Holocene trends in tropical Pacific sea surface temperatures and the El Niño-Southern Oscillation

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Introduction

The El Niño-Southern Oscillation (ENSO) dominates modern climate variability and considerable effort has been invested in reconstructing its history. Much of this effort has focused on the Holocene for two important reasons: (1) Holocene boundary conditions have been similar to present-day (the orbital configuration being an important exception) providing a useful analog for long-term ENSO dynamics in an interglacial climate; and (2) a growing number of studies indicate significant Holocene ENSO changes, including a marked decline in activity in the early-middle Holocene (e.g. Moy et al., 2002). If correct, the latter implies that strong ENSO reorganizations can arise from gradual shifts in background climate conditions, which has important implications for the future. However, a number of challenges continue to hinder adequate understanding of the Holocene evolution of ENSO, including: (1) lack of optimally located continuous ENSO archives with annual or sub-annual resolution; (2) lack of a rigorous theoretical underpinning of how ENSO depends on the background (i.e. time-averaged) climate state; and (3) slow progress toward realistic modeling of tropical ocean-atmosphere dynamics, particularly as it applies to the equatorial annual cycle. As a consequence, our understanding of Holocene ENSO variability lags behind that of other tropical climate systems such as the monsoons and the Intertropical Convergence Zone (ITCZ).

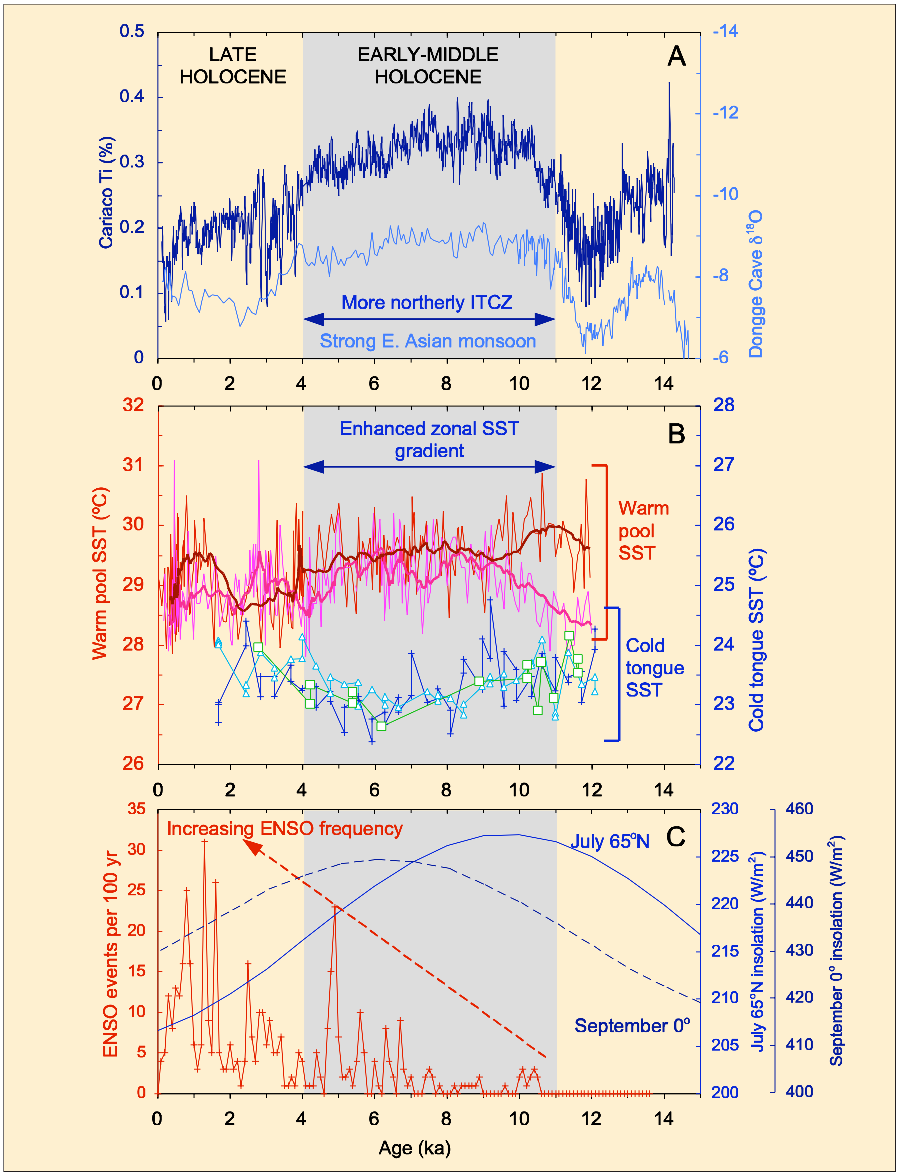

*Figure 1: Holocene climate trends in regions dominated by monsoon, ITCZ and ENSO dynamics: (**A**) Titanium concentrations (%) in ODP site 1002C from the Cariaco Basin (dark blue) (Haug et al., 2001); $\delta^{18}O$ of the D4 stalagmite from Dongge Cave, China (light blue) (Yuan et al., 2004). (**B**) Mg/Ca SSTs from the western Pacific warm pool (MD98-2181, red; MD98-2176, pink) (Stott et al., 2004) and eastern Pacific cold tongue (V21-30, blue; V19-28, green) (Koutavas et al., 2006). (**C**) Holocene ENSO frequency from Laguna Pallcacocha sediment color changes (Moy et al., 2002).*

The role of orbital variations

Monsoon- and ITCZ-related climate anomalies are currently understood as responses to varying northern summer insolation. The July maximum ~10 ky ago is widely thought to have strengthened monsoon activity and accentuated the northerly bias of the ITCZ. It is worth noting that late summer (e.g. September) insolation peaked as late as 6 ky ago (Fig. 1) and in many locations this may have pushed the timing of the climate response well into the mid-Holocene. Accordingly, sites affected by the monsoons typically reflect positive precipitation anomalies spanning much of the early and middle Holocene. Notable examples include speleothems from southeast China (Yuan et al., 2004) (Fig. 1A) and Oman (Fleitmann et al., 2003), and marine records from the Bay of Bengal (Kudrass et al., 2001), the Arabian Sea (Gupta et al., 2003) and the west coast of North Africa (deMenocal et al., 2000). Similarly, locations sensitive to the migration of the ITCZ, such as the Cariaco Basin in the western Atlantic, show evidence for a more northerly mean ITCZ position (Haug et al., 2001) (Fig. 1A).

The potential of orbital forcing to affect ENSO has been demonstrated in climate models (Clement et al., 1999) and is believed to act through its influence on the large annual cycle of sea surface temperature (SST), convection and cloud cover in the eastern tropical Pacific. The interaction between ENSO and the annual cycle has long been regarded as a key element of the low-frequency ENSO modulation (e.g. Tziperman et al., 1994; Chang et al., 1995), giving rise to well-founded expectation that orbital effects, either local or remote, exert a major influence. Unfortunately, realistic simulation of the equatorial annual cycle remains a challenge for current-generation climate models and this limits their usefulness for elucidating the ENSO response to orbital variations. This limitation renders more acute the need for extensive paleo-ENSO reconstructions as a means of advancing our understanding.

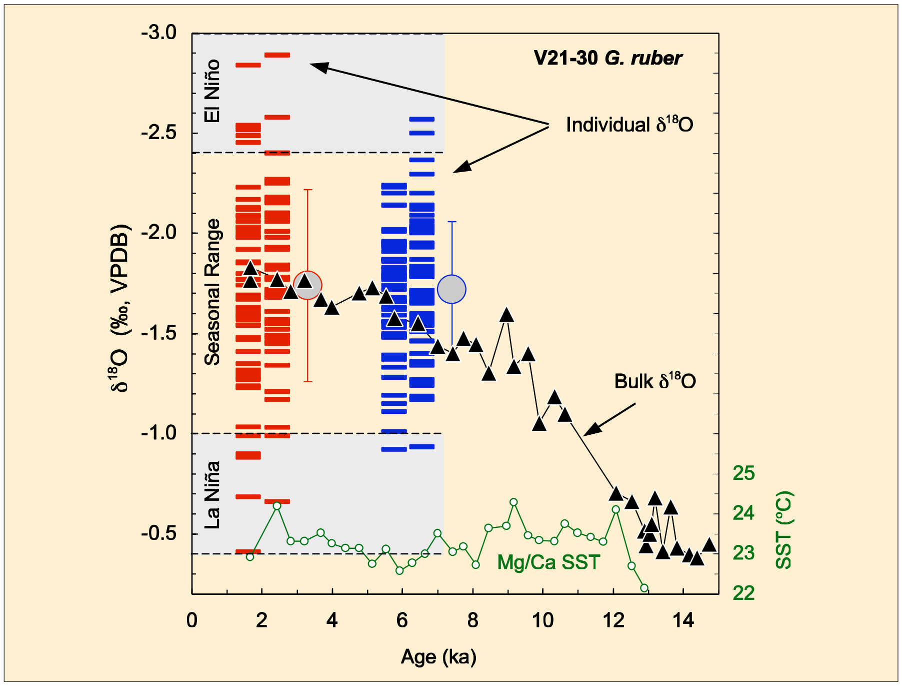

Figure 2: $\delta^{18}O$ of individual G. ruber from two late Holocene (red bars) and two mid-Holocene (blue bars) samples from core V21-30 (Koutavas et al., 2006). Downcore $\delta^{18}O$ data on bulk G. ruber (black triangles) and Mg/Ca SST estimates (green circles). Filled circles with error bars are the mean and standard deviation of the pooled late Holocene (n=93) and mid-Holocene (n=96) individual analyses. The standard deviation of the mid-Holocene data (σ=0.34) is 30% less than the late Holocene (σ=0.48), and the total variance (σ^2) is 50% less, consistent with weaker ENSO.

Tropical Pacific SSTs

We constrained long-term Holocene SST progression in the tropical Pacific using Mg/Ca thermometry in two sites from the eastern Pacific and comparing the results with records from the west. Cores V21-30 and V19-28 from the equatorial cold tongue revealed consistent SST histories, marked by a broad minimum between 5-9 ky BP (Fig. 1B) (Koutavas et al., 2006). This contrasts with reconstructions from the western Pacific indicating the opposite; warmest conditions prevailed prior to 5 ky BP (Stott et al., 2004). Due to the inverse east-west climate trends, the zonal SST gradient along the equator was 20-30% higher in the early-middle Holocene, a pattern reminiscent of the cold ENSO phase, i.e. La Niña.

It is noteworthy that this anomalous SST configuration coincided with the hemispheric-scale strengthening of the northern monsoons and northward–displaced ITCZ (Fig. 1A). This suggests a common (orbital) origin of the combined monsoon-ITCZ-Pacific SST evolution. But it also hints that coupled interactions among these systems were equally important in accomplishing the observed anomalies. A good example involves the interaction of the ITCZ with equatorial SST and by extension with ENSO. A northward-displaced ITCZ favors strong cross-equatorial winds, which induce upwelling, cool the SST and help maintain the ITCZ displaced north. Given this, one scenario for the anomalous early-middle Holocene climate may involve an initial northerly "nudge" of the ITCZ in response to insolation, which in turn triggers an equatorial ocean response (i.e. cool upwelling) that acts as a positive feedback. An alternative scenario may be that the surface ocean feels the orbital influence first, responding with an amplified Bjerknes feedback, as predicted by the ocean dynamical thermostat of Clement et al. (1996). The resulting cooling in the eastern Pacific serves to keep the ITCZ off the equator.

Holocene ENSO

How does the Holocene history of ENSO fit with these general climate trends? Despite gaps in observations, converging evidence points to weaker El Niño activity in the early-middle Holocene. However, important questions persist:

(a) Was the decline in El Niño accompanied by a de- or increase in La Niña activity?
(b) Was the difference in mean climate conditions a cause or consequence of the altered ENSO?
(c) Was the ENSO dampening associated with a weaker or stronger seasonal cycle?
(d) Was the change triggered by local (equatorial) or remote (extratropical) orbital mechanisms?

To help address these questions and further refine our view of ENSO variability we developed a new approach based on $\delta^{18}O$ distributions of individual G. ruber foraminifera with a life span of approx. 1 month (Fig. 2). Thus far, results from core V21-30 near the Galapagos Islands corroborate a mid-Holocene reduction in $\delta^{18}O$ variance, apparently due to both fewer El Niño and La Niña events. This suggests that the Mg/Ca SST trends do not merely reflect the integrated influence of weaker ENSO on the mean climate. Rather, it seems more likely that ENSO itself adjusted to the background climate shift and, in this regard, the ITCZ may again have been instrumental. Two scenarios seem plausible: (1) the northward-shifted summer ITCZ lengthened the upwelling season (presently August-September) and in so doing inhibited the growth of El Niño, which typically occurs between September and November; or (2) an expanded seasonal ITCZ range (more northerly summertime position) reinforced the annual cycle, causing it to act as a pacemaker-regulator of SST, inhibiting interannual anomalies. Whichever the case, the interaction of the seasonal and interannual modes is a crucially important factor for the long-term ENSO modulation. Annually resolved corals (e.g. Tudhope et al., 2000) remain our best hope for investigating this relationship and their potential should be aggressively pursued. But the ubiquitous availability of foraminifera in continuous deep-sea sediments may be a tantalizing alternative until sufficient coral records become available, and this approach also ought to be exploited more rigorously.

Although still blurry, the picture is gaining clarity and it now seems undeniable that a strong relationship between ITCZ position, equatorial SSTs, and ENSO operated throughout the Holocene. While it is likely that this dynamic system will be sensitive to future perturbations from greenhouse forcing, it is somewhat disconcerting that our understanding of its past behavior is still so rudimentary that any prediction for the future is fraught with uncertainty.

Note

Data will data will be available from the NOAA Paleoclimatology website at http://www.ncdc.noaa.gov/paleo/paleo.html

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