Obliquity pacing of the western Pacific Intertropical Convergence Zone over the past 282,000 years

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The Intertropical Convergence Zone (ITCZ) encompasses the heaviest rain belt on the Earth. Few direct long-term records, especially in the Pacific, limit our understanding of long-term natural variability for predicting future ITCZ migration. Here we present a tropical precipitation record from the Southern Hemisphere covering the past 282,000 years, inferred from a marine sedimentary sequence collected off the eastern coast of Papua New Guinea. Unlike the precession paradigm expressed in its East Asian counterpart, our record shows that the western Pacific ITCZ migration was influenced by combined precession and obliquity changes. The obliquity forcing could be primarily delivered by a cross-hemispherical thermal/pressure contrast, resulting from the asymmetric continental configuration between Asia and Australia in a coupled East Asian–Australian circulation system. Our finding suggests that the obliquity forcing may play a more important role in global hydroclimate cycles than previously thought.
The Intertropical Convergence Zone (ITCZ) migrates meridionally with the seasonal angle of the sun\(^1\) and circles the globe in the tropics, marking the Earth’s meteorological equator (Fig. 1). The convergence of inter-hemispheric trade winds leads to strong convective clouds, heavy precipitation and intense latent-heat transfer, dominating rainfall patterns worldwide. Owing to its intensive rainfall gradient, a small displacement in the position of the ITCZ can cause dramatic changes in hydrology and the frequency of extreme weather events—such as droughts, floods and tropical cyclones\(^2\). The collapse of the Mayan civilization and several Chinese Dynasties has been attributed to persistent droughts associated with ITCZ migrations\(^3,4\). The current build-up of atmospheric greenhouse gases has the potential to affect the future position of the ITCZ and corresponding climate\(^5\). An in-depth reconstruction of the position, structure and migration of the ITCZ is thus critical to our understanding of global climate and sustainable human socioeconomic development.

Lines of evidence from the past 210–220 kyr in Asian and American monsoon records\(^6,7\) suggest that the ITCZ was predominately driven by precessional forcing (\(\sim 20\) kyr). Within the ITCZ territory, short-term terrestrial\(^8–10\) and marine\(^11,12\) proxy records have been reported. Few 100s-kyr records\(^13\) from the meteorological core of the ITCZ in the low-latitude Pacific, the southern counterpart of East Asia, severely hinders our understanding of the natural ITCZ variability related to orbital forcings in the Quaternary. Knowledge of the past variability of western Pacific ITCZ has global significance because this region is the largest heat and moisture source in the world.

Papua New Guinea (PNG), a mountainous terrain located at the southern border of the ITCZ (Fig. 1 and Supplementary Fig. 1), delivers a large amount of suspended sediments and solutes to the adjacent oceans as a result of the prodigious precipitation (\(>2,000\) mm yr\(^{-1}\)) in the region\(^14,15\). This transport occurs mostly in the wet season (\(>90\%\) annual load) when the ITCZ is located over PNG\(^16\). Sediment archives from nearby marine basins, therefore, reflect this fluvial delivery and provide important information on precipitation related to the ITCZ position.

Relatively high rare earth element (REE) contents (for example, Nd \(\sim 30\) \(\mu\)g g\(^{-1}\)) are characteristic of solid crustal materials, as compared with dissolved riverine (for example, \(\sim 30\) ng g\(^{-1}\)) or seawater values (\(<1\) pg g\(^{-1}\))\(^17\). This feature has led to the study of these elements and isotopes as terrestrial sediment tracers\(^17–19\) in the ocean.

Using inductively coupled plasma sector field mass spectrometric (ICP-SF-MS) techniques with 2\(\sigma\) precision of \(\pm 2–6\%\) (ref. 20), we establish a 282-kyr-long record of REEs to calcium (REE/Ca) ratios in the planktonic foraminifera *Globigerinoides ruber* (Supplementary Fig. 2). The foraminiferal tests were sampled from a marine sediment core MD05-2925 (9°21’S, 151°28’E; water depth 1,661 m; Fig. 1 and Supplementary Fig. 1), collected 50 km off southeastern PNG to reveal the orbital-scale evolution of ITCZ precipitation intensity. Further, new calculations from a previous orbital-accelerated transient experiment\(^21,22\) using a coupled fast ocean-atmosphere model (FOAM) forced by variations in orbital parameters (see Methods for details) are conducted to offer clues of possible dynamical ITCZ migration processes in the western Pacific. Our geochemical records and modelling results reveal an important influence of obliquity forcing on the western Pacific ITCZ variability.

### Results

**Planktonic foraminiferal REE.** Marine carbonates can record seawater REE composition even though seawater REE contents vary by an order of magnitude\(^23,24\). Planktonic foraminifera\(^23\) from the eastern Pacific and coral carbonates\(^24\) from the High Island of the Great Barrier Reef (GBR) have typical seawater REE patterns\(^25\), characterized by shale-normalized (SN)\(^26\) light (LREE, La–Nd) and middle REE (MREE, Sm–Ho) depletions, and heavy REE (HREE, Er–Lu) enrichments (Nd/Yb\(_{SN}\) = 0.17–0.28 and Gd/Yb\(_{SN}\) = 0.41–0.70; Fig. 2c,f,g). Deviating from seawater\(^23\) and marine carbonates\(^23,24\) from the open ocean, the REE patterns for the foraminiferal carbonates at the study site are characterized by enrichments of LREE and MREE (average Nd/Yb\(_{SN}\) = 0.45 ± 0.04 (1 s.d. of the mean, \(\sigma_\text{m}\)) and Gd/Yb\(_{SN}\) = 0.88 ± 0.06 (1\(\sigma_\text{m}\)) and high REE concentrations (Fig. 2a), resembling more like the composition of PNG coastal seawater\(^27\) (Nd/Yb\(_{SN}\) = 0.31 and Gd/Yb\(_{SN}\) = 0.83; Fig. 2c). The local MREE-enriched source\(^17\) (Fig. 2b) combined with the REE fractionations in seawater\(^28\) produces the pattern illustrated in Fig. 2a. These features are consistent with dominance of river
input to the upper water column as recorded in PNG coastal corals from Misima Island\textsuperscript{29} (Fig. 2e), which is termed PNG ‘island-weathering signature’ supplied by precipitation-dependent river runoff\textsuperscript{17}. The observations of an oxidative state at this core site, the absence of the formation of Mn-Fe oxides (see Methods) and no correlation between foraminiferal Nd/Ca and Fe/Ca data (Supplementary Figs 3 and 4), also support the assertion that the cleaned planktonic foraminifer REE can reliably capture the sea surface water condition.

There is no significant difference between REE patterns for periods with low and high foraminiferal REE contents over the entire MD05-2925 record (Supplementary Fig. 5). Only 10–20% variation of Nd/Yb\textsubscript{SN} and Gd/Yb\textsubscript{SN} ratios shows stable LREE/HREE and MREE/HREE ratios over the entire sequence (Supplementary Figs 4 and 5). This temporally consistent REE pattern shows that a terrestrial source is dominant in the record (see Supplementary Note 1 for detailed evaluation of the controls on foraminiferal REE/Ca). The implication is also supported by Nd isotopic data (Supplementary Fig. 2 and Supplementary Table 2) and a replicade record from an adjacent marine sedimentary core, ODP-1115B (9°11’S, 151°34’E; water depth 1,149 m) (Supplementary Note 1 and Supplementary Fig. 6). Therefore, the down-core planktonic foraminiferal REE/Ca sequence at MD05-2925 site can reflect the river runoff flux and be used as a qualitative proxy record of past ITZC-related precipitation over PNG. All measured \textit{G. ruber} REEs/Ca ratios (Supplementary Data 1) of core MD05-2925 consistently co-vary with a high correlation coefficient of $>0.97$ (except for Ce) over the past 282 kyr (Supplementary Fig. 2). Here we use Nd/Ca time series (Fig. 3c) to represent REE variability and to infer regional ITZC-related precipitation changes.

**Inferred precipitation records.** The MD05-2925 Nd/Ca sequence can be characterized by a sinusoidal-like curve with low values of 0.2–0.3 μmol mol$^{-1}$ and 10 s-kyr wide peaks of 0.4–1.2 μmol mol$^{-1}$. \textit{G. ruber} Nd/Ca cycles are generally aligned with changes in precession-dominated Southern Hemisphere (SH) summer insolation values (Fig. 3c,e and Supplementary Fig. 7a). The agreement indicates that PNG precipitation variations are broadly driven by precessional forcing. Intense PNG precipitation results from the large temperature gradient between land and ocean in response to high SH summer insolation.

Comparison of our Nd/Ca record with contemporaneous stacked Chinese stalagmite $\delta^{18}$O records\textsuperscript{6,30–32} over the past 282 kyr is illustrated in Fig. 3. The stalagmite $\delta^{18}$O record has been interpreted as a record of summer monsoon precipitation and Asian summer monsoon (ASM) intensity; with more negative (positive) stalagmite $\delta^{18}$O values indicating higher (lower) precipitation/stronger (weaker) ASM intensities\textsuperscript{30,31}. High foraminiferal Nd/Ca-inferred wet periods at PNG generally match positive stalagmite $\delta^{18}$O-derived dry conditions in mainland China and vice versa (Fig. 3b,c). This interhemispheric precipitation anti-phasing over the Asia-Pacific realm can be attributed to latitudinal shifts of the ITCZ and associated rain belts, driven by precession-dominated changes in seasonal insolation (Supplementary Fig. 7a).

In China, cave record-inferred precession-dominated precipitation intensity co-varies with solar radiation\textsuperscript{6} (Fig. 3a,b). However, our planktonic foraminiferal REE/Ca series (Fig. 3c) shows that precession is not the only orbital forcing mechanism operating on the ITCZ in the southern low-latitude Pacific. In PNG, there are six incompatible periods of low Nd/Ca-inferred precipitation at about 45, 90, 140, 165, 210 and 250 kyr BP (highlighted with grey bars in Fig. 3), when the Earth’s axial tilt was high (Fig. 3c,f). Modelling results, synchronous with our proxy sequence (Fig. 3d and Supplementary Figs 8 and 9), also show consistent suppressed summer precipitation over PNG in the SH tropics at high obliquity periods. Indeed, spectral power analysis indicates that our foraminiferal Nd/Ca time series is dominated by obliquity periodicity (Supplementary Fig. 7d), highlighting the important role of Earth’s axial tilt in modulating precipitation in the region of PNG.
Discussion

The obliquity effect on SH tropical Pacific precipitation is most likely associated with its control on the meridional thermal-pressure contrast. Modelling results by FOAM suggest that high obliquity is responsible for the establishment of a strong Siberian high cell (Supplementary Fig. 8a) and East Asian winter monsoon system\textsuperscript{22,33,34}. In an experiment using the Geophysical Fluid Dynamics Laboratory modelling, climate feedbacks and seasonal response may outcompete the local radiative forcing of obliquity and induce complicated response of northern high-latitude climate\textsuperscript{35}. However, FOAM-inferred atmospheric response (Supplementary Fig. 8) is supported by other simulation results using Community Climate System Model version 3 (ref. 36; Supplementary Fig. 10) and Community Earth System version 1 (Supplementary Fig. 11).

Similar with the Siberian high, the Australian low, the counterpart of the meridional circulation loop, is also affected by obliquity (Supplementary Fig. 8c). Although, precessional forcing dominates local land-ocean thermal contrasts and influences the Australian low, the simulated Australian low does not rigidly follow precession. Extreme low pressures are always induced by high obliquity during the past 282 kyr and distinguitably stronger than those induced by precession (Supplementary Fig. 8). Obliquity-induced meridional circulation can affect the intensity of the Australian summer monsoon, the hemispheric counterpart of the Asian winter monsoon, through a cross-equatorial ‘pressure-push’ process\textsuperscript{37}. Specifically at high obliquity, a strong pressure gradient between an intensified Siberian high and Australian low enhances cross-equatorial flow of northerly winds (Supplementary Fig. 8a–c). Similar with the Australian low, the relative intensity of peak northerly winds at high obliquity are significantly raised, although the precession cycle is still obvious in the wind change, attributed to the effect of local thermal contrast. The enlarged peak northerly winds subsequently reinforce the southward shift of the ITCZ rain belt to its southernmost position (Fig. 4a). This northward/southward shift of the ITCZ leaves distinct rainfall patterns in different locations. The net effect is to increase precipitation in North Australia (Supplementary Fig. 8f) with compensated amounts in PNG at the six periods tagged in Fig. 3. The precipitation, thus, is relatively reduced at PNG despite high seasonal insolation and presents a stronger obliquity component (Supplementary Fig. 7). The intensified obliquity cycle in modelling PNG precipitation is qualitatively in agreement

![Figure 3](https://example.com/fig3.png)

**Figure 3** | Comparison of PNG planktonic foraminifera G. ruber Nd/Ca from MD05-2925 with other records over the past 282 kyr. (a) Northern hemisphere summer insolation (NHSI, 15 July) at 30°N (ref. 61). (b) Stacked δ\(^{18}\)O of Chinese stalagmites\textsuperscript{6,30–32}. (c) MD05-2925 G. ruber Nd/Ca (2σ precision: ± 2.6%, ref. 20). (d) Modelled PNG precipitation (5–12°S and 130–160°E). (e) Southern hemisphere summer insolation (SHSI, 15 January) at 15°S (ref. 61). (f) Earth obliquity\textsuperscript{61}. Arrows depict an increase of the ASM and the foraminifera-inferred PNG precipitation. PNG precipitation is intensified at six periods with high SHSI (vertical grass green bars with Nd/Ca >0.75 μmol mol\(^{-1}\)), but does not closely reflect high SHSI at six other intervals (grey bars).
with our reconstruction (Fig. 3c,d). Support for such a strong southward migration of the ITCZ by high obliquity also comes from a 100-kyr record at Gregory Lakes (20°15’S, 127°30’E), on the fringe of the desert in semi-arid northwestern Australia38 (Figs 1 and 4). The occurrence of two past high lake stands at 37–50 and 95–105 kyr BP (Fig. 4 of ref. 38) matches the high-obliquity window and provides a SH terrestrial complement to our marine record.

At low obliquity, the ‘pressure-push’ forcing 37, strengthened by the capacious Asian landmass, is weak and the northerly wind intensity and ITCZ shift tends to follow precession-dominated insolation. The peak northerly wind and Australian low occur at high precession (~20, 70, 115, 185 and 230 kyr BP; Supplementary Fig. 8). However, these precession-induced changes are not more vigorous than ones at intervals with high obliquity (Supplementary Fig. 8). For the scenario with low obliquity and high precession, the northerly wind is not as strong as relative to high-obliquity and high-precession cases and the centre of the strong convergence rain belt stays relatively in the north. As a result, PNG experiences enormous rainfall while North Australia receives less rainfall. AL, Australian low; SH, Siberian high; light blue arrow, surface wind intensity; solid white line, core position of the western Pacific ITCZ; blue circle, marine sediment core MD05-2925 site; brown circle, Gregory Lakes38.

Methods

Core site. The selected marine sediment core, MD05-2925, is 2,843 cm in length, was recovered in June 2002 during the MAGES XIII-P scaffold (Past Equatorial Climate: Tracking El Niño) cruise on board the R.V. Marion Dufresne of the French Polar Institute (IPEV). The core site is located at the southern margin of the Western Pacific Warm Pool, 110 km to Fergusson Island, 50 km off southeastern tip of PNG (Fig. 1 and Supplementary Fig. 1). The selected core sediment is composed of a mixture of biogenic carbonate and silty clay 39. The chlorophyll level of 0.2 mg m⁻² (ref. 41) for surrounding surface water in eastern PNG suggests low regional productivity. The dissolved-oxygen concentrations are high (~3 ml l⁻¹) through the whole water column including bottom waters of eastern PNG 42. The local benthic oxygen flux, reflecting organic-matter remineralization, is only 0.1 ml m⁻² per year (ref. 43). It is lower than the values of 0.8 ml m⁻² per year for the reducing margins (notably in the eastern boundary upwelling systems and North Indian Ocean) 43.

Age model. The age model was established based on accelerator mass spectrometry (AMS) radiocarbon (¹⁴C) dates (Supplementary Table 1) and oxygen isotope stratigraphy (Supplementary Fig. 12). A series of planktonic foraminiferal AMS ¹⁴C dates at 19 different depths, including 200 individuals of Globigerinoides ruber (>500 μm) each, from the upper 292 cm of the core were measured. Dates were calibrated to calendar ages (before 1950 AD) using CALIB 6.0.1 software 44 with a reservoir age difference (ΔR) estimated from the Marine Reservoir Correction Database (http://calib.qub.ac.uk/marine/). The calculated weighted mean ΔR value is 64 ± 23 years for the selected four sites around the Solomon Sea 39. The chronology was based on linear interpolation between calibrated ¹⁴C dates (Supplementary Table 1).

For the depths >292 cm, the age model was developed by correlating the composite benthic foraminiferal oxygen isotope data of core MD05-2925 to the LR04 stack record 46 (Supplementary Fig. 12). Composite benthic foraminiferal oxygen isotope data are established with benthic foraminifera (>250 μm, 2–4 individuals each depth), including Uvigerina spp. (201 samples), Cibicidoides wuellerstorfi (11 samples) and Bulimina spp. (7 samples) at core depths of 157–1,897 cm (Supplementary Fig. 13). Measurement of δ¹⁸O data, relative to Vienna Pee Dee Belemnite carbonate standard, was performed on a Micromass IsoPrime isotope ratio mass spectrometer with 1σ reproducibility of ±0.05‰ (ref. 47). δ¹⁸O offsets of C. wuellerstorfi (+0.64‰) 48 and Bulimina spp. (~0.11‰) 49 from Uvigerina spp. were corrected. This age model is supported by the last occurrence of G. ruber (pink) occurred at depths of 830–835 cm, corresponding to 129.8 kyr BP (Supplementary Fig. 12), consistent with the observation in the southern South China Sea 50.

Screening for diagenesis. Scanning electron microscopy images of 30 uncleaved individuals of planktonic foraminifera G. ruber (white, s.s. 250–300 μm) at six depths of 477 (50.1 kyr BP) and 617 cm (81.6 kyr BP) with low REE content, 527 (56.8 kyr BP) and 577 cm (73.2 kyr BP) with high REE content and 877 (135.0 kyr BP) and 917 cm (146.1 kyr BP) with moderate REE content (Supplementary Fig. 14) were carefully screened. Thirty more uncleaved individuals picked from six depths (87, 267, 787, 1,087, 1,317 and 1,477 cm), respectively, at marine isotope stages 1, 2, 5, 6, 7 and 8 were also checked with scanning electron microscopy. No nodules of Mn–Fe oxides were noticeable and all shell walls were intact and preserved (Supplementary Fig. 14). Additional careful inspection under microscope did not observe Mn–Fe oxides for 1,200 tests from the selected 12 depths. For conservative consideration, we still applied a full cleaning procedure on all samples.

Measurement of foraminiferal trace elements. REE contents of down-core planktonic foraminifera G. ruber (white, s.s. 250–300 μm) at six depths of 477 (50.1 kyr BP) and 617 cm (81.6 kyr BP) with low REE content, 527 (56.8 kyr BP) and 577 cm (73.2 kyr BP) with high REE content and 877 (135.0 kyr BP) and 917 cm (146.1 kyr BP) with moderate REE content (Supplementary Fig. 14) were carefully measured. Although no Mn–Fe nodules were noticeable (Supplementary Fig. 14), G. ruber tests were cleaned with a full cleaning procedure for foraminiferal trace metal analysis, modified from refs 51,52. About 20 foraminiferal individuals were gently crushed, placed in a Teflon vial and washed sequentially with the following reagents (at all pH 8.5–9.0): i) ethanol + H₂O,
(ii) 1% H₂O₂, (iii) 0.56 M NH₄Cl and (iv) 0.43 M NH₂OH. Cleaned tests, polished
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C. wuellerstorfi
by an interlaboratory comparison for analysing REE/Ca ratios of benthic
Nd isotopic measurement. Planktonic foraminifera G. ruber and sediment
(<63 μm) samples were collected from two depth intervals of 472–477 cm
(49.5–50.1 kyr BP, 580 individuals, >250 μm) and 537–542 cm (58.8–60.6 kyr BP, 250 individuals, >250 μm) of core MD05-2925 (Supplementary Fig. 2). The picked
planktonic foraminifera samples were cleaned with the same protocol for REE/Ca ratio analysis and then dissolved in 2 M HNO₃. The sediment samples were first cleaned with 10% CH₃COOH to remove carbonate, and subsequently cleaned with a reductive reagent (1 M NH₄OH: HCl in 25% CH₃COOH) to remove possible Fe-Mn phases on the sample surface. The cleaned sediment samples were
decomposed in a mixed solution of HF, HClO₄ and HNO₃, and then dissolved in 2 M HNO₃.
Neodymium in the 2 M HNO₃ dissolved samples was extracted by a two-stage column separation. The REE fraction in the solution was purified from the
remaining major and trace elements using Eichrom Ln resin. Neodymium was subsequently separated from the other REE with Eichrom Ln resin.
Neodymium isotopic compositions were measured by a multi-collector ICP-MS, Thermo Fisher Neptune, in the HISPEC. The measured 143Nd/144Nd ratios were normalized to 0.72191 using an exponential law. La Jolla standard was measured at 0.1811 ± 0.000014 (or ±0.27 σ, n = 13). All 143Nd/144Nd ratios were calibrated to the reported value relative to the
La Jolla standard value of 0.511858 (ref. 57). Sample 143Nd/144Nd ratios
were expressed as notation defined by an equation of $^{143}$Nd/$^{144}$Nd$_{LaJolla} = (1 - \delta^{143}$Nd/$^{144}$Nd$_{sample}$) / (1 - \delta^{143}$Nd/$^{144}$Nd$_{CHUR}$) × 10^4, where the
143Nd/144Nd ratio of CHUR standard for Chondritic Uniform Reservoir
$^{143}$Nd/$^{144}$Nd$_{CHUR}$ is 0.512638 (ref. 58).

Modelling simulation. The simulated precipitation and climatological records used in this study are from an orbital coupled transient run using FOAM conducted by Kutzbach et al.21 and re-analysed by Shi et al.22. FOAM, a fully coupled, mixed-resolution, and high-throughput general circulation model, provides a good simulation of mean condition and variability. With a factor of 100, FOAM was integrated for 2,820 years under orbital forcing only to obtain climate evolution over the past 282 kyr. Changes in global ice volume/sea level and greenhouse gases were not considered. The spatial resolution is set to 4° × 7.5° for atmosphere and 1.4° × 2.8° for ocean. Because of the limitation of orbital acceleration, it is difficult for the deep ocean to reach equilibrium so that the full potential of the deep ocean feedback cannot be achieved. However, in previous studies23,24,25, the responses of monsoon precipitation, mostly considered as a
description to the changes in the atmosphere-surface ocean system, to the orbital insolation can be successfully retrieved in the annual variability. A detailed description on the transient experiment is available in ref. 21.

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