SST gradient may not be as tightly tied to ENSO variability in the last millennium as it seems to have been during the Holocene (e.g., Koutavas et al., 2006). Alternatively, the limitations of available ENSO proxies may be hindering our understanding of how interannual variability is related to the mean state of the tropical Pacific.

Observations and model simulations indicate that a strong zonal SST gradient in the tropical Pacific favors persistent drought in western North America (e.g., Seager et al., 2007). A comparison of the western North American drought area index (Cook et al., 2004) and the zonal SST gradient indicates that the most widespread droughts of the last 1.2 ka occurred from 1000-1300 AD, when the zonal SST gradient was strongest. However, other climate modes, such as North Atlantic SST variability, also impact western North American hydroclimate, making it difficult to attribute all low frequency droughts in this region to tropical Pacific SST variability (Conroy et al., 2009b).

Directions for future tropical Pacific research

Understanding the history of tropical Pacific SST and ENSO variability requires a high resolution, multi-site, multi-proxy approach. More annually resolved ENSO reconstructions would be particularly useful, as lower frequency ENSO reconstructions will never be able to separate changes in event frequency, intensity, and duration from longer-term variability. Also, annual records from within the tropical Pacific domain of ENSO are more tightly linked to the physical phenomena of ENSO, and more desirable than reconstructions from outside this domain. A potentially powerful solution to the limitations of existing ENSO proxies is to combine high-resolution SST reconstructions from windows of fossil corals with the continuous records of tropical Pacific lake and marine sediment records. Additional continuous, calibrated, high-resolution SST records from the tropical Pacific will also improve estimates of the zonal SST gradient.

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Modes of eastern equatorial Pacific thermocline variability: Implications for ENSO variability over the last glacial period

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Repeated isotopic analyses of single specimen of the thermocline-dwelling planktonic foraminifer *Neogloboquadrina dutertrei* provide snapshots of past changes in the amplitude and frequency of El Niño and La Niña.

One of the most difficult tasks when reconstructing past El Niño-Southern Oscillation (ENSO) activity is to extract a pure ENSO record by avoiding non-ENSO climate signals embedded in climate archives. Among the non-ENSO climatic signals to be avoided, seasons are probably the most important parameter to be considered because their imprint in climate archives overwhelmingly conceal any interannual mode of climatic variability.

To date, few paleoceanographic archives, such as tropical Pacific corals (Cobb et al., 2003) or eastern tropical Pacific laminated sediments (Grelaud et al., 2009), provide the sub-annual time resolution required to separate the ocean variability due to ENSO from that linked to seasonality. Further, these archives are either restricted in time coverage (e.g., decades or centuries for corals, Cobb et al., 2003), or sample warm periods exclusively (Grelaud et al., 2009). From this perspective, further efforts to reconstruct ENSO from marine sediment cores collected in areas strongly impacted by ENSO variability (both the amplitude and frequency of El Niño warm events and La Niña cold events) and with comparatively minor seasonality changes are required.

These conditions are found within the thermocline of the permanently stratified eastern equatorial Pacific warm pool. In this region, the large temperature anomalies associated with interannual thermocline tilt occurring zonally across the Pacific are barely influenced by seasonal changes. Hence any foraminifers living

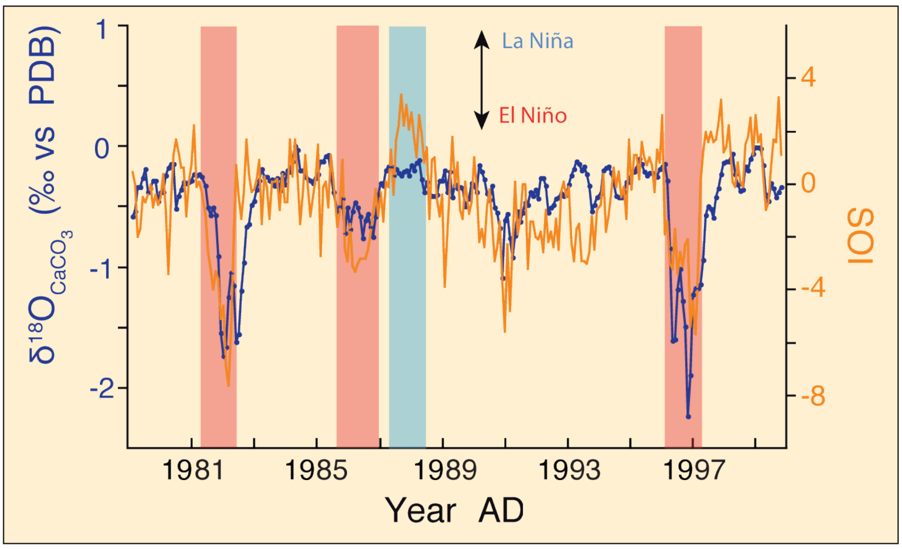

Figure 1: Expected $\delta^{18}O_{CaCO_3}$ (of N. dutertrei*) at equilibrium calculated using temperature and salinity data at 50 m water depth at the core location (**blue curve**) compared to the Southern Oscillation Index (SOI; **orange curve**; Australian Bureau of Meteorology) for 1980-2000 AD. Figure modified from Leduc et al., 2009a.*

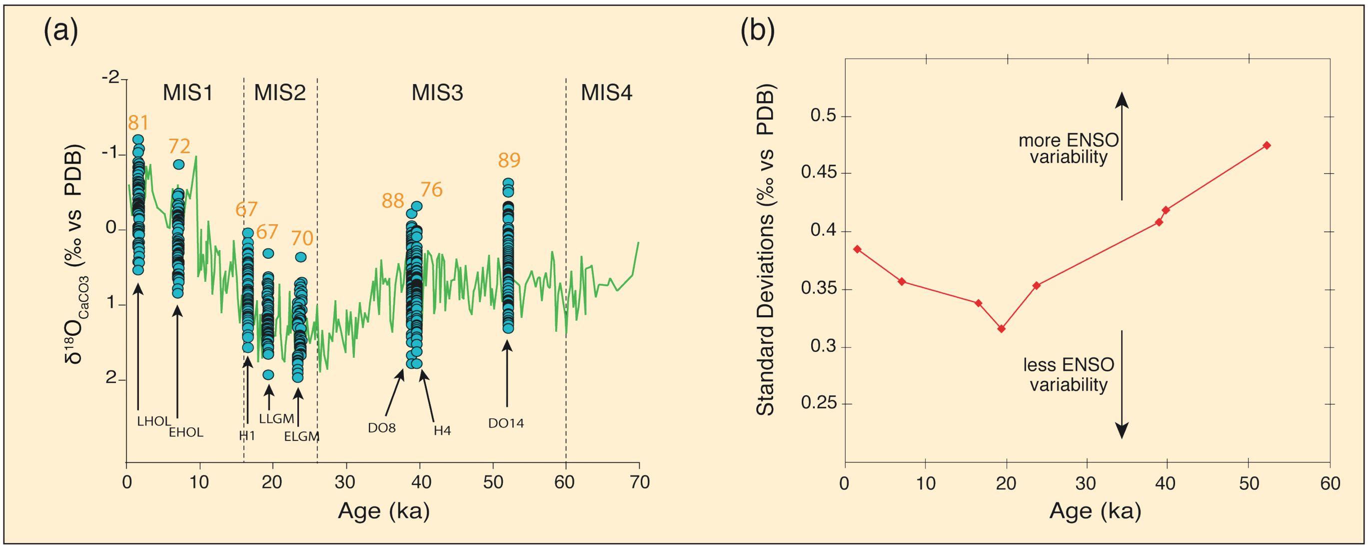

*Figure 2: **a**) Multiple-specimen (green curve) and individual specimen (blue circles) $\delta^{18}O_{CaCO3}$ measurements performed on* N. dutertrei *planktonic foraminifera. Orange numbers indicate the number of individual foraminifer tests measured from each interval. Marine Isotopic Stages (MIS) are labeled. LHOL = Late Holocene, EHOL = Early Holocene, H1 and H4 = Heinrich events 1 and 4, LLGM = Late Last Glacial Maximum, ELGM = Early Last Glacial Maximum, DO8 and DO14 = Dansgaard-Oeschger interstadials 8 and 14. **b**) Standard deviations of the individual $\delta^{18}O$ measurements for each time slice, interpreted as thermocline variability induced by ENSO activity. Figures modified from Leduc et al., 2009a.*

within the thermocline may record changes in ENSO activity, with the added benefit that the seasonality effect is expected to be of second order (Fig. 1).

Approach

We studied a marine sediment core with a well-constrained stratigraphy and containing abundant tests of the thermocline-dwelling planktonic foraminifer *N. dutertrei* (Leduc et al., 2009a). We performed repeated $\delta^{18}O$ measurements on up to 90 individual foraminifer tests for eight intervals in the sediment core. Each interval integrates approximately 100 years. Ideally, measuring a large number of individual tests at selected core depths provides snapshots of the full hydrographic variability during narrow time windows (see also Koutavas et al., 2006 for a similar approach). The $\delta^{18}O$ of foraminifers records a mixed signal of temperature and $\delta^{18}O$ of seawater (a proxy for salinity), therefore the *N. dutertrei* individual measurements provide insight on subsurface water hydrological variability over the studied time intervals. At the core location, ENSO variability has a profound impact on subsurface temperature, with an additional influence on salinity, making the $\delta^{18}O$ of foraminifers particularly sensitive to ENSO (Fig. 1, Leduc et al. 2009a). Since the subsurface hydrology at the coring site is little affected by seasonal variability, we interpret the scattering of intra-sample *N. dutertrei* $\delta^{18}O$ measurements as a signal for past changes in amplitude and frequency of ENSO activity. Some secondary overprint of other factors linked to the foraminifer living-depth or to past changes in the thermocline seasonality cannot be ruled out. However the modern oceanography at the studied core site strongly suggests that the first order mode of hydrological variability captured by this method is induced by ENSO activity (Leduc et al., 2009a).

The time slices we have investigated are the late and mid Holocene, Heinrich event 1 (which occurred during the last deglaciation), early and late periods of the Last Glacial Maximum (LGM), and three time slices specifically targeting the cold Heinrich events and warm Dansgaard-Oeschger interstadials that punctuated the last glacial period. This range of samples encompasses most of the modes of climatic variability that affected the last 50 ka, such as glacial-interglacial, Milankovitch (precession) and rapid (millennial) climate changes that shaped most of the paleo-records covering this period.

Results of individual *N. dutertrei* $\delta^{18}O$ measurements

The $\delta^{18}O$ variability for all time slices ranges from ~1.5 to 2.1 ‰, corresponding to ~8 to >10°C (Fig. 2a), i.e., comparable to what is found between El Niño and La Niña years nowadays at coring site (Fig. 1). Overall, the $\delta^{18}O$ distributions did not dramatically change among the time intervals we studied. This indicates that ENSO persisted throughout the time interval studied and that the past modes of ENSO activity under radically different climatic backgrounds are unlikely to have been much different from today.

To better quantify the scattering of individual $\delta^{18}O$ measurements, we calculated the standard deviation of isotopic data for each time slice as a measure of ENSO activity. The standard deviation data suggest that smooth, long-term ENSO changes occurred over the last 50 ka. Over this time period, ENSO activity decreased steadily during the last glacial period, reaching a minimum of variability during the Last Glacial Maximum (LGM). The ENSO variability then increased again from the LGM to the present (Fig. 2b).

Some features of this reconstruction of past ENSO are particularly interesting. First, these results provide the first indications of reduced ENSO activity during the LGM, which is particularly important in providing useful targets for model intercomparison exercises. Further, the smooth changes in ENSO during the last glacial period, which encompasses periods of contrasting climatic backgrounds—such as Heinrich events and Dansgaard-Oeschger interstadials—confirm recent hypotheses proposing that millennial-scale changes in the tropical Pacific hydrological cycle were decoupled from ENSO variability (Leduc et al., 2009b). Finally, the highest ENSO variability is found during the Marine Isotope Stage 3, at a time when the background climate was neither fully glacial nor fully interglacial. This suggests that the main driver of ENSO is decoupled from global climatic conditions.

New perspectives from intra-sample isotopic variability

The efforts we made to minimize non-ENSO hydrological signals contained in marine sediment cores also provided new and unexpected results that contrast with what is widely acknowledged in the literature. For example, the gentle ENSO activity increase recorded between the mid- and late-Holocene is not statistically significant, which contrasts with a series of other paleo-ENSO reconstructions suggesting a prominently increased ENSO activity during the Holocene period (see Koutavas et al., 2006, and references therein). This result can potentially be due to the low resolution in our record. On the other hand, this result also raises the question whether Holocene climatic signals from archives in ENSO-sensitive regions contain non-ENSO signals, such as seasonally-induced Inter-Tropical Convergence Zone migrations.

Most reconstructions of past changes in climatological parameters linked to ENSO activity do not account for the potential impact of past seasonality. Yet seasons can have a considerable impact on the geological record of past climate (Leduc et al., 2010; Laepple and Lohmann, 2009). We emphasize that a careful examination of records of past hydrological changes from oceanic regions without seasonal cycles, together with sampling strategies collecting the full spectrum of hydrological variability within the time intervals studied, would help to clarify which climatic phenomenon modulates the first-order climatic signal archived in geological records.

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Data

The data are available on the World Data Center on the NOAA website at ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/leduc2009/leduc2009.txt

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Southern Hemisphere intermediate water formation and the bi-polar seesaw

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Periodic intensifications of Antarctic Intermediate Water flow occurred as part of the millennial-scale climate oscillations in the glacial period.

During the last glacial period, a profound millennial-scale climate variation prevailed. First discovered in Greenland ice cores, it has subsequently been documented around the globe, yet the underlying mechanisms controlling this variability have not been indentified. Adding to the complexity of this rapid climate change is an interhemispheric asynchronicity, known as the bipolar seesaw. A significant clue towards unraveling the controls of millennial-scale variability came from the deep ocean off Portugal (Shackleton et al., 2000). Here, stable oxygen isotope variability in surface dwelling planktic foraminifera shows clear ties to Greenland climate variability, whereas the respective record based on benthic foraminifers living on the seafloor relates to Antarctic climate variation, reflecting the southern origin of the Antarctic Bottom Water that prevails in the abyssal Atlantic off Portugal.

One likely mechanism for the climatic asynchronicity involves an interhemispheric imbalance in heat storage (Stocker and Johnsen, 2003). Surface ocean records from the South Atlantic Ocean (Barker et al., 2009) indeed show a climate change pattern opposed to that in Greenland ice cores supporting the view that asynchronous heat storage is instrumental in off-setting Northern and Southern Hemisphere climate change at the millennial-scale.

The role of southern-source intermediate water (Antarctic Intermediate Water, AAIW) in the bipolar seesaw is of global relevance due to its large volume and associated energy storage capacity. However, data-based evidence is rare. Benthic stable isotope data from the intermediate depth SW Pacific (Pahnke and Zahn, 2005) show periods of intensified glacial AAIW formation during the cold Heinrich Events in the North Atlantic. During Heinrich Events, the large continental ice masses surrounding the North Atlantic released "flotillas" of icebergs into the ocean. The melting of these icebergs disrupted the formation of North Atlantic Deep Water (NADW) and hence slowed down the overturning circulation in the Atlantic. Thus the data from the SW Pacific suggest that glacial AAIW formation was intensified in the SW Pacific during a time when the overturning circulation in the North Atlantic was strongly

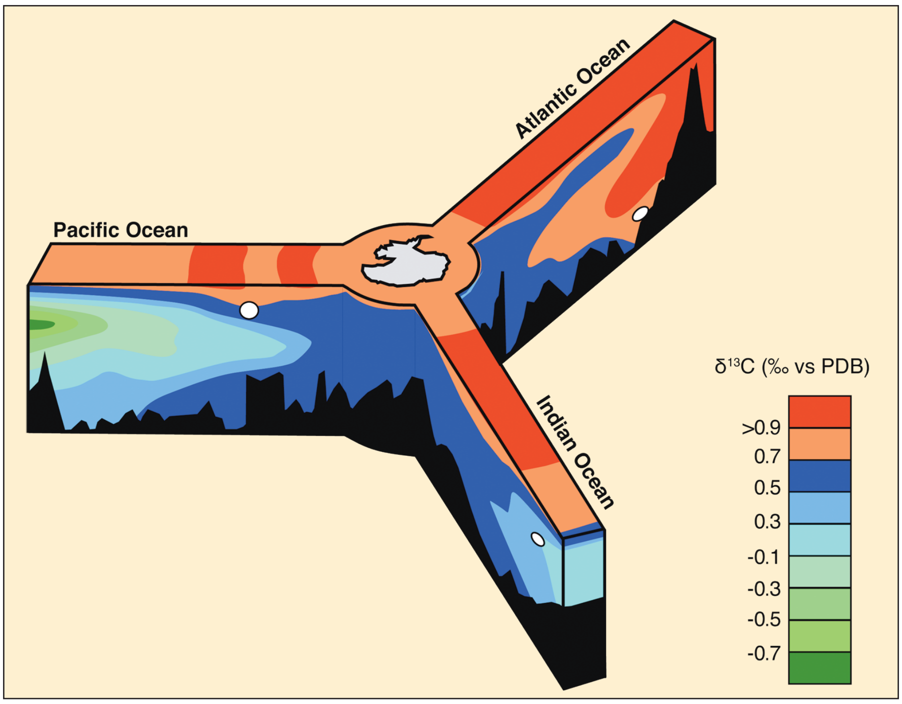

Figure 1: Distribution of $\delta^{13}C$ in the modern ocean (redrawn from Charles and Fairbanks, 1992). ***White circles*** *indicate the location of sediment cores NIOP 905 (Indian Ocean; Jung et al., 2009), MD95-2042 (Atlantic Ocean; Shackleton et al., 2000) and MD97-2120 (Pacific Ocean; Pahnke and Zahn, 2005).*

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