El Niño–Southern Oscillation: Absent in the Early Holocene?

Xavier Rodó

Climate Research Group, CMC, PCB, University of Barcelona, Barcelona, Catalonia, Spain, and Center for Ocean–Land–Atmosphere Studies, IGES, Calverton, Maryland

Miquel-Angel Rodriguez-Arias

Climate Research Group, CMC, PCB, University of Barcelona, Barcelona, Catalonia, Spain

16 June 2003 and 30 September 2003

ABSTRACT

High-resolution sedimentary proxies from low latitudes are rare but nevertheless important to understanding the role of tropical regions in the global climate. The reanalysis of a sedimentary record from Lake Pallcacocha (Andes) shows that ENSO was present throughout the Holocene. Even from 10 000 to 7000 calendar years before present, when the Tropics underwent a period of low variance, there is still evidence of a weak ENSO. This weakening, however, has been strongly overestimated. A frequency decomposition shows that all frequency components, except the millennial band (which has a different origin), covary synchronically for more than 6000 yr. A need to reconcile methodologies and results from climate studies at different time scales thus arises.

1. Introduction

Continuous high-resolution millennial sedimentary proxies of tropical climate are invaluable but also extremely rare (Moy et al. 2002, hereafter MO02; Tudhope et al. 2001). This scarcity is further aggravated by global warming and the melting of the few remaining high-altitude glaciers in low latitudes, because such records are central to the validation of long-term predictions from general circulation models (GCMs). For instance, a suitable reconstruction of tropical climate is crucial to our understanding of the evolution of ENSO during the Holocene and the central role of low latitudes in the regulation of climate at the planetary scale (Kerr 2003). In this respect, the possible weakening or even absence of ENSO variability at certain times and the factors responsible, are still controversial (Fedorov and Philander 2000). Our understanding of how the earth responds to such situations is important to climate research, and so these records should be scrutinized with care.

A preliminary interpretation of an unprecedented high-resolution sediment record of 9 m from Lake Pallcacocha (Ecuadorian Andes) indicated a lack of moderate to strong ENSO events in the early Holocene [from 10 000 to 7000 calendar years before present (yr B.P.); see MO02]. Closer examination of this record, which is continuous for the past 12 000 yr, shows that some of these conclusions need to be revisited.

2. Data and analytical approach

During ENSO events, hundreds of light-colored, inorganic clastic laminae were probably deposited in Lake Pallcacocha sediments (Rodbell et al. 1999). A measure of reflectance obtained by digitally scanning the surface of the core sections (known as the intensity of red color, RCI), yields an analog of ENSO variability that can be traced throughout the Holocene. A detailed explanation of the methods used to obtain RCI time series, together with the age models applied, can be found in MO02.

Due to changes in the sedimentation rate occurring in the core, previous studies revealed a shift in ENSO-modern band (2–8 yr) toward lower-frequency signals (4–15 yr) for the early to mid-Holocene. During the interval from 10 000 to 7000 yr B.P. Lake Pallcacocha does not recover frequencies under 5 yr because the sedimentation rate was lower. In most of the more recent record, however, the spacing between samples is roughly 1 yr or less (mainly from 5000 to 4500 yr B.P., from 3500 to 2500 yr B.P., and from 2000 yr B.P. until present). On the basis of these findings, following MO02,

Corresponding author address: Dr. Xavier Rodó, Climate Research Group, Center of Meteorology and Climatology, BSP-University of Barcelona, C. Baldini I Reixach, 4-6, Torre D. Barcelona 08018, Spain.
E-mail: xrodo@pcb.ub.es

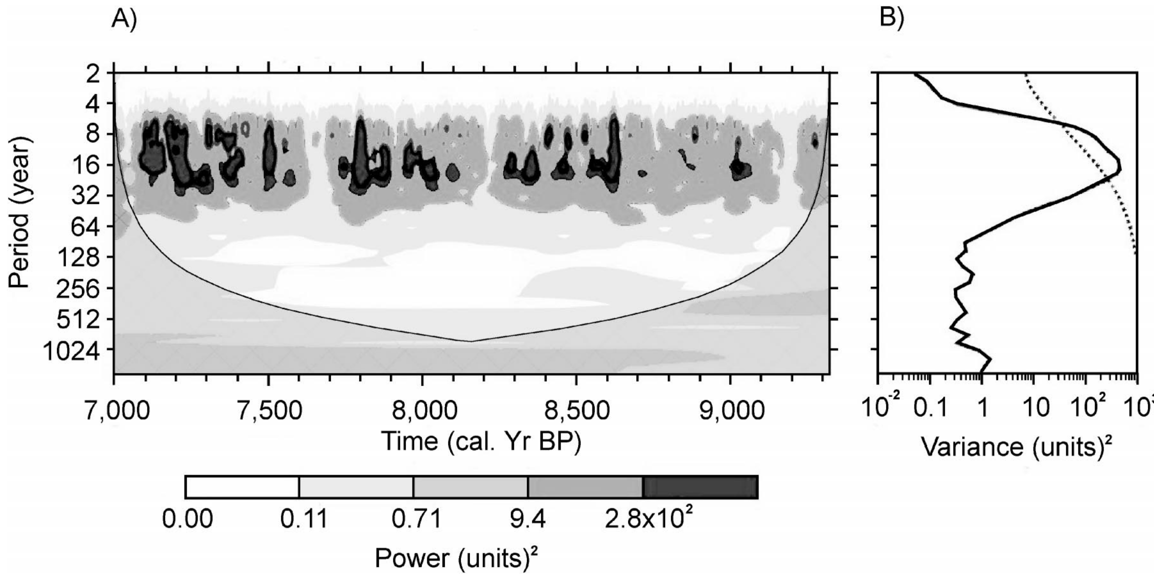

FIG. 1. (a) The wavelet power spectrum of the ENSO band-filtered time series (rc2–rc8 of the original series) of red color intensity in Lake Pallcacocha from 7000 through 9350 yr B.P. (The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively.) The shaded region is the cone of influence, where zero padding has reduced the variance. The black contour is the 1% significance level, with respect to a red-noise background spectrum. (b) The global wavelet power (GWP) spectrum (dark line). The dashed line is the 1% significance level for the GWP, assuming same conditions as in (a).

we took a conservative stance and similarly attributed all variance between 4 and 15 yr to El Niño variability.

To avoid the masking effects of high-variance signals, the various components must be separated appropriately. Here, the original data were subject to a singular spectrum analysis (SSA) decomposition (Yiou et al. 2000), prior to the recalculation of the wavelet in the absence of the millennial signal.

To test for the absence of modern ENSO periodicities in the early to mid-Holocene—stated by MO02 to be between 9500 and 7000 yr B.P.—we used the data between ~10 000 and 6300 yr B.P. (the effective interval for the analysis is 9350–7000 yr B.P., which is the portion lying within the cone of influence). This interval covers the period for which the millennial band is absent. SSA then allows us to obtain independent reconstructed components (rc), and, thus, focus on those exclusively containing periods between 4 and 15 yr. Indeed, known periodicities, like orbital forcing, often generate much of the variance at lower frequencies and alter the rest of the spectrum (Ghil et al. 2002). In such a situation, it might be highly desirable to discriminate between major contributing frequencies, rather than attempting to obtain a comprehensive picture from a single analysis. This is particularly true in this case, for this series is clearly nonstationary and, moreover, it cannot be well approximated by an autoregressive (AR) process.

Changes in the structure of variance for the last 11 000 yr were identified by wavelet decomposition (Torrence and Compo 1998), which enabled the separation of the original series into the different frequency components. Centered overlapping windows of a thousand points were used for the computation of variance in all cases. The first and last 500 points of the series were subsequently discarded from this representation.

3. Results

According to SSA decomposition, the first rc accounts for frequencies lower than 15 yr and concentrates ~60% of total variance ($p < 0.01$). Only variance from the ENSO band (4–15 yr) is isolated from rc2 to rc8, though the former component still captures some slightly longer-term variability. However, rc2 was kept for subsequent analyses, because its main contribution appeared in the range of 8–16 yr ($p < 0.01$). ENSO variance accounted for by rc2–rc8 ranges from 20% to 30% of the total. Figure 1 displays the wavelet power spectrum and the global wavelet for rc2–rc8 (Figs. 1a and 1b, respectively). The time interval shown is the same as that in which no ENSO signature was detected in a more rudimentary analysis (MO02). In the present analysis, however, the ENSO recent mode shows up clearly. This highlights the risk of misinterpretation of results, due to the presence of strong (high amplitude) components. These latter signals may dramatically override other weaker contributions, as is the case here, which remain embedded as a result. Figure 2 shows the changes in variance distribution in Lake Pallcacocha, separated along different frequency bands of interest [sub-ENSO, SE (1–4 yr); ENSO (4–20 yr); decadal, D (20–100 yr); centennial, C (100–1000 yr) and millennial, M (>1000 yr)]. To capture their lower-frequency evolution, over-

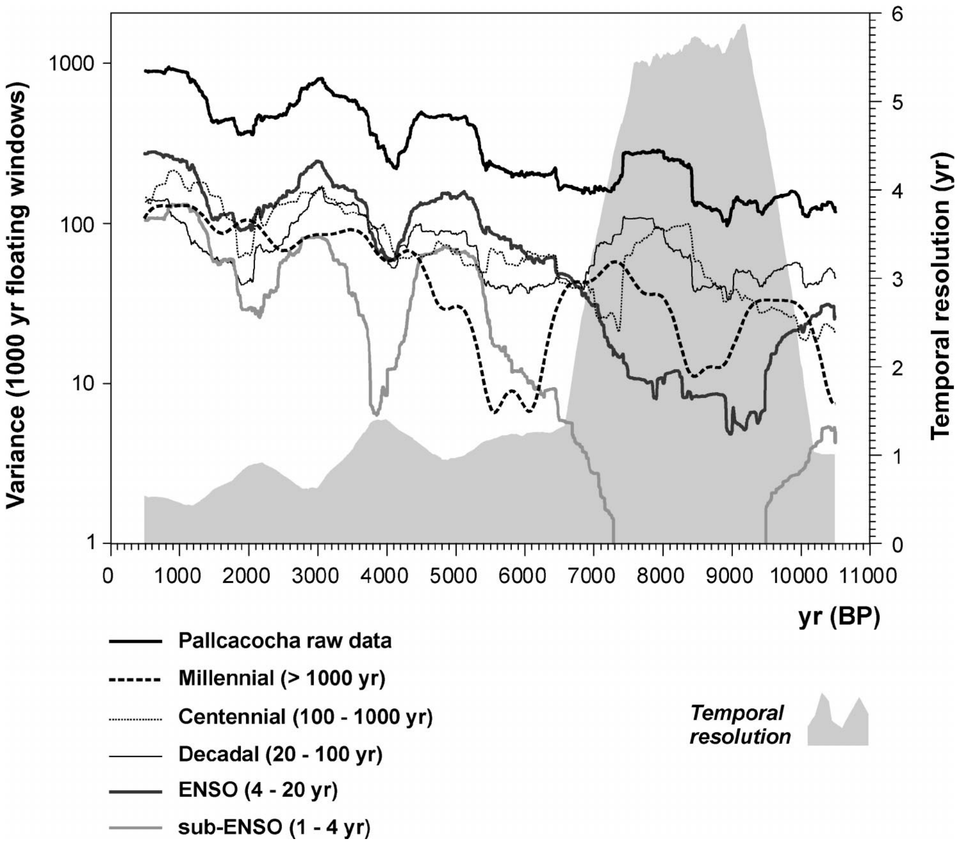

FIG. 2. Evolution of variance in millennial overlapping windows for Lake Pallcacocha raw data and its different frequency components, separated with a wavelet decomposition [viz., sub-ENSO (1–4 yr), ENSO (4–20 yr), decadal (20–100 yr), centennial (100–1000 yr), and millennial (>1000 yr)]. The variable temporal resolution is indicated by the gray area (for comparison with the frequency components, same overlapping windows were applied).

lapping windows of 1000 yr were calculated. The temporal resolution of the record is also shown (gray area) to facilitate comparison.

From the previous figure, it is clear that variance in the ENSO band shows similar evolution to other components (namely SE, D, and C bands). This covariation is clear for at least the interval from 6000 yr B.P. to present, and possibly also before 10 000 yr B.P. This common evolution also indicates a common origin in the tropical Pacific for the variation in these components, which all display fluctuations at millennial time scales (viz., in all SE, ENSO, D, and C bands). Conversely, the millennial band shows no coherent changes with the above-mentioned components, which points to a different, possibly wider-scale origin.

One consequence of the acute changes in the sedimentation rates in Lake Pallcacocha from 10 000 to 7000 yr B.P. is the drastic decrease in the temporal resolution of the record (from more than 1 to less than 5 yr). Consequently, both the variance of SE and ENSO bands appear strongly altered, and uncoupled from the D and C components. These latter two components still keep covarying coherently.

4. Discussion

Previous results from Lake Pallcacocha, possibly the best tropical record found for the Holocene in terms of resolution, seemed to indicate that ENSO variance first became significant around 7000 yr B.P. (Fig. 1 in MO02). This assumption, however, now appears invalid in the light of the current reanalysis. The main flaw was the failure to consider the masking effect of strong low-frequency signals accounting for most of the variance in the data series, prior to searching for ENSO. Our analysis removes the interference of the high-amplitude millennial component, and confirms the presence of a significant ENSO signal in this interval. Although both overall and ENSO variances appear to have increased from 10 000 to 7000 yr B.P., this increase—coherent and monotonic in all frequency components—indicates a general growing trend affecting the climate system as a whole.

With the exception of the millennial band, the rest of components (viz., SE, ENSO, D, and C) display clear covariations throughout the record back until 11 000 yr B.P. The only exception is for SE and ENSO in the interval 10 000–7000 yr B.P. This finding indicates a common basinwide origin linked to ENSO up to the centennial time scale. On the other hand, millennial variance is completely uncoupled from the rest of the components, apparently not associated with ENSO. At the beginning of this anomalous interval, near 10 000 yr B.P., the sedimentation rate in the lake decreased more than fivefold. Though the behavior of D, C, and the raw data shows no disturbances during this interval, there is a dramatic shift in both SE and ENSO components; SE disappears from the record and the ENSO band is severely affected, for about 3000 yr, More recently, about 7000–6500 yr B.P., SE and ENSO variances recover their normal values and again appear to covary with both the D and C signals. The latter are also main contributors to overall variance, which closely mimics their evolution. We hypothesize that during this interval of more than 3000 yr there is a change in the impact of ENSO on the Lake Pallcacocha basin. This shift in the main centers of action in ENSO might prevent the lake region from recording ENSO phenomenon throughout all its time scales. Only lower-frequency components, which are also associated with higher spatial coverage, and the more intense episodes, appear to leave an unaltered signature throughout the Holocene. These changes in ENSO have recurred (i.e., the Pacific regime shift in late 1970s), and do not necessarily imply either a relaxation or the absence of ENSO (Kumar et al. 1999). The fact that it is only within this interval that the variance in the higher-frequency components (SE and ENSO) uncouples from the rest and has no structure, seems rather to point to a change in the capacity of the lake to act as a sensor of this high-frequency behavior. This result would oppose the assertion of a general relaxation or even absence of ENSO during this interval. Indeed, it is hard to imagine a plausible explanation of how a dynamical alteration in ENSO affecting only higher-frequency components could take place, which does not affect the decadal and centennial variability in ENSO, for more than 3000 yr!

Additionally, the substantial reduction in total variance associated with this interval (10 000–7000 yr B.P.), together with a similar decrease in both ENSO and the rest of components, indicates a general long-term linear trend in all main components of the climate system. This is clearly seen in Fig. 2.

5. Conclusions

The sedimentary record of Lake Pallcacocha is an extremely important proxy to reconstruct ENSO and the tropical climate at high resolution throughout the Holocene. However, our new analysis shows now some discrepancies in crucial points with respect to that postulated from first interpretations. The following statements can be derived from this climatic inference.

1) A significant ENSO band can be isolated throughout the Holocene, including the interval 10 000–7000 yr B.P., where it was previously said to be absent.
2) The reason for this alleged ‘‘absence’’ lies in a severe masking effect arising from a clear near-millennial band. In addition, after examining the behavior of variance during the last 11 000 yr, the millennial component does not appear to be ENSO related. This strongly opposes to the pattern of the sub-ENSO, decadal, and centennial variances, which show coherent evolution, concomitant with ENSO for the last 7000 yr. The origin of this synchrony lies in regionwide changes within the scale of the Pacific basin, whereas the isolated millennial component indicates a wider-scale influence and, thus, a different origin. In addition, all frequency components except of the millennial band show a synchronic modulation in amplitude at the scale of 2000 yr, for the last 6000 yr. Conversely, there appears to be a submillennial modulation in the millennial band, which might well be a harmonic of the millennial cycle.
3) There is a weakening in ENSO variance from 7000 to 10 000 yr B.P., concomitant with a general ‘‘relaxation’’ of the climate system during this period.
4) The weakening in ENSO first reported from Lake Pallcacocha appears to have been severely overestimated by a factor of 10. Instead, the likely reduction in variance that took place was about one-third at most, as inferred from the synchronic evolution of both the decadal and centennial components within this interval.
5) According to these results, there is an urgent need to reconcile the diverse statistical approaches followed by different climate disciplines to tackle similar problems, irrespective of the time scale investigated.

REFERENCES

Fedorov, A. V., and S. G. H. Philander, 2000: Is El Niño changing? *Science*, **288,** 1997–2002.
Ghil, M., and Coauthors, 2002: Advanced spectral methods for climatic time series. *Rev. Geophys.,* **40**, 1003, doi:10.1029/2000RG000092.
Kerr, R. A., 2003: Huge Pacific waves trigger wild weather half a world away. *Science*, **300,** 1081.
Kumar, K. K., B. Rajagopalan, and M. A. Cane, 1999: On the weakening relationship between ENSO and monsoons. *Science*, **284,** 2156–2159.
Moy, C. M., G. O. Seltzer, D. T. Rodbell, and D. M. Anderson, 2002: Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, **420,** 162–165.
Rodbell, D. T., G. O. Seltzer, D. M. Anderson, M. B. Abbott, D. B. Enfield, and J. H. Newman, 1999: An ~15,000-year record of El Niño-driven alleviation in southwestern Ecuador. *Science,* **283,** 516–520.
Torrence, C., and G. P. Compo, 1998: A practical guide to wavelet analysis. *Bull. Amer. Meteor. Soc.,* **79,** 61–78.
Tudhope, A. W., and Coauthors, 2001: Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle. *Science*, **291,** 1511–1517.
Yiou, P., D. Sornette, and M. Ghil, 2000: Data-adaptaive wavelets and multi-scale SSA. *Physica D,* **142,** 254–290.