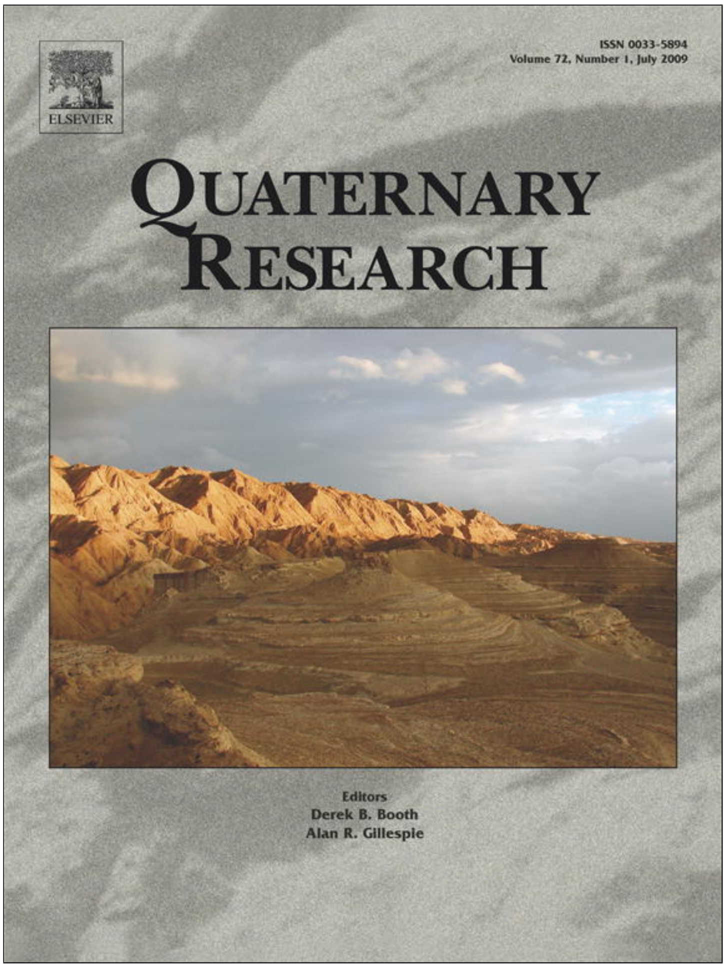
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ITCZ rather than ENSO signature for abrupt climate changes across the tropical Pacific?

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ABSTRACT

Latitudinal movements of the Intertropical Convergence Zone (ITCZ), analogous to its present-day seasonal shifts, and El Niño Southern Oscillation (ENSO)-type variability both potentially impacted rainfall changes at the millennial timescale during the last glacial period. In this study we compare tropical Pacific sedimentary records of paleoprecipitation to decipher which climate mechanism was responsible for the past rainfall changes. We find that latitudinal movements of the ITCZ are consistent with the observed rainfall patterns, challenging the ENSO hypothesis for explaining the rapid rainfall changes at low latitudes. The ITCZ-related mechanism appears to reflect large-scale atmospheric rearrangements over the tropical belt, with a pronounced Heinrich–Dansgaard/Oeschger signature. This observation is coherent with the simulated tropical rainfall anomalies induced by a weakening of the Atlantic thermohaline circulation in modeling experiments.

Introduction

The abrupt climate changes that occurred at the millennial timescale during the last glacial period are best documented in the $\delta^{18}O$ record of the Greenland ice sheet (e.g., Dansgaard et al., 1993), namely the cold and warm Dansgaard–Oeschger (DO) stadials and interstadials, respectively. Apart from these rapid temperature changes over Greenland, some cold extremes were accompanied by iceberg discharges in the North Atlantic sector, the so-called Heinrich events (H) (e.g., Hemming, 2004). This rapid climate variability has been widely studied in various types of paleoclimate archives in the Northern Hemisphere, pointing to a large-scale impact of these events (Voelker et al., 2002).

Further paleoclimate studies focusing on the low latitudes have evidenced the millennial-scale variability within the northern tropics (e.g., Peterson et al., 2000; Wang et al., 2001; Stott et al., 2002; Ivanochko et al., 2005; Leduc et al., 2007; Weldeab et al., 2007), especially in areas sensitive to seasonal latitudinal shifts of the Intertropical Convergence Zone (ITCZ) and its related precipitation changes under current climate. These studies point out that at times of DO stadials and H events the Northern tropics were marked by dry events (Wang et al., 2007a).

Modeling experiments attempting to reproduce H events are commonly forced by excess freshwater input in the North Atlantic surface ocean (Ganopolski and Rahmstorf, 2001; Knutti et al., 2004; Dahl et al., 2005). These freshwater experiments induce a substantial reduction of the Atlantic overturning circulation and are accompanied by a southward displacement of the mean ITCZ position in response to an asymmetry of tropical sea-surface temperatures (SST) (Knutti et al., 2004; Dahl et al., 2005; Zhang and Delworth, 2005; LeGrande et al., 2006; Stouffer et al., 2006). Therefore, paleoclimate reconstructions and modeling studies point out that an intimate link exists between the North Atlantic climate background and the mean ITCZ position.

Under current conditions, the El Niño-Southern Oscillation (ENSO) variability is another climate phenomenon that has a profound impact on interannual variations of precipitation in the tropical Pacific Ocean. During ENSO warm phases (i.e., El Niño events), unusual dry (wet) conditions occur in the western (central) tropical Pacific (Dai and Wigley, 2000). Since ENSO variability has worldwide repercussions through different modes of climatic teleconnections, changes in ENSO variability is a potential candidate for explaining past climate changes. Such an ENSO-type analogy has been proposed for paleoceanographical records from the northwestern tropical Pacific (NWP) (Stott et al., 2002), a region marked by unusual dry conditions during El Niño years. NWP sea-surface salinities (SSS) records documented H-DO features, inferring rapid changes of precipitation over the studied area (Stott et al., 2002). The authors have concluded that changes in ENSO can explain these millennial-scale rainfall changes during the last glacial period in the NWP (Stott et al., 2002).

To determine which process is consistent for describing the H-DO variability at low latitudes (analogously to modern latitudinal shifts of ITCZ or ENSO-like variability), it is useful to examine how the tropical Pacific precipitation evolved at the millennial timescale. At the seasonal scale, the ITCZ latitudinal shifts and its associated precipitation changes induce an in-phase response in the northeastern tropical Pacific (NEP) and NWP rainfall variability, but an antiphase response

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between the northern tropical Pacific and the southwestern tropical Pacific (SWP) seasonal (Figs. 1a, b, 2a). On the other hand, El Niño years are marked in the tropical Pacific by positive precipitation anomalies above the central and eastern tropical Pacific Ocean, while concomitant episodes of dryness mark the entire western tropical Pacific region (Figs. 1c, 2b), and vice-versa for La Niña years.

In this study we consider three published datasets localized at key targeted areas over the tropical Pacific Ocean (Fig. 1): two marine sediment cores from the NWP (core MD98-2181; Stott et al., 2002) and the NEP (core MD02-2529; Leduc et al., 2007), and one continental sedimentary core from the SWP (Lynch's crater, north-eastern Australia; Turney et al., 2004). The geographic coverage of the cores allows us to distinguish the "ITCZ" vs. "ENSO" variability as follows: one H event would lead to reduced rainfall in the northern tropical Pacific records if the climatic anomaly was triggered by changes in the mean position of the ITCZ, or in the western tropical Pacific if the climatic anomaly was rather induced by changes in ENSO activity (i.e., toward more "El Niño-like" conditions according to Stott et al., 2002). Comparing these sedimentary records of rapid rainfall changes gives us the opportunity to clarify which climate phenomenon is involved in the tropical precipitation variability, which is the main purpose of this study. We are aware that the use of the ITCZ and ENSO acronyms as analogs for describing the estimated past changes in precipitation patterns imply shortcomings because boundary

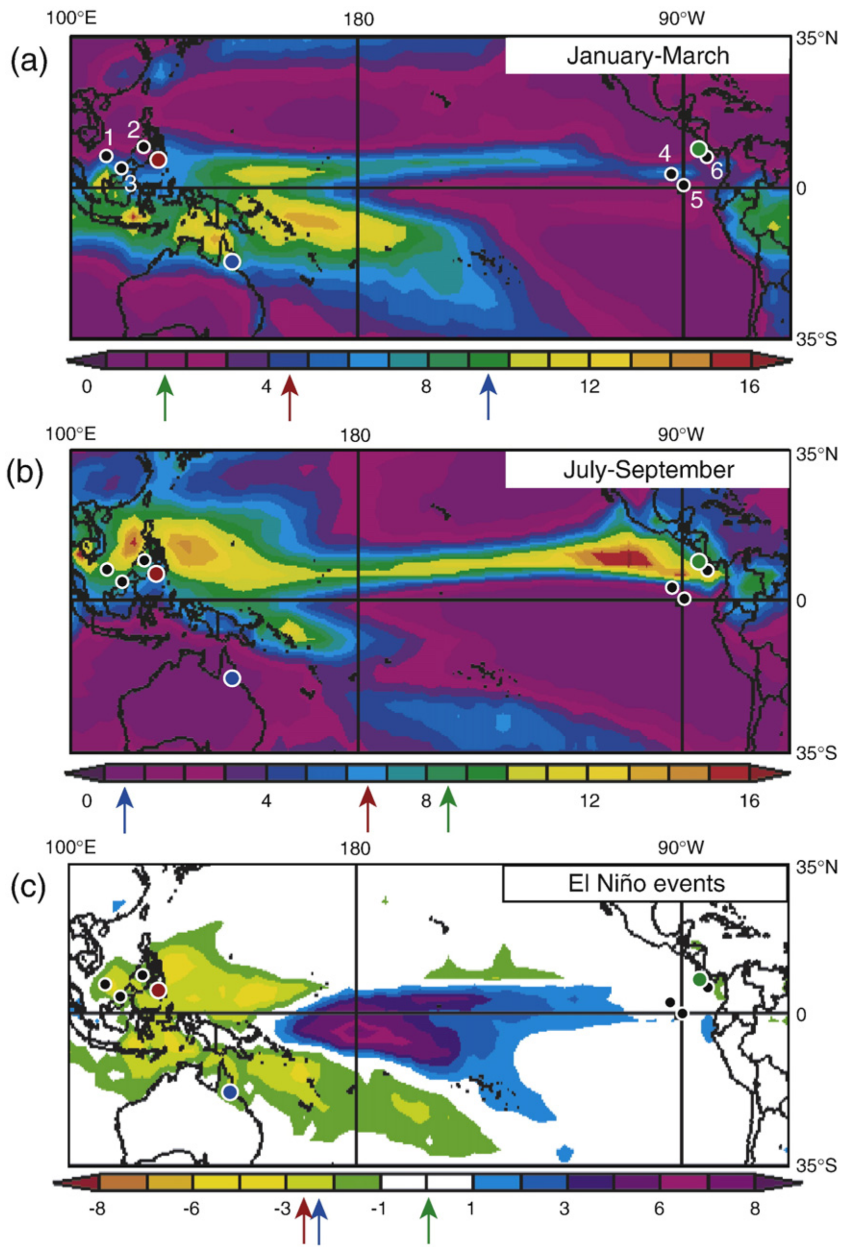

Figure 1. Tropical mean precipitation rates (in mm day^{-1}) derived from the Arkin-Xie CMAP precipitation standard available at http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl, for the 1948–2008 time interval averaged from January to March (a), from July to September (b), and from anomalies computed from December to February for El Niño years (http://ggweather.com/enso/years.htm). The location of sediment cores shown in Fig. 5 are indicated as follows: core MD98-2181 NWP (red dot) (Stott et al., 2002), Lynch's crater in the SWP (blue dot) (Turney et al., 2004), core MD02-2529 in the NEP (green dot) (Leduc et al., 2007). Additional archives covering the Younger Dryas chronozone marked by decreased precipitation are numbered: (1) for core 18287-3 (Kienast et al., 2001), (2) for core MD97-2141 (Rosenthal et al., 2003), (3) for Borneo speleothems (Partin et al., 2007), (4) for core TR163-19 (Lea et al., 2000), (5) for core V21-30 (Koutavas et al., 2002), (6) for cores ME0005A-43JC/ODP Hole 1242 (Benway et al., 2006). Colored arrows indicate precipitation rates and precipitation anomalies for the NWP (red arrow), the SWP (blue arrow) and the NEP (green arrow) sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

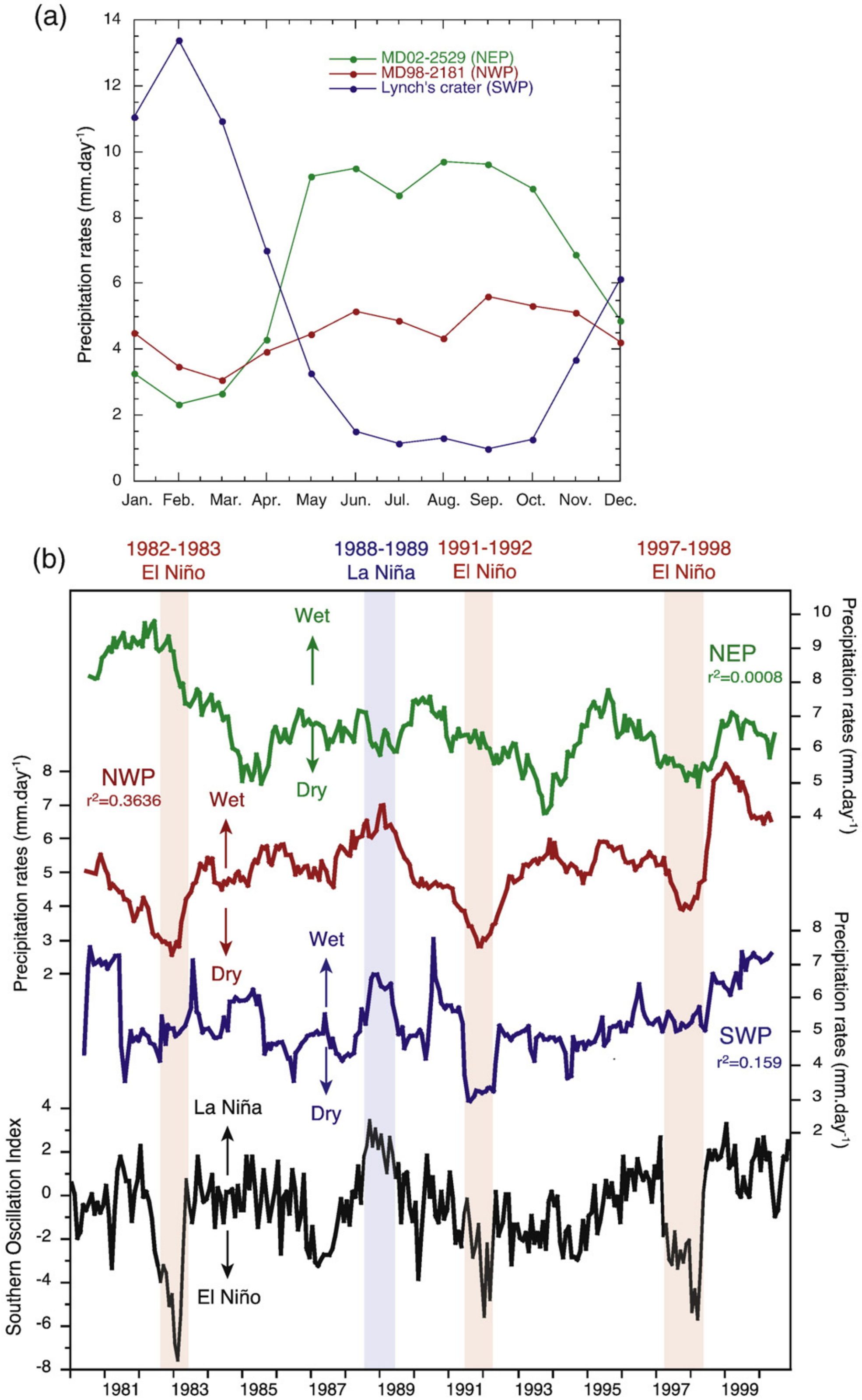

Figure 2. (a) Annual mean precipitation rates in the vicinity of the sedimentary records presented in Fig. 5, averaged over the AD 1980–2000 time interval. (b) Interannual precipitation anomalies in the vicinity of the sedimentary records presented in Fig. 5 for the 1980–2000 time interval, and compared to the Southern Oscillation Index (SOI, a proxy for the ENSO climatic variability, reported here as the standardized sea level pressure difference between Tahiti and Darwin). These interannual rainfall anomalies were calculated by computing the running average over 12 months in order to remove seasonality. The blue and red vertical bars indicate the major La Niña and El Niño events, respectively. The correlation coefficients between the SOI and each interannual rainfall time series are indicated. For these datasets (240° of freedom), the SWP and NWP interannual rainfall variability are positively correlated to the SOI with a confidence level of 98%, while the NEP site is not correlated to the SOI. Precipitation data are available at http://iridl.ldeo.columbia.edu/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conditions may change their expression regionally (see, e.g., Rosenthal and Broccoli, 2004). However, it provides useful benchmarks for describing the first-order sign of rainfall change at sites we considered.

Methodology

At low latitudes, past hydrological changes at the millennial timescale can be reconstructed by estimating the $\delta^{18}O$ of surface seawater ($\delta^{18}O_{sw}$) from marine sediment cores. This is achieved by paired measurements of $\delta^{18}O$ performed on planktonic foraminifera and of proxies for SST (Kienast et al., 2001; Stott et al., 2002; Dannenmann et al., 2003; Rosenthal et al., 2003; Benway et al., 2006; Leduc et al., 2007). This method is based on the assumption that enhanced precipitation rates induce a lowering of SSS, reflected in $\delta^{18}O_{sw}$ since these parameters are roughly linearly related (Fig. 3).

Changes in present-day precipitation rates in the NEP are paced by seasonal ITCZ migrations that induce strong salinity changes, while there is no discernable effect of ENSO on rainfall variability (Fig. 2). This climatic variability is faithfully recorded in the $\delta^{18}O$ variability of modern corals: while the ITCZ-related seasonal variations are of ~0.9‰ amplitude with minima occurring during the wet season, the seasonal-scale SST effect on the $\delta^{18}O$ of corals is negligible (Linsley et al., 1994). During El Niño years, 1 to 2°C warming correspond to 0.2 to 0.4‰ decreases in $\delta^{18}O$ of corals, making the coral $\delta^{18}O$ seasonal changes slightly larger during El Niño years than during normal years (Linsley et al., 1994). Such a seasonal variability in modern corals was also recorded by $\delta^{18}O$ measurements performed on the surface-dwelling planktonic foraminifera *Globigerinoides ruber* recovered by sediment traps in the same region, indicating that the *G. ruber* $\delta^{18}O$ seasonal range was ~1‰ (Curry et al., 1983). These results also point that a pronounced *G. ruber* $\delta^{18}O$ minimum is concomitant with the wet season (Curry et al., 1983), when ~80% of the annual *G. ruber* flux to the sediment trap occurs (Thunell et al., 1983).

In the NWP, it has been suggested that *G. ruber* preferentially records warm summer SST (Stott et al., 2002). Recent corals from the NWP indicate that interannual changes in SST and precipitation rates

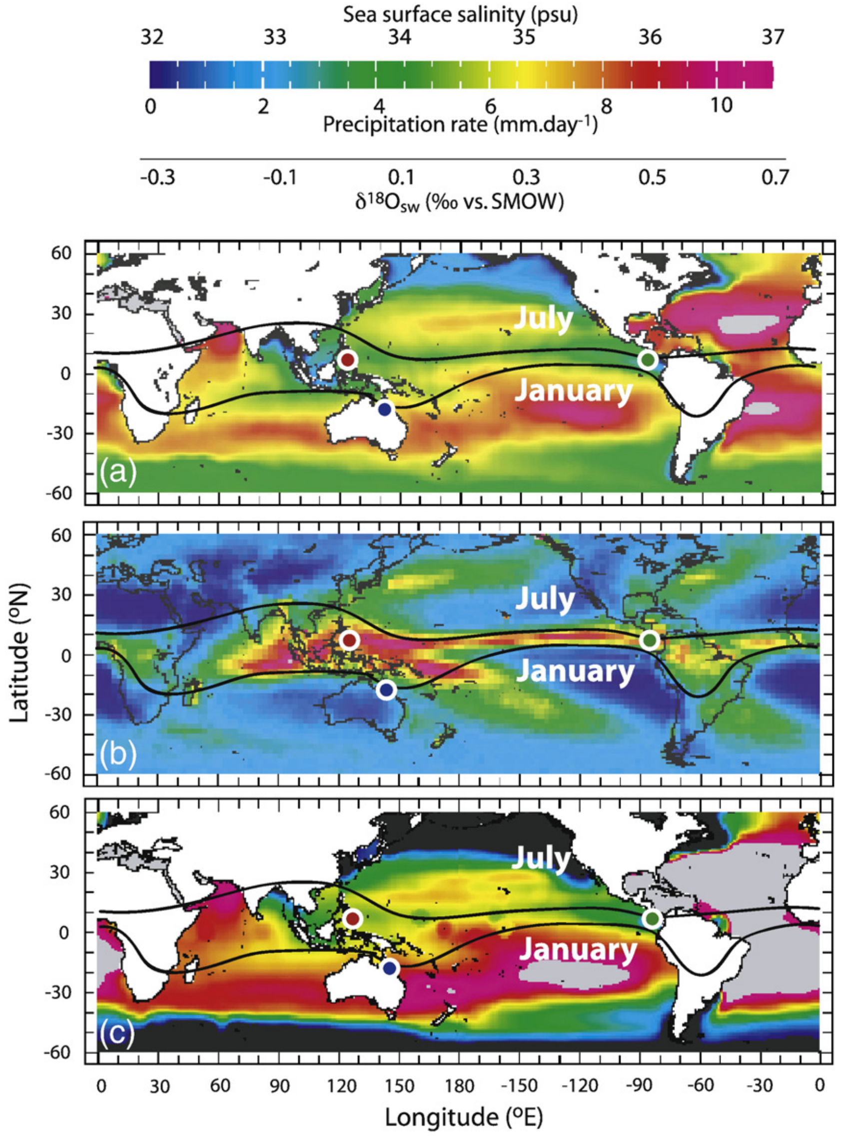

Figure 3. Comparison of (a) the annual SSS fields with (b) the mean daily precipitation rates averaged for the AD 1984–1988 period (in order to avoid the strong 1983 El Niño year and the strong 1989 La Niña year) and (c) the surface $\delta^{18}O_{sw}$ fields. Note that, in the tropical Pacific, areas of intense precipitation rates are corresponding to low SSS and $\delta^{18}O_{sw}$. The SSS data are retrieved from the World Ocean Atlas 2001 (Conkright et al., 2002) (a). The precipitation rates are from the CMAP Estimated Precipitation from NOAA NCEP, available at http://iridl.ldeo.columbia.edu/. (b). The $\delta^{18}O_{sw}$ are derived from the global gridded data set of the oxygen isotopic composition in seawater of LeGrande and Schmidt (2006), available at http://iridl.ldeo.columbia.edu/. (c). The black lines indicate the approximate location of the ITCZ for January and July. Also are shown the location of sediment cores shown as depicted in Fig. 1.

associated with ENSO variability generate significant second-order $\delta^{18}O$ signals superimposed on the seasonal $\delta^{18}O$ signal, allowing coral $\delta^{18}O$ interannual anomalies to isolate ENSO changes from the seasonal $\delta^{18}O$ signals (Fairbanks et al., 1997; Gagan et al., 2000). Then, temporal variations in the $\delta^{18}O$ of planktonic foraminifera from the NWP may reflect a mixture of changes in both the ITCZ dynamics and the ENSO variability.

For the marine sediment cores, $\delta^{18}O$ measurements were performed on *G. ruber* and have been corrected for the SST and the long-term global $\delta^{18}O_{sw}$ variations due to global ice volume (Waelbroeck et al., 2002) in order to extract the regional $\delta^{18}O_{sw}$ signal (see Fig. 4 for the original datasets and Leduc et al., 2007 for details of the calculation of regional $\delta^{18}O_{sw}$ ($\Delta\delta^{18}O_{sw}$)). Ideally, the $\delta^{18}O_{sw}$ calculation based on planktonic foraminifera $\delta^{18}O$ corrected for SST changes should be derived from Mg/Ca SST estimates from the same species, to minimize potential biases inherent to ecological preferences of planktonic organisms that ultimately generate the sedimentary signals, as it has been done for core MD98-2181. For MD02-2529, SST are derived from the high-resolution alkenones unsaturation index to calculate the $\delta^{18}O_{sw}$ because the Mg/Ca was of lower resolution. We feel confident in our estimation based on alkenone-derived SST, however, because (1) the MD02-2529 sedimentation rate—which is higher than 10 cm ka^{-1}—considerably decreases the phase shift between the two different size fractions and reduces the signal attenuation due to mixing of deep-sea sediment by benthic organisms (Bard, 2001); (2) sediment trap studies in NEP region indicate that *G. ruber* fluxes maxima are concurrent with the main coccolithophores bloom during summer months, suggesting that the $\delta^{18}O$ of *G. ruber* and alkenones should have recorded comparable hydrological patterns (Thunell et al., 1983); (3) Mg/Ca and alkenone-based SST are in agreement (both in amplitude and phase) during MIS 3 (Leduc et al., 2007); (4) MD02-2529 $\delta^{18}O_{sw}$ calculation is confirmed by high-resolution Mg/Ca time series on a nearby core for the last 30 ka (Benway et al., 2006), suggesting that SST reconstruction from both proxies are comparable; and (5) the amplitude of the estimated $\delta^{18}O_{sw}$ changes in MD02-2529 at the millennial timescale (attaining 1‰) would require a temperature bias of up to 5°C to cancel out the sign of salinity changes, which is far too much to invoke any temperature bias linked to proxy discrepancies (Mix, 2006; de Garidel-Thoron et al., 2007; Steinke et al., 2008).

Under present-day hydrological conditions, the $\delta^{18}O_{sw}$ and SSS are linearly related, with a slope of ~0.2‰ $\delta^{18}O_{sw}$ per p.s.u. for the western (Fairbanks et al., 1997) and of ~0.25‰ $\delta^{18}O_{sw}$ per p.s.u. for the eastern (Benway and Mix, 2004) Pacific sectors. Though changes in the inter-oceanic basin exchange of water complicate the relationship between $\delta^{18}O_{sw}$ and SSS (Benway and Mix, 2004; Oppo et al., 2007), we assume as a first approximation that the sign of $\Delta\delta^{18}O_{sw}$ changes reflects past regional rainfall changes at the millennial timescale; in the following

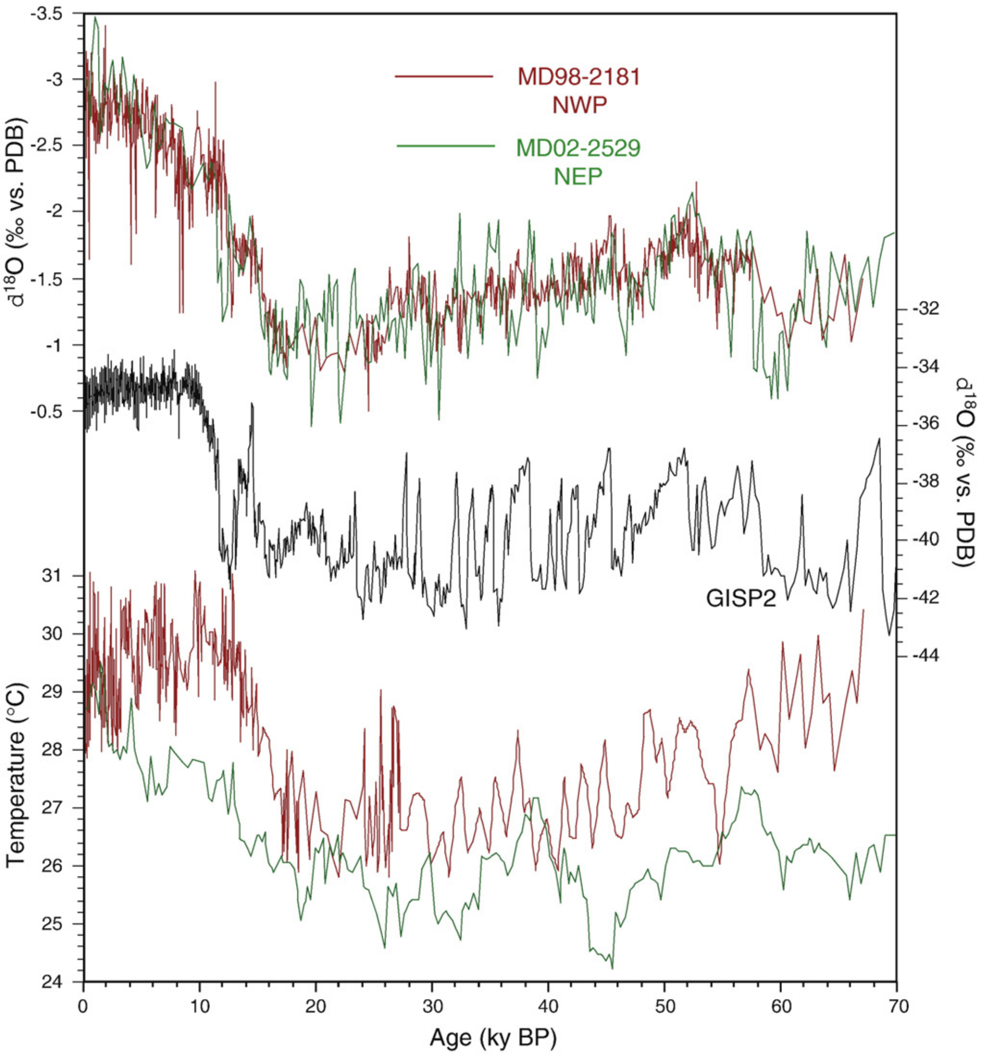

Figure 4. Temporal variations of *G. ruber* $\delta^{18}O$ measured on MD98-2181 (Stott et al., 2002) and on MD02-2529 (Leduc et al., 2007) sediment cores (top panel), and of SST (bottom panel) used to calculate the $\Delta\delta^{18}O$ variations presented in Fig. 5 (to obtain a SST value for each $\delta^{18}O_{G.\ ruber}$ measurement, the SST records were linearly interpolated). Also are shown the temporal variations of $\delta^{18}O$ recorded in the GISP2 ice core (middle panel; Stuiver and Grootes, 2000).

discussion we will use the $\Delta\delta^{18}O_{sw}$ as an indicator of rainfall intensity variations during the last glacial period. Reconstructing the $\delta^{18}O_{sw}$ through paired $\delta^{18}O$ and Mg/Ca analyses on carbonates may lead to random, non-systematic errors of $\pm 0.2‰$ (1σ) that are purely induced by analytical precision and calibration uncertainties (Rohling, 2007). However, the facts that (1) MD02-2529 $\Delta\delta^{18}O_{sw}$ variations largely exceed this value, and (2) MD98-2181 $\Delta\delta^{18}O_{sw}$ variations interpreted in this study are documented with a time resolution greatly higher than the events described, support that the millennial-scale signal recorded in both marine sediment cores are significant.

At Lynch's crater (SWP), Turney et al. (2004) estimated the peat decomposition (i.e., the degree of humification) through high-resolution measurements of the sedimentary optical absorption, and used it use as an indicator of the surface sediment wetness at the time of sediment deposition (i.e., a proxy for regional rainfall). High values of peat absorption are related to dry surface conditions because of increased microbial activity under aerobic conditions (Turney et al., 2004). These dry conditions are also related to periods of increased burning—determined by charcoal counts—and to decreased cyperaceae/poaceae pollen ratios that indicate drier conditions (Turney et al., 2004).

Age control

The marine sediment cores were dated by radiocarbon measurements performed on planktonic foraminifera up to 40 and 30 ka for MD02-2529 and MD98-2181, respectively. For MD02-2529, additional age control points were determined by benthic foraminiferal $\delta^{18}O$ stratigraphy between 40 and 70 ka. For core MD98-2181, the age model for the oldest part of the sequence was improved by aligning DO interstadials 8 and a point near the base of the core to their corresponding $\delta^{18}O$ shifts in the GISP2 $\delta^{18}O$ record. This dating strategy has been further justified by the comparison of geomagnetic field Relative Paleointensity between the MD98-2181 and an independently dated sediment core from the North Atlantic (Stott et al., 2002). The Lynch's crater terrestrial record has been dated by calibrated radiocarbon ages until 45 ka.

Precipitation patterns of the tropical Pacific during the last glacial period

The data presented in Fig. 5 are on their own published original timescales; further fine-tuning of the sedimentary records to the

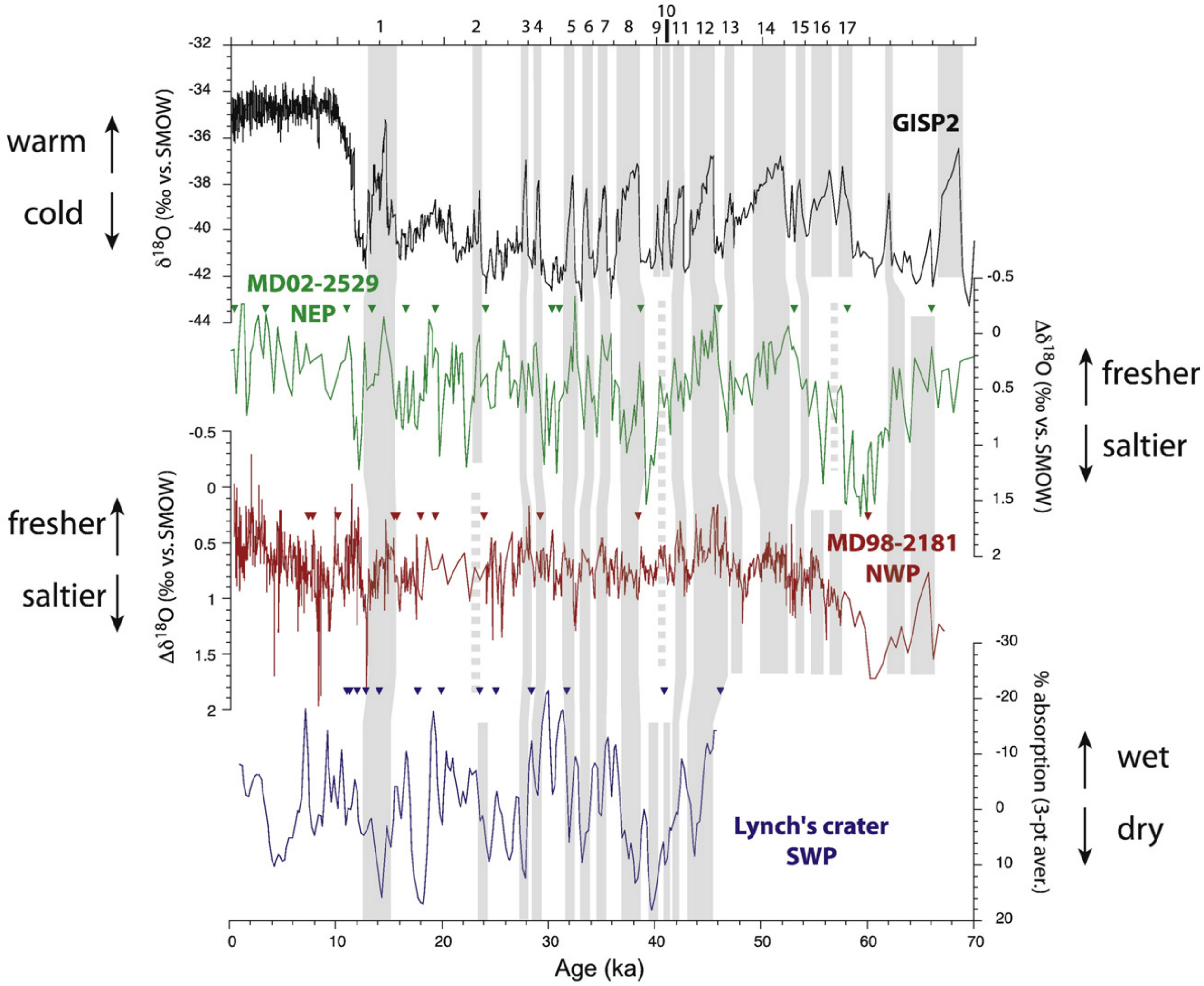

Figure 5. Comparison of the GISP2 $\delta^{18}O$ record (black curve; Stuiver and Grootes, 2000) with the $\Delta\delta^{18}O_{sw}$ MD02-2529 (NEP, green curve), the $\Delta\delta^{18}O_{sw}$ MD98-2181 (NWP, red curve) and the Lynch's crater peat (SWP, blue curve). All data are presented on their published original timescale. The gray bars localize the DO interstadials of the GISP2 ice core that are labeled at the top of the figure, and their corresponding millennial-scale rainfall changes across the tropical Pacific. The triangles indicate the age control points.

GISP2 record does not significantly alter the age model (Fig. 6). For all these records, the correspondence between the millennial-scale precipitation shifts and the GISP2 H-DO variability has previously been acknowledged, making our mechanistic interpretation realistic with respect to the timing of rapid precipitation changes (Stott et al., 2002; Turney et al., 2004; Leduc et al., 2007).

Both NEP and NWP $\Delta\delta^{18}O_{sw}$ records exhibit millennial-scale variations, with $\Delta\delta^{18}O_{sw}$ minima (high precipitation rates) occurring at times of DO interstadials in the GISP2 $\delta^{18}O$ record, and vice-versa during DO stadials and H events (Fig. 5). It indicates that both the western and eastern sides of the northern tropical Pacific area simultaneously experienced wetter conditions during DO interstadials and drier periods at times of H events (see core locations in Fig. 1 for similar observations in the tropical Pacific). These in-phase responses on both sides of the northern tropical Pacific suggest that changes in the ITCZ dynamics may be a valid analog for explaining the $\Delta\delta^{18}O_{sw}$ record of both marine sediment cores.

At Lynch's crater, wet periods inferred from peat deposits are recorded at times of DO stadials and during H events, while periods of aridity occurred during DO interstadials (Fig. 5). This precipitation response to H-DO variability has been re-assessed by the identification of sedimentary layers containing high amounts of biogenic silica at times of H events, confirming increased rainfall at these times (Muller et al., 2008), as well as by new speleothems results from southern Indonesia (Griffiths et al., 2007; Bretherton et al., 2008). This result indicates that the millennial-scale precipitation changes in the SWP region responded in a reversed manner of what is observed in the marine records localized in the NWP and NEP. Hence, the north/south precipitation antiphase illustrated in Fig. 5 does not support that past zonal rainfall anomalies such as the modern ENSO variability was responsible for the observed precipitation changes in the tropical Pacific, as recently suggested by results from Brazilian speleothems (Wang et al., 2007b).

Although the overall timing of millennial-scale changes in precipitation is consistent for most of the DO interstadials, some mismatch between the tropical sedimentary records and the GISP2 are observed between 40 and 45 ka in Lynch's crater and during the Younger Dryas (YD) in the NWP record (Fig. 5). It is plausible that some incorporation of young carbon in the oldest part of Lynch's crater record have biased the radiocarbon dating (Muller et al., 2008). This explanation is coherent with the positive age offset required to match Lynch's crater data to the GISP2 ice core (Fig. 6). Even though numerous marine records in the NWP and adjacent seas were clearly marked by salinity increases during the YD (see additional core locations in Fig. 1) (Rosenthal et al., 2003), recent results from Borneo speleothems show no clear evidence for any YD event but were rather marked at ~13.2 ka by a slight interruption of the monotonous deglacial trend (Partin et al., 2007). This latter result suggests that other climatic mechanisms and feedbacks may have operated during the course of the deglaciation in the western tropical Pacific.

Global ITCZ patterns at the millennial timescale: model–data comparison

It is now largely accepted that wet periods occurred broadly during interstadials in the Northern tropical band, even if recent NEP results coupled to a regionally resolved ocean–atmosphere model suggested that this global view may be oversimplified (Pahnke et al., 2007). Despite the scarcity of paleoclimatic evidences in the Southern Hemisphere, the available records support that during DO stadials and H events the mean ITCZ position have shifted southward (Turney et al., 2004; Wang et al., 2004; Garcin et al., 2006; Wang et al., 2007b; Muller et al., 2008), suggesting that ITCZ latitudinal movements at the millennial timescale is a general feature in the tropical belt (Wang et al., 2007a).

Simulations of H events generally lead to an abrupt cooling in the North Atlantic region in response to the weakening of the North Atlantic Deep Water (NADW) formation, and hence to an increased equator-to-pole temperature gradient in the North Atlantic. As described by Dahl et al. (2005), this increased temperature gradient requires strengthened poleward heat transport by atmospheric circulation, leading to a subsequent southward ITCZ shift in the Atlantic sector and a strengthening of cross-equatorial heat transport. This latitudinal teleconnection contributing to redistribute heat seems to be a robust, global climate feature of modeling experiments since (i) it is observed in numerous Earth Models of Intermediate Complexity and Atmosphere-Ocean General Circulation Models (AOGCM) (Stouffer et al., 2006), (ii) the ITCZ southward shift is observed in the entire Atlantic and Indo-Pacific areas, in parallel with a SST asymmetry between both hemispheres (Knutti et al., 2004; Zhang and Delworth,

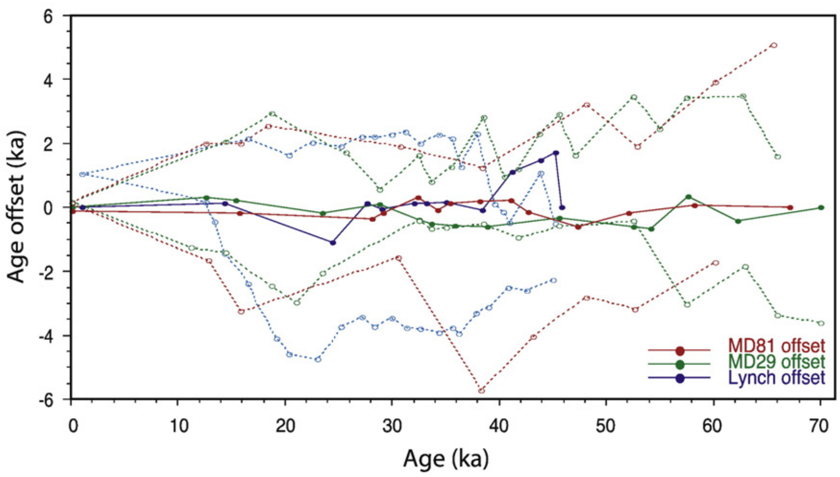

Figure 6. Age offset after tuning of the millennial-scale tropical paleoclimatic sequences (as shown in Fig. 5) to the GISP2 $\delta^{18}O$ record obtained by aligning millennial-scale rainfall changes to their corresponding D-O events in the GISP2 record (solid lines). Note that the age offsets are lower than the age error associated with the initial chronologies. Also are shown in dashed line the resulting age offsets of alternative hypothetical scenarios in which the precipitation changes in the sedimentary records may have responded in a reversed manner, i.e. if Lynch's crater would have been dry and if the MD cores would have experienced wetter periods during Heinrich events. These alternative scenarios were computed through fine-tuning between the sedimentary records and the GISP2 record by assigning any event whenever possible to its corresponding preceding and succeeding event, in a way that the interpretation of millennial-scale rainfall changes will be reversed. Since the age offsets of these scenarios are higher than the offsets corresponding to the original interpretation of these sedimentary records we refute the possibility that the rainfall changes at the millennial timescale may have responded in a reversed manner than what has already been interpreted in the original publications.

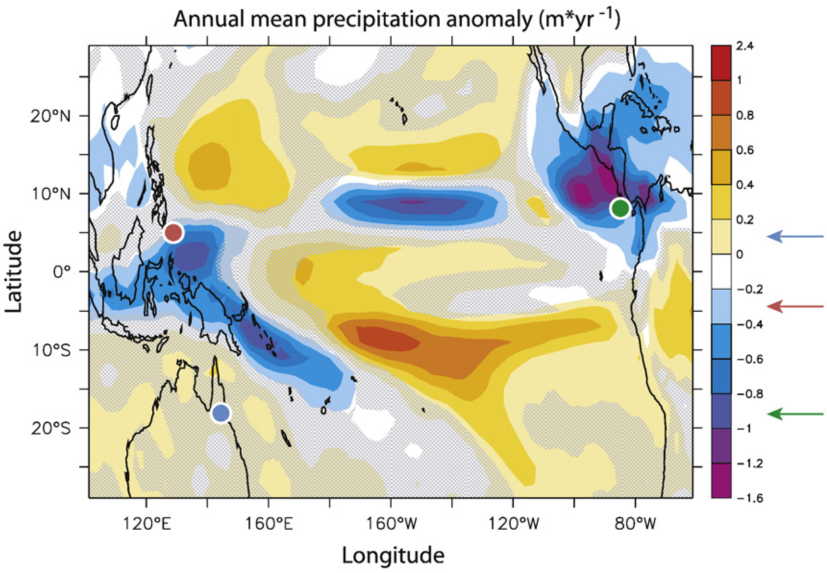

Figure 7. Tropical Pacific mean annual precipitation anomalies in a coupled AOGCM experiment (GFDL's CM2.0 model), induced by a weakening of NADW (Zhang and Delworth, 2005). The locations of sedimentary sequences highlighted in Fig. 5 are indicated as in Fig. 1. Colored arrows indicate precipitation anomalies for the NWP (red arrow), the SWP (blue arrow) and the NEP (green arrow) sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2005; Timmermann et al., 2005), and (iii) the ITCZ southward shift has been reproduced by applying an asymmetric mid-latitude temperature contrast, suggesting a potential impact of the “bipolar seesaw” on low latitudes hydrological cycle (Dahl et al., 2005). These modeling experiments suggest that the thermohaline circulation has the potential to control the low-latitudes hydrological cycle through an oceanic connection, in which SST latitudinal gradients play a crucial role.

In Fig. 7 we present precipitation anomalies induced by a NADW weakening in a coupled AOGCM (Zhang and Delworth, 2005). In this modeling experiment output, both NEP and NWP are marked by drier conditions while wetter conditions are recorded in SWP (Fig. 3), a result in full agreement with the mechanism proposed in this study and, as discussed by the authors, that is unlikely to be driven by El Niño events (Zhang and Delworth, 2005). Such a tropical rainfall response to a weakening of the NADW has recently been confirmed by coupled AOGCM modeling experiments with glacial boundary conditions (Menviel et al., 2008).

The low-latitude atmospheric variability may also play some active role in the NADW formation process by modulating the Atlantic salt budget via the atmospheric vapor transport between the Atlantic and the Pacific oceans (Peterson et al., 2000; Benway et al., 2006; Leduc et al., 2007). The comparison between Greenland $\delta^{18}O$ and deuterium excess records reveals a clear antiphasing between Greenland temperatures and Greenland moisture source temperature, indicating that the geographical location of the Greenland moisture source was shifted northward during DO interstadials and vice-versa during DO stadials and H events (Masson-Delmotte et al., 2005). These local vs. remote temperature antiphases imprinted in Greenland ice stable isotopes demonstrate that the atmospheric dynamics is an essential link between the tropical water cycle to the high latitudes climate changes at the H-DO timescale (Masson-Delmotte et al., 2005). Major changes in the ITCZ seasonal cycle may then support the idea that the tropics could have actively participated to the millennial-scale climate variability during the MIS3, as recently highlighted by high-resolution NGRIP multi-proxy results (Steffensen et al., 2008).

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