Title: A Wavelet Analysis of Holocene ENSO Variability

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Rodbell et al. (1999) hypothesized that light-colored laminae exhibited in sediment cores retrieved from Laguna Pallcacocha, a high altitude lake in the southern Ecuadorian Andes (2°46'S, 79°14'W; 4200 m.a.s.l.), were deposited by El Nino-driven alluviation episodes within the drainage basin. The results of this study suggested that warm El Ni⋆o-Southern Oscillation (ENSO) events were less intense during the early to mid Holocene, and that statistically significant variance in the modern ENSO band developed in the last ca. 6000 years. Here we present a continuous 11,500 yr record of ENSO variability from Laguna Pallcacocha using two 8 meter long sediment cores taken during July of 1999. We apply wavelet analysis to identify significant frequency components of changes in sedimentation as a function of time in these records. Our main conclusions support the interpretation of Rodbell et al. (1999) and also indicate that El Nino activity pulsed at approximately 2000 yr intervals, peaking at 1200 cal yr BP and decreasing towards modern.

A Geotek linescan camera was used to digitally scan the surface of the sediment cores and generate a composite down-core profile of red, green, and blue color. High color intensity values correspond to the light-colored laminae in the core, as well as bright colored glacial silts at the base of the record. Nine radiocarbon dates were transferred from the Rodbell et al. (1999) study and two age models—the constant carbon accumulation model (CCAM) and the event model (EM)—were applied to the composite down-core profile of red color intensity. These age models, which account for the large changes in sedimentation rates that occur between deposition of the light- and dark-colored laminae, were used to generate a number of time series of laminae concentration or ENSO variability through the Holocene (Fig. 1). The time series illustrates reduced ENSO variability during the early Holocene with gradually increasing variability through the mid to late Holocene, culminating at ~1200 cal yr BP and then decreasing towards modern. The increase in ENSO activity through the Holocene is pulsing in nature rather than monotonic, which reflects the presence of periods of high and low ENSO activity in the record.

Wavelet analysis was chosen as the spectral analysis method to identify the principal frequency components in the red color intensity time series because: 1) it simultaneously maps the time series into time-frequency space, thereby preserving all information from the time domain, 2) it can be applied to non-stationary time series, and 3) results can be tested against a red noise model to identify statistically significant frequencies in the record. A continuous wavelet transform (CWT) was performed on the time series using a Matlab algorithm generated by Torrence and Compo (1998). A wavelet, which is localized in time and frequency space and has a zero mean, is advanced along the length of the time series. The wavelet is passed with a fixed period or scale and good correlation between the wavelet and the time series corresponds to higher degrees of variance in the wavelet power spectrum. The CWT is defined as the convolution of the time series (x_n) and the scaled and translated wavelet function ($\Psi(\eta)$):

$$W_{n'}(s) = \sum_{n'=0}^{N-1} x_n y * [((n'-n)dt)/s)]$$

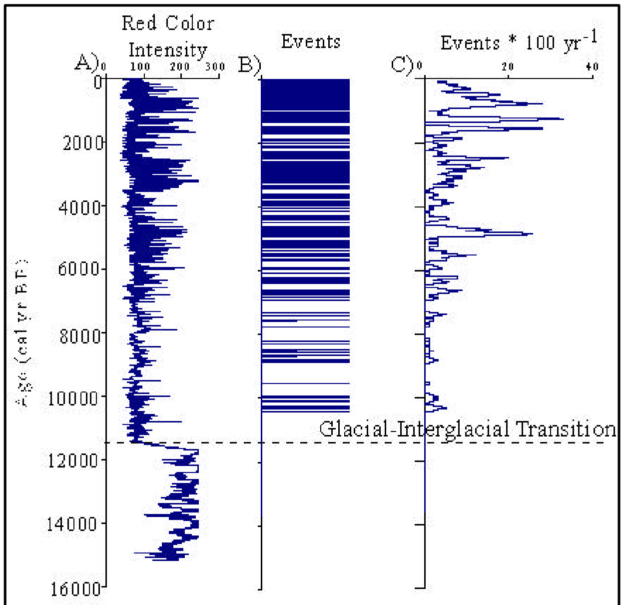

Figure 1. A) Composite red color intensity time series generated from the constant carbon accumulation model. High red color intensity values correspond to the light-colored laminae and the bright colored glacial silts exposed at the base of the record. B) Event stratigraphy constructed from the event model. Each horizontal line reflects a single event with a 6 month duration. C) Number of events (taken from the event model) in a 100 yr moving window. Dashed line indicates glacial-interglacial transition.

where the (*) indicates the complex conjugate, N is the number of data points in the time series, n' and n are the localized time index and are involved in shifting the wavelet, and s is the wavelet scale (Torrence and Compo, 1998). Because there is always a trade-off between frequency and time localization, two wavelet functions, the Morlet and the Mexican Hat, were used. The Morlet, which provides improved frequency localization over the Mexican Hat, is defined as:

$$\Psi(\eta) = \pi^{-1/4} e^{i\omega \eta} e^{\eta\wedge 2/2}$$

where Ψ is the wavelet function, η is a nondimensional time parameter, and ω_0 is the nondimensional frequency. The Mexican Hat, which proves better time localization over the Morlet wavelet, is defined as:

$$\Psi(\eta) = 2/3^{1/2} \pi^{-1/4} (1-\eta^2)e^{-t\wedge 2/2}$$

where Ψ is the wavelet function and η is a nondimensional time parameter.

Figure 2 displays the wavelet power spectrums calculated using both the Morlet and Mexican Hat wavelets. Here, variance is plotted as a function of both period and time. White and light gray colors are indicative of higher degrees of variance and the contour levels are chosen so that 5%, 25%, 50%, and 75% of the overall variance is above each level. Blue contours surround regions where variance exceeds the 99.98% confidence interval for a red noise process. The concentric ring at the base of the plots is the cone of influence. Variance below this line has been reduced due to the wavelet approaching the end of the finite time series. The plots reveal significant variance at millennial, centennial, inter-decadal, and sub-decadal time scales. Variance in the millennial band is centered on a period of 2000 years and is significant throughout the Holocene, while variance in the centennial band is centered on a period of ~600 years and is significant only during the most recent 5000 years of the record. Variance in the inter-decadal band is centered on a period of 70 years and displays some significant broadband variance. Variance in the sub-decadal or ENSO band is broadband as well. The variance in the decadal and ENSO band is significant throughout the Holocene, but it is predominantly found in the past 7,000 yrs of the record.

A Monte Carlo test was performed to test the null hypothesis that errors associated with radiocarbon dating and calibration can cause a shift in the variance outside the 2-7 yr ENSO band. The test generated 100 random age-depth profiles that were then applied to the line scan data using the constant carbon accumulation age model. From these 100 time series, 15 were selected and a power spectrum calculated. All of the selected time series displayed significant variance in the ENSO band, thus the null hypothesis was rejected. In addition, it was found that by expanding the duration of time between radiocarbon dates in the radiocarbon stratigraphy by a factor of 4, which is a more significant perturbation to the radiocarbon chronology than any of the Monte Carlo simulations, significant variance still remains in the 2-7 yr ENSO band. These two tests indicate that the ENSO band variance is stable and can be evaluated in the presence of ± 120 yr uncertainty in our age model.

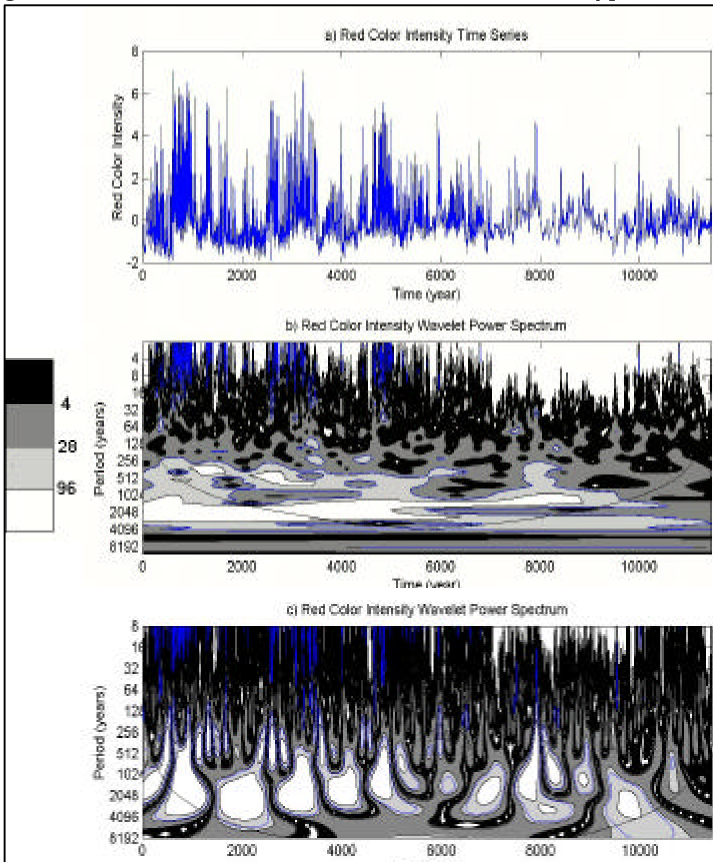

Figure 2. A) Red color intensity time series. B) Wavelet power spectrum calculated using the Morlet wavelet. C) Wavelet power spectrum calculated using the Mexican Hat wavelet.

References:

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