For the near-equator sites within the Maritime Continent waters, the most significant thermocline warming occurs in the Middle Holocene. These records share two main features: (i) a cooling spell in 18-15 ka and (ii) a warming peak at ~7 ka (Fig. 4A). These sites are apparently less directly influenced by the southern Pacific sourced signal of the Early Holocene TWTA peak. The Middle Holocene peak type TWTA varies in-phase with the equatorial September insolation change (Fig. 4A) that dominates ENSO-related activities in the tropical Pacific (41). For example, the overall pattern of the MH-peak type TWTA is consistent with the W-E zonal temperature difference in both the sea surface (42)

and sub-surface across the equatorial Pacific, which show maxima in Middle Holocene and minima in the early stage of the deglaciation (Fig. 4B). Likewise, the strength of the ascending limb of the Walker Circulation, as indicated by the Borneo stalagmite $\delta^{18}\text{O}$ records, shows a minimum (more positive $\delta^{18}\text{O}$) around 17-16 ka and a maximum (more negative $\delta^{18}\text{O}$) around 7 ka (Fig. 4C), suggesting enhanced atmospheric convection over Borneo in the Middle Holocene.

The hydroclimate changes revealed by Borneo stalagmite are supported by our CESM simulation of annual mean rainfall timeseries over Borneo forced solely by orbital insolation change (Fig. 4C). In addition to the Borneo stalagmite records, the surface seawater $\delta^{18}\text{O}$ stack ($\delta^{18}\text{O}_{\text{sw}}$) of the IPWP shows positive excursions in the last deglacial and a negative peak in the Middle Holocene (Fig. 4D), indicating strengthened convective precipitation over evaporation in the Middle Holocene. Thus, we argue that the Middle Holocene thermocline warming of the near-equator IPWP is dynamically linked to the equatorial Pacific ENSO-like changes (e.g., enhanced Walker Circulation and strengthened W-E zonal thermal contrast in the Middle Holocene). Our model simulations verify that September insolation maximum forces a warming in the IPWP thermocline (Fig. 4E) and a stronger zonal thermal difference across the equatorial Pacific (Fig. 4F). The atmospheric response to an increased zonal thermal gradient leads to increased rainfall over western equatorial Pacific (Fig. 4G) and a stronger Walker Circulation (Fig. 4H).

Discussion

The long-term evolution of the tropical Pacific mean state, including the IPWP's thermocline temperature, the W-E temperature gradients and the western equatorial Pacific hydroclimate, have the potential to shape shorter-term climate oscillations, i.e. interannual ENSO activity, as suggested by simple model simulations (41, 43). In fact, an Early- to Middle-Holocene depression of ENSO activity associated with strengthening of the Walker Circulation relative to modern is evidenced by several proxy records and model simulations (13, 16, 44). Our findings suggest that, the evolution of the equatorial Pacific climate in response to precession forcing could be understood in analogy to the modern seasonal development of the equatorial Pacific air-sea coupled system (2). That is, in the Early Holocene under the precession minimum, the thermocline of the open-ocean IPWP warmed widely, thereby likely suppressing ENSO activity. During the Middle Holocene, maximal September insolation may have caused an overall thermocline warming, increased precipitation, and decreased sea surface salinity in the IPWP and strengthening of the Walker Circulation (Fig. 4D). A maximum in W-E upper-ocean thermal contrast (Fig. 4B) ultimately led to an extreme reduction of ENSO activity in the Middle Holocene.

The response of ENSO activity to future global warming and consequences to Earth's climate evolution are not well constrained by either modern observations or model simulations (45), thus necessitating additional observations from paleoclimate records. Our study shows that warming of the western equatorial Pacific thermocline coupled with increased W-E thermal gradient and strengthened Walker Circulation, may have ultimately led to the reduction in ENSO activity during the Early and Middle Holocene, when climate was arguably slightly warmer than at present (39, 46). This inference raises the possibility that enhanced anthropogenic heat sequestration in the western equatorial Pacific subsurface warm pool, through the shallow overturning cell and equatorial Pacific air-sea coupled system, may further augment heat uptake in the eastern equatorial Pacific cold tongue due to reduced ENSO activity. In the near future, these may subsequently lead to an intermittent

slowdown of surface warming, likely for short periods, in a pattern akin to the “global warming hiatus” between 2000 and 2014 (3, 5, 9).

Materials and Methods

We analyzed Mg/Ca and $\delta^{18}\text{O}$ of *G. ruber* (250-350 μm) and *P. obliquiloculata* (350-440 μm) at the State Key Laboratory of Marine Geology, Tongji University, Shanghai, PR China. Mg/Ca measurements were conducted on an ICP-MS (Thermo VG-X7) with measurement reproductivity of 2.2% for *G. ruber* (N=311) and 4.8% for *P. obliquiloculata* (N=302), estimated by replicate samples (N: total replicates of the 4 cores of this study, for details see [Supplementary Table S2](#)). Shell $\delta^{18}\text{O}$ of the two species was measured with a Finnigan-MAT253 mass spectrometer. Conversion to the international Pee Dee Belemnite (PDB) scale was performed using NBS19 standard, and the long-term variability of $\delta^{18}\text{O}$ is better than 0.07‰. Details of pre-treatments and procedures are described elsewhere (20).

The age models for the IPWP cores were all established mainly by linear relationships of radiocarbon dates, first corrected for the ^{14}C reservoir ages by the Marine Reservoir Correction and then calibrated to calendar age using CALIB7.1 software (<http://calib.org>) ([Supplementary Tables S1 and S3](#)). The time-series of proxies (SST, TWT and $\delta^{18}\text{O}$) were then averaged at 150-yr non-overlapping bins using the stair-case integration re-sampling method. The temperature gradients of IPWP relative to the eastern equatorial Pacific or extra-tropical seas are calculated by the differences between the respective temperature anomaly records and on temporal steps determined by the average temporal resolution of the corresponding records (150 yr for W-E subsurface temperature gradient, 500 yr for W-E SST gradient, and 600 yr for South-Equatorial Pacific SST gradient).

Here we use the Community Earth System Model 1.0.4 (CESM) with T31_gx3v7 resolution ($3.75^\circ \times 3.75^\circ$ for atmosphere and nominal 3° resolution for ocean, 37) to simulate the response of Pacific upper-ocean thermal structure to the forcing of orbital configuration (obliquity and precession) and change in atmospheric greenhouse gas content (GHG) (38). As a spin-up, the CESM was first run for 200 model years under orbital parameters and GHG of 300 ka and other boundary conditions in 1950 AD. Then the model was integrated for 3000 model years with the transient orbital insolation forcing and GHG changes of the past 300,000 years, in which orbital parameters and GHG were advanced by 100 years at the end of each model year (experiment CESM_GHG). A similar transient accelerated experiment (CESM_ORB) was only forced by orbital insolation changes since 300 ka (38). The outputs in the last 3000 model years of these two experiments were both analyzed, and they exhibit similar responses to orbital insolation forcing. Thus, only the results from experiment CESM_GHG are shown. At first, ocean temperature, salinity, atmospheric circulation and precipitation are extracted from original outputs along multiple profiles (i.e. the latitude-longitude profile at 120 m water depth, the longitude-vertical profile along the equator, the latitude-vertical profile zonally averaged over the open Pacific (140°E - 140°W) or the western Pacific (100°E - 140°E)). Then these oceanic and atmospheric variables were linearly regressed onto the normalized timeseries of specific orbital forcing (i.e. obliquity parameter changes, GHG changes, and the June or September insolation changes defined by the solstice or equinox precessional mode, respectively, 38). Associated regression coefficients represent the Pacific air-sea coupled responses between maxima and minima of each orbital forcing. Statistical significance is assessed by the 95% confidence level of t test.

H2: Supplementary Materials

Section S1: *P. obliquiloculata* Mg/Ca records and dissolution effect

Section S2: Reconstructions of proxy data

Fig. S1: *P. obliquiloculata* Mg/Ca records from different water depth

Fig. S2: Comparison of the Mg/Ca-temperature records among calibrations and cleaning-methods

Fig. S3: Comparison of the TWTa changes with other records

Fig. S4: CESM simulated Pacific sub-surface temperature responses to obliquity and CO₂ forcings

Table S1: The sediment cores analyzed in this study

Table S2: Mg/Ca measurement reproductivity of core MD10-3340, SO18480, KX21-2 and MD01-2386

Table S3: Radiocarbon dates of core MD10-3340, SO18480-3, KX973-21-2 and MD01-2386.

References and Notes

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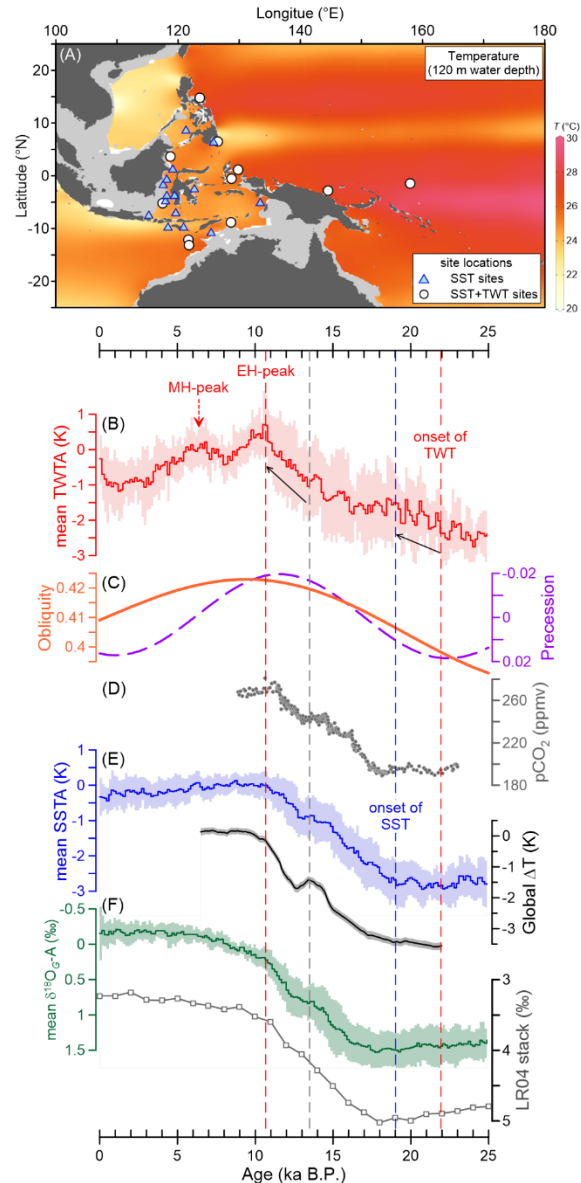
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Data and materials availability: The data that support the findings of this study are reported in the Supplementary Information. All the data can also be obtained from NOAA (ncdc.noaa.gov) and PANGAEA (pangaea.de), or from ZJ (email: jian@tongji.edu.cn).

Figures and Tables

Figure 1. Timeseries of thermocline and sea surface temperature anomalies in the IPWP compared to global climate indices during the past 25,000 years.

(A) Site locations of paired SST and TWT records (white circles) and SST-only records (blue triangles) ([Supplementary Table S1](#)). Shadings indicate temperatures at 120 m water depth. (B) Mean TWTA (red) of the IPWP records. Solid black arrows mark the two major warming phases of TWTA between 22-19 ka and 13-11 ka, respectively. (C) precession (dashed purple) and obliquity (orange) parameters ([47](#)). (D) Atmospheric pCO₂ derived from Antarctic WDC ice core (gray dots, [26](#)). (E) Mean SSTA (blue) of the IPWP records and the global mean SST anomaly (ΔT , dark gray line, [48](#)). (F) Mean IPWP *G. ruber* $\delta^{18}\text{O}_G$ anomaly ($\delta^{18}\text{O}_G\text{-A}$, green) and LR04 benthic $\delta^{18}\text{O}$ stack (gray line and symbols, [49](#)). Shadings of proxy records show the 1 σ standard deviation. Vertical dashed lines denote the timing of the deglacial onset of SST (~19 ka, blue) and TWT (~22 ka, red), the onset of the second deglacial warming step (gray) and the Early-Holocene peak of TWT (EH-peak, ~10.8 ka, red). Dotted red arrow denotes the Middle Holocene peak of TWT (MH-peak, 7 ka).



561 **Figure 2. The two types of thermocline temperature anomaly (TWTA) records in the IPWP**
 562 **since the LGM.**
 563 (A) The average TWTA (brown) and the original TWTA records of the open-ocean sites. (B)
 564 Same as (A) but for the near-equator sites in the Maritime Continent waters. The TWT records in
 565 (A) and (B) are defined as Early-Holocene (EH) and Middle-Holocene (MH) peak types,
 566 respectively. (C) The first (blue) and second (red) principal components of all the TWTA records.
 567 PC1 and PC2 explain 62% and 16% of the total variance, respectively. (D, E) Loadings of PC1
 568 (D) and PC2 (E) for each site. (F) Linear combinations of PC1 and PC2 that resemble the Early-
 569 Holocene peak type (PC1-PC2) and Middle-Holocene peak type (PC1+PC2), respectively.

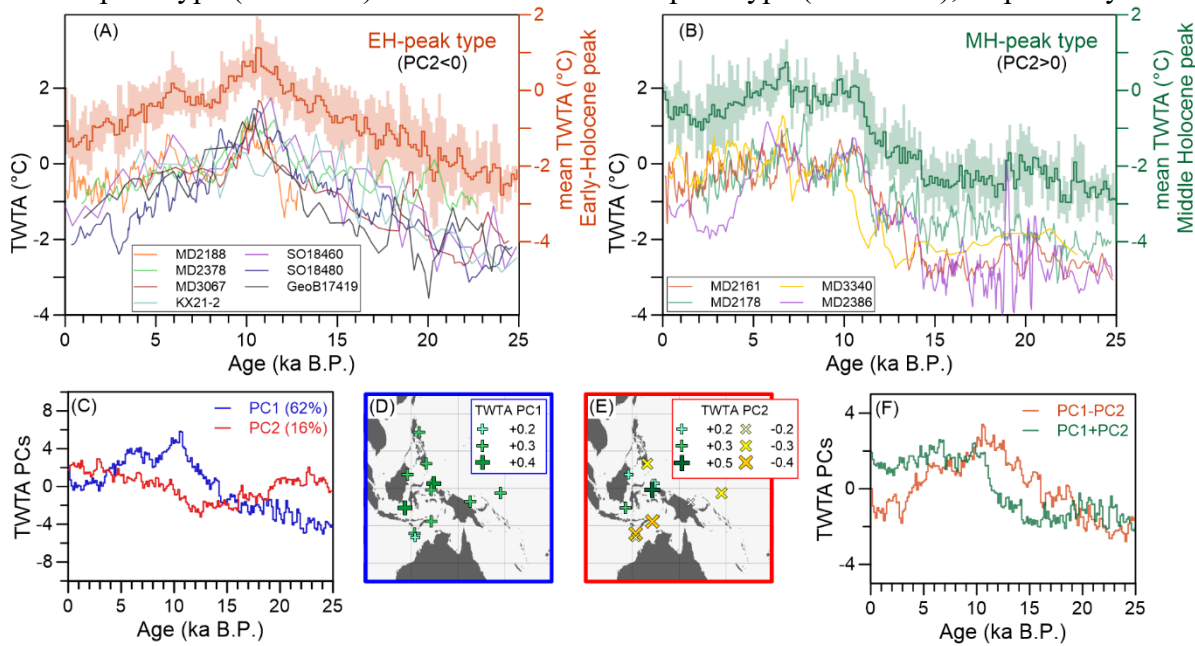


Figure 3. Precession-forced Early-Holocene TWTA peak.

(A) The mean TWTA of the Early-Holocene peak type (brown), precession (red dashed line) and obliquity (gray dotted line, 47). (B) Meridional SSTA gradient between southwest Pacific (SWP, site MD97-2120, from 45.5°S, 174.9°E, 31-32) and the IPWP. Holocene, last Deglaciation, and LGM are separated by dashed vertical lines. CESM simulated responses of Pacific sub-surface temperature to June insolation in the Early Holocene are shown in (C-F): horizontal temperature anomaly distributions of upper-thermocline (at 120 m, C) and deeper thermocline (160-180 m water depths average, D), and meridional upper-water temperature anomaly profiles in the open Pacific (140°E-140°W, E) and the Maritime Continent waters (100°E-140°E, F). Temperature anomalies in (C-F) are shown as regression coefficients against the standardized time series of the June insolation at precessional band in experiment CESM_GHG. White shadings mask insignificant results below 95% confidence level (t-test).

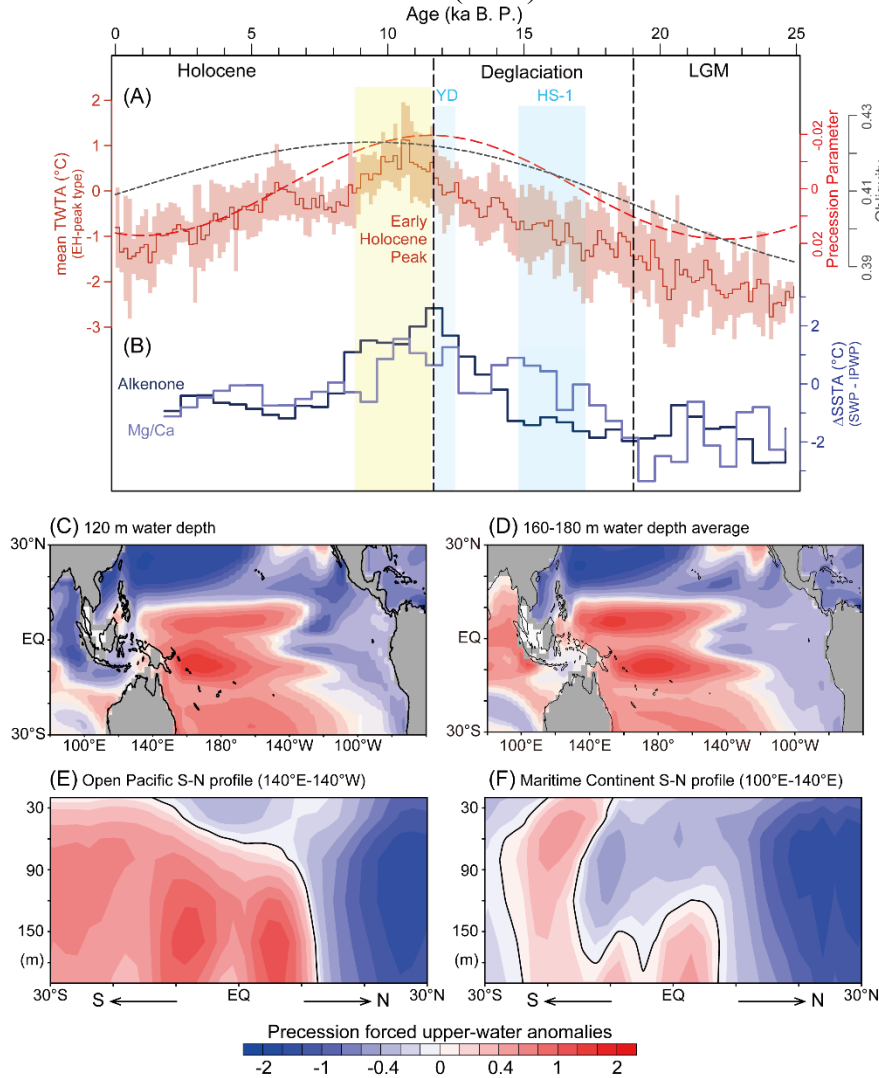


Figure 4. Timeseries and simulated temperature and rainfall anomalies in the IPWP since the LGM.

(A) Mean TWTA of Middle-Holocene peak type (green) and the September 21st insolation at the Equator (dashed red line) and obliquity (gray dotted line, 47). (B) Zonal temperature gradients at sub-surface ($\Delta_{\text{sub-TA}}$, in gray) and at sea surface (Δ_{SSTA} , light green, 42) shown as the difference between the WEP and EEP. (C) $\delta^{18}\text{O}$ records of northern Borneo stalagmites (15, 16) (dark and light green) and simulated annual mean rainfall (mm day⁻¹) over Borneo (dark gray, this study). (D) Mean anomaly of seawater $\delta^{18}\text{O}$ of IPWP ($\delta^{18}\text{O}_{\text{sw}}$, dark gray, shading shows the standard deviation of the records). Shadings, vertical bars and dashed lines as in Fig. 3. Simulated response of the Pacific sub-surface temperature and atmospheric variables to September insolation maximum are shown in (E-H): (E) Annual mean TWTA at 120 m water depth. (F) Depth profile of the annual mean temperature anomaly across the Pacific between 5°S and 5°N. (G) Late autumn (October-to-December) anomalies of mean rainfall (colors, in mm day⁻¹) and horizontal winds at 850 hPa (arrows, in m s⁻¹, reference arrow on top right). (H) Late autumn mean Walker circulation anomalies between 5°S and 5°N across the Pacific, as indicated by anomalies in wind (arrows, in m s⁻¹, reference arrow on top right) and in vertical velocity (colors, in Pa s⁻¹). Positive values in red indicate upward motion and negative values in blue indicate downward motion. These anomalies in (E-H) are shown as regression coefficients against the standardized time series of the September insolation at precessional band in experiment CESM_GHG.

