Reconstructing ENSO – Methods, Proxy Data and Teleconnections

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Abstract

The El Niño/Southern Oscillation (ENSO) is globally important and influences climate at interannual and decadal time-scales with resultant links with extreme weather events and associated socio-economic problems. An understanding of the ENSO system is therefore crucial to allow for a better understanding of how ENSO will ‘react’ under current global warming. Palaeoclimate reconstructions of ENSO variability allow extension prior to the relatively short instrumental record. However, due to the paucity of relevant annually resolved proxy archives (e.g. corals) in the central and eastern Pacific, reconstructions must rely on proxy data that are located in regions where the local climate is teleconnected with the tropical Pacific. In this study we compare three newly developed independent NINO3.4 SST reconstructions using data from (1) the central Pacific (corals), (2) the TexMex region of the United States (tree-rings), and (3) other regions in the tropics (corals and an ice-core) which are teleconnected with central Pacific SSTs in the 20th century. Although these three reconstructions are strongly calibrated and well verified, inter-proxy comparison shows a significant weakening in inter-proxy coherence in the 19th century. This break down in common signal could be related to insufficient data, dating errors in some of the proxy records or a break down in ENSO’s influence on other regions. However, spectral analysis indicates that each reconstruction portrays ENSO-like spectral properties. Superposed epoch analysis also shows that each reconstruction shows a generally consistent ‘El-Niño-like’ response to major volcanic events in the following year, while during years T+4 to T+7, ‘La Niña-like’ conditions prevail. These results suggest that each of the series expresses ENSO-like ‘behaviour’ but this ‘behaviour’ however does not appear to be spatially or temporally consistent. This result may
reflect published observations that there appear to be distinct ‘types’ of ENSO variability depending on location within the tropical Pacific. Future work must address potential dating issues within some proxies (i.e. sampling of multiple coral heads for one location) as well as assessing the time-stability of local climate relationships with central Pacific SSTs. More emphasis is needed upon sampling new and extending old coral proxy records from the crucial central and eastern tropical Pacific region.

**Keywords:**
ENSO, Reconstruction, Corals, Tree-rings, Teleconnection

**Introduction**

Despite the global importance of the El Niño/Southern Oscillation (ENSO) for influencing weather and climate at interannual time-scales (Broeinnmann et al. 2007), only a small section of the recent 2007 IPCC report (Solomon et al., 2007) was dedicated to ENSO variability over recent centuries. This is somewhat surprising, as this phenomenon is often linked with extreme weather events such as flooding and drought and associated socio-economic problems (Allan et al. 1996; Glantz 2000; Gergis and Fowler 2006). There are also considerable uncertainties that need to be resolved in both climate models and instrumental data regarding how the tropical Pacific and the ENSO system will respond to global warming (Vecchi et al. 2008). Although numerical model experiments may help to understand the changing dynamics of ENSO variability under different forcing scenarios, these models differ in their projections about ENSO under global warming - for example, whether or not the tropical Pacific will move to a more ‘El Niño-like’ or ‘La Niña-like’ state or whether the climate system can be locked into such distinct states (Clement et al. 1996; Cane et al. 1997; Vecchi et al. 2008). The instrumental record is also not long enough to assess whether recent changes in ENSO variability (particularly at lower frequencies – e.g. Ault et al. submitted, Allan and D’Arrigo 1999 and Allan 2000) are unique in a longer-term context.

Thus, a true understanding of the variability of the tropical Pacific over recent centuries must rely upon palaeoclimate reconstructions to provide information on changes in mean state and variability prior to measured observations. Over the last decade, there have been several attempts to reconstruct continuous time-series of ENSO variability: Stahle et al. (1998) utilised tree-ring data from the southwestern USA and Java to produce a Dec-Feb record of the Southern Oscillation Index (SOI) from 1706-1977. Mann et al. (2000) derived a multi-proxy reconstruction of Oct-Mar NINO3 sea surface temperatures (SSTs) from 1650-1980. Evans et al. (2002) developed a coral based reconstruction of the leading SST mode in the Pacific Ocean, while a more recent coral based reconstruction of tropic wide annual SSTs (Wilson et al. 2006) also showed that the high frequency
component was strongly related to ENSO. The longest published reconstruction to date (D’Arrigo et al. 2005a – the so called “Cook” reconstruction) calibrated tree-ring records from the American southwest to reconstruct Dec-Feb NINO3 SSTs back to 1408 AD. All of these studies are consistent in that they are well calibrated (explaining more than 50% of the target instrumental data variance) and verified (i.e. reconstructed values correlate significantly when compared to independent climate data).

One of the key issues with regards to ENSO is how much of this phenomenon’s variability may be a response to radiative forcing (anthropogenic or natural) or a product of internal forcing within the ocean-atmospheric system itself. Adams et al. (2003) and Mann et al. (2005a) have shown that there may be an increased probability of warm El Niños after major volcanic events as well as “El Niño-like” states during periods of low solar irradiance (see also D’Arrigo et al. (2005a) and Waple et al. (2002)). However, Chen et al. (2004) also showed that it was possible to predict El Niño events without knowledge of volcanic forcing for the last 148 years, although it could be argued that over this period there had been no volcanic events of sufficient strength to set up conditions favourable for El Niños (Emile-Geay et al. (in press)).

Although ENSO has a global impact, it is likely that its spatial influence changes over time which will not only complicate predictions, but also palaeoclimatic reconstructions – especially those that rely on proxy data located in regions that are only teleconnected with the central Pacific. Cole and Cook (1998) showed a significant relationship between ENSO and drought across the North American continent over the 20th century but that its influence varied spatially over time - likely partly modulated by the Pacific Decadal Oscillation (PDO) - and that the only time-stable relationship was found in the American southwest. Mann et al. (2000) and D’Arrigo et al. (2005b) also showed evidence for a weakening in the ENSO spatial pattern in the first half of the 19th century which may reflect a weakening of the ENSO influence on other regions during this period.

To further complicate the issue, within the tropical Pacific itself, Kao and Yu (in press) identify two distinct types of ENSO – an eastern and central Pacific mode – which exhibit different teleconnections with the Indian Ocean and other regions with resultant implications for proxy data location and relevant predictand ENSO indices for reconstruction. Similar Pacific ENSO modes or phases of the phenomenon have been reported in the literature by Folland et al. (1999), Trenberth and Stepaniak (2001) and Trenberth et al. (2002). Allan and D’Arrigo (1999) have discussed different patterns of Pacific SSTs during interannual and longer ‘protracted’ ENSO episodes with ‘El Niño-like’ and ‘La Niña-like’ characteristics. Finally, Allan et al. (1996) and Allan (2000) have indicated that ENSO has many ‘flavours’ (from weak, moderate to strong) encompassing quasibiennial, interannual to decadal temporal signatures, and even abortive events.
In this paper, we return to the challenge of reconstructing past ENSO variability with particular emphasis on examining the time-stability of the teleconnected relationships. To do this we introduce an updated and extended version of the D’Arrigo et al. (2005a) NINO3 SST reconstruction (Cook et al. 2008), as well as derive two new reconstructions of NINO3.4 SSTs – each one using a completely independent proxy data-set. One reconstruction relies on coral proxy records located from the central and eastern Pacific (defining this region as the “centre of action” with respect to ENSO variability in the tropical Pacific), while the other reconstruction uses multi-proxy data sources from locations that are teleconnected with the central Pacific. These three, entirely independent NINO3.4 reconstructions are used to assess the temporal stability of the ENSO fingerprint between these regions and to also examine the apparent post volcanic response of ENSO. The paper concludes with a series of recommendations that palaeoclimate researchers should consider in the future to allow for better estimates of past ENSO variability.

**Proxy Data and Screening**

Figure 1 presents correlations (calculated over 1925-1979) between NINO3.4 SSTs and individual 1x1 degree grid cells using the HADISST data-set (Rayner et al. 2003) for the annualised previous December - current November season. The spatial correlation pattern clearly shows the ‘classic’ ENSO pattern and highlights those regions which are ‘linked’ to central Pacific climate. This annual season was chosen as it includes the more classic ‘cold’ season commonly targeted for reconstructions of ENSO variability (Stahle et al. 1998; Mann et al. 2000; D’Arrigo et al. 2005a) while also taking into account that some of the proxy records used in this study have annual (as opposed to monthly) resolution only. Finally, we appreciate that both the ENSO phenomenon and the patterns of impacts and physical manifestations it causes evolve in space and time, and that proxy records may miss parts of this structure.

To realise the main aim of this study, annually resolved proxy archives were only included if they were located in the tropics (30S – 30N). Although, the climate of certain extra-tropical regions is also teleconnected with the central Pacific (Allan et al. 1996; Gergis and Fowler 2006; Bronnimann et al. 2007; see also Figure 1), we hypothesise that the probability that these relationships are temporally stable will decrease the further away from the tropics. We delineate the tropics into two regions with respect to the influence of ENSO; the ‘centre of action’ (COA) region is defined as the region in the central and eastern Pacific where SSTs are positively correlated with NINO3.4 SSTs while the ‘teleconnection’ (TEL) region covers all other tropical areas where SSTs are either inversely (e.g. Indonesia to Tonga) or positively (e.g. Indian Ocean) correlated with NINO3.4 SSTs (see Figure 1).
From the NOAA Palaeoclimatology Program (http://www.ncdc.noaa.gov/paleo/) and unpublished sources, we identified 40 candidate annually resolved proxy records (Table 1) from different regions within the tropics (30S - 30N – Figure 1) that start in the 19th century of earlier, and which have been interpreted to represent different climatic parameters. The bulk of these records are coral δ18O time-series, many of which have been utilised in earlier studies to reconstruct tropical SSTs (Mann et al. 2000; Evans et al. 2002, Wilson et al. 2006; D’Arrigo et al. 2006a; D’arrigo et al. (in review)). Non coral candidate data-sets include (1) tree-ring data from Indonesia which have been shown to cohere with ENSO variability (Stahle et al. 1998; D’Arrigo et al. 2006b); (2) an averaged pre and post-monsoon air temperature reconstruction based on tree rings from Nepal (Cook et al. 2003); (3) a tree-ring based reconstruction of rainfall for Zimbabwe (Therrell et al. 2006) and (4) a δ18O ice core record for Quelccaya, Peru (Thompson et al. 2006). As many of the coral time-series portray long term trends which are climatologically difficult to interpret (i.e. conflicting temperature and salinity influences), prior to analysis, all the proxy time-series were detrended with a 150-year cubic smoothing spline (50% cut-off) which allows the retention of potential climatic information at 50 years or higher time-scales, but removes all longer term secular trends. This detrending choice allows any potential multi-decadal variability (outside the classic 2-7 year ENSO bandwidth) to be captured in the reconstructions if it exists (Allan 2000).

The candidate proxy time-series (annualised for those with higher resolution) were screened against NINO3.4 annual SSTs over the 1925-1979 period (Table 1). 22 series were found to correlate significantly (95% C.L.) with ENSO variability. Of these, 8 were located in the COA region and 14 in the defined TEL areas (see Table 1). We should note that the TEL data-set was reduced to 12 predictor series as the GBRain and GBRiv coral luminescence series (Lough 2007) are effectively the same data and are highly correlated (r = 0.94, 1631-2004). HVI (Isdale et al. 1998), another luminescence series in the GBR region and used to reconstruct river flow, was found to have minor dating issues (Hendy et al. 2003). Therefore, of the three luminescence series, due to its slightly superior correlations with HADISST NINO3.4, we utilise only the GBRiv series in the following analyses.

Reconstruction Methods

Independent reconstructions of annual NINO3.4 SSTs were developed for the COA and TEL regions. However, as there is currently much methodological debate as to what methods are most appropriate to derive robust reconstructions from proxy data-sets (von Storch et al. 2004; Esper et al. 2005; Mann et al. 2005, 2007a, 2007b; Rutherford et al. 2005; Smerdon and Kaplan 2007; von Storch et al. in press) and since the final reconstruction outcome could be sensitive to
method, we experimented with three approaches; (1) Composite plus regression; (2) Principal component regression and (3) Regularized expectation maximization.

**Composite Plus Regression (CPR)**

This is the simplest of the three reconstruction methods and essentially relies on simple averaging of the proxy series. This approach has not been previously used to derive estimates of past ENSO variability per se although Wilson et al. (2006) used this approach to developed a 250-year reconstruction of tropic wide SSTs. It should be noted that a variation of CPR – composite plus scaling – is often used for the reconstruction of Northern Hemisphere temperatures (Esper et al. 2002; D’Arrigo et al. 2006c; Wilson et al. 2007).

The CPR method can be summarised as follows: Firstly, the 20 records retained for analysis had their sign adjusted so that they correlated positively with NINO3.4 SSTs. Theoretically, if the individual proxies used in each data-set were temporally consistent proxies of ENSO variability, their between series-coherence should be relatively stable through time. One interesting advantage of the CPR approach is that the between proxy coherence can be assessed using running mean correlation (RBAR) time-series (Wigley et al. 1984; Briffa 1995). The RBAR time-series are derived by calculating running 31-year correlation time-series between each bivariate pair of proxy series and calculating a mean of these values. This was undertaken separately for the COA and TEL data-sets (Figure 2). Over the 1925-1979 screening period, RBAR is slightly higher ($r = -0.35$) for the COA data-set compared to $-0.21$ for the TEL data suggesting a generally stronger between proxy common signal within the central Pacific. Prior to the screening period, however, RBAR values remain at similar levels until they start decreasing in the late 19th century. The decrease is less marked for the COA data-set, again suggesting reasonable between proxy coherence in the central Pacific. However, for the TEL data, correlation values reach zero around the mid 19th century – suggesting a loss in common signal between these proxy records in the 19th century - the implications of which are discussed later in the paper.

To derive the CPR reconstructions, for both the COA and TEL data-sets, the proxy time-series were normalized over the respective periods common to all series (1897-1981 for COA and 1885-1979 for TEL) and then averaged to formulate a nested composite mean. To extend the composite record as far back in time as possible using proxy series of different length, the shortest proxy series were removed from the data matrix, and the remaining series were again normalized to the extended common period before averaging. This process is undertaken iteratively until the final longest proxy record remains. Nests were also developed for the post-1981 (1979 for TEL) period, as the number of available series also declines when going forward in time (Table 1) allowing reconstruction extension to 1998 for both regional reconstructions. For each nested series,
calibration was made over the 1925-1979 screening period while verification was undertaken over the 1897-1924 period (1871-1924 for longer nests). Verification using independent data is a crucial step as it represents a stringent assessment of the derived nested reconstruction independent of the initial screening process. For model validation, we used the coefficient of determination ($r^2$), reduction of error (RE) and coefficient of efficiency (CE) statistics, commonly used in dendroclimatology (Cook et al., 1994) but also recently utilised for tropical SST reconstructions (D’Arrigo et al. 2006a; Wilson et al. 2006; D’Arrigo et al. (in review)). The root mean square error was also calculated over the verification period to derive a 2-sigma confidence interval for each predicted annual value.

To derive the final reconstruction time series, the mean and variance of each nested series were adjusted to that of the shortest (most replicated) nested reconstruction and the relevant sections spliced together. The rescaling of the data removes artificial changes in the variance of the final time series, owing to the weakening in explained variance (related to the decreasing number of proxy series), while retaining potential real changes in variance that may represent a response to actual changes in climatic variability. The 2-sigma error bars were also adjusted (inflated), using the same scaling function as used for each nested series, to account for the decrease in explained variance in each nest.

**Principal Component Regression (PCR)**

PCR has been a staple reconstruction method (Briffa et al. 1983, 1986; Cook et al. 1994) for producing climate field reconstructions in the tropics (Mann et al. 2000; Evans et al. 2002; Ault et al. (submitted)) and elsewhere (Cook et al. 1999). Essentially, the PCR approach, as applied in this study, is very similar to the CPR method described above, but rather than simple averaging the relevant proxies for each nest, the input data-matrix was reduced to a few component scores (with a minimum eigenvalue of 1.0) using a principal component analysis. PC scores were then entered into the calibration regression model using a stepwise procedure. When the number of input proxy series was three or less, a simple mean (i.e. the CPR approach) was used as the predictor variable. The nested reconstruction time-series were spliced together and error bars calculated in the same manner as used for CPR, after appropriate scaling.

**Regularized expectation maximization (RegEM)**

RegEM is a covariance-based iterative algorithm, which linearly models the relationship between available and missing values (given plausible ones). The method is based on the expectation maximization (EM) algorithm, and a regularization scheme to take into account under-determined settings. The conventional iterative EM algorithm estimates the mean and the
covariance matrix of an incomplete data matrix (Schneider et al. 2001). The EM algorithm is used under the assumption that the predictand and predictor data are Gaussian. In cases where the number of variables exceeds sample size the EM algorithm has to be regularized. Thus, the regularization scheme truncated total least squares (TTLS) is applied (a departure from the procedure described by Schneider et al. (2001)). In order to regularize the covariance matrix its principal components are truncated, i.e. only a specific number of principal components are considered, according to the truncation parameter. Optimal truncation parameters are identified based on the criterion proposed by Mann et al. (2007a). Here RegEM is used to reconstruct a single series, while usually it is applied to reconstruct climatic fields.

The NINO3.4 SST reconstructions

Calibration and Verification results

Figures 3 and 4 present associated calibration and verification results, using each reconstruction method, for the COA and TEL data-sets respectively. On the whole, the results between the three calibration methods are quite similar. For the COA reconstruction, calibration (Figure 3b) explains ~80% of the variance over the most replicated nest with associated verification $r^2$, RE and CE values (Figure 3c-e) around ~0.60. Unfortunately, the COA data-set is quite small and the period from 1840-1880 is represented by only three proxy series (URV, JAR and MAI). Despite this, calibration is high ($r^2 = 0.65$) and verification still acceptable ($r^2 = 0.29$; RE = 0.24; CE = 0.23). Prior to 1840, however, verification weakens markedly and this period, represented by only the URV series, is likely not a robust representation of ENSO variability.

Calibration using the TEL data-set over the most replicated period (1885-1979) is not as strong as the COA data-set, but is still reasonable at 67% (Figure 4b). Verification, however, is robust with $r^2$, RE and CE values around ~0.65 (Figure 4c-e). As would be expected, there is a generally weakening in calibration and verification as the number of proxy records drop out from the data matrix. When considering the CPR, PCR and RegEM results, verification is robust from 1727 onwards where a minimum of four proxy records (QUE, GBRiv, AML and RAR) are used. From 1727-1775, the calibration explains 38% (CPR) / 32% (PCR) of the variance while verification $r^2$, RE and CE is > 0.20. On the whole, there is little statistical difference between the CPR and PCR results. The RegEM results, however, are markedly weaker, especially prior to 1727 which appears to be associated with greater variance in the reconstructed time-series at this time (Figure 4a). The variance is also slightly higher using the COA data-set (Figure 3a). These slightly different results using the RegEM method suggest that this method may not work well with relatively sparse data-sets.
**Inter-reconstruction comparison**

In the previous section, it was shown for both the COA and TEL NINO3.4 reconstructions that there is statistically little difference between the series generated using either CPR, PCR or RegEM, although there is some potential variance inflation in the least replicated part of the RegEM versions. Therefore, for the remainder of this paper, the three reconstruction ‘flavours’ were transformed to z-scores (same mean and variance over their common period) and their composite average used for further analyses. In this section we compare the resultant COA and TEL reconstructions with the Mann et al. (2000) NINO3 reconstruction (hereafter referred to as MANN) and the newly updated Cook et al. (2008) TEXMEX NINO3.4 reconstruction (see Figure 1 for location). We do not make any comparison to the Stahle et al. (1998) and D’Arrigo et al. (2005a) series as the TExMEX reconstruction utilises an expanded data-set of these earlier studies and supersedes them. It should be noted that the MANN and TExMEX reconstructions are not entirely independent as they share some input tree-ring data. One other caveat worthy of note is that the MANN and TExMEX series were calibrated against ‘cold’ season SSTs. The correlation using the HADISST instrumental data between the DJF and annual previous Dec-Nov seasons is 0.70 (1871-2007) so it should not be expected that there will be perfect coherence between the proxy reconstructions.

Figure 5 presents time-series plots of each ENSO related reconstruction with associated running 31-year variance plots. D’Arrigo et al. (2005a) highlighted a relatively consistent change in year-to-year variance between several records that portrayed ‘ENSO-like’ variability - the Stahle et al. (1998), Mann et al. (2000) and D’Arrigo et al. (2005a) series being included in that comparison. D’Arrigo et al. (2005a) showed evidence of increased proxy variance during periods of low solar irradiance (e.g. Dalton (1790 to 1830) minimum) and a further increase in variance in the recent period. TEL and COA may partly challenge the D’Arrigo et al. (2005a) observations, however, with TEL showing generally low year-to-year variance from the mid 18th to late 19th century period and COA expressing a more constant rise in year-to-year variability since the mid 19th century. Despite these discrepancies between the four ENSO reconstructions, there appears to be an overall pattern of reduced variance during the 19th century compared to the 20th century.

Table 2 presents a correlation matrix between the four ENSO records for the 1871-1980 (verification and calibration period) and 1800-1870 period. The latter period is not ideal for comparative analysis as it incorporates a period (pre-1840) which was defined as non-robust in the COA record (Figure 3). Despite the different target seasonal windows, coherence is generally good between the four records since 1871. The strongest correlations (r = 0.82) are noted between both COA and TEL and TExMEX and MANN, while the weakest correlation (r = 0.50) is noted between TEL and TExMEX. Over the earlier 1800-1870 period, however, between reconstruction
coherence weakens markedly. All correlations with COA over this period are close to zero. In fact the only significant (95% C.L.) correlations are between TEL and TEXMEX (r = 0.33) and TEXMEX and MANN (r = 0.57). The latter correlation is likely higher due to the shared tree-ring data used for both these reconstructions. The TEL/TEXMEX correlation, however, does indicate some degree of coherence between these independent reconstructions. To better explore the between reconstruction coherence, we employ a Kalman filter analysis (Visser and Molenaar 1988) which allows an assessment of the between series relationship using regression models with time-varying coefficients. The COA reconstruction shows a consistent decrease in common signal (Figure 6) with the other ENSO reconstructions from the 20th century into the 19th century. In fact by the mid-19th century, there is no significant common variance with the other reconstruction at all. This result is entirely consistent with the calibration/verification results (Figure 3) which indicated that the reconstruction is not robust prior to 1840 simply due to low replication of input proxy series. This is a frustrating result as the COA series, of all the reconstructions, should theoretically best portray past ENSO variability as the original proxy data are located in the central and eastern Pacific (Figure 1). The coherence of TEL with TEXMEX and MANN again show high coherence in the 20th century which weakens back in time. The common signal breaks down during the first half of the 19th century. Intriguingly, there is some significant coherence between TEL and TEXMEX during the ~1570-1650 period although caution is advised when interpreting this observation as the proxy replication for TEL is only one or two series through this period. As was stated above, the TEXMEX and MANN series are not independent, and coherence is significant between the two-series through their period of common overlap, although it also decreases back in time.

**Spectral Properties of ENSO reconstructions**

In the previous section, inter-correlation and Kalman filter analysis indicated a weakening in the common signal expressed by the four ENSO reconstructions in the 19th century compared to the 20th century. There are several reasons why this loss in coherence could be observed:

1. COA is not a robust representation of NINO3.4 SSTs prior to 1840 due to a lack of sufficient input proxy records from the central Pacific.
2. Although minor, the probability of dating errors will likely increase in the coral/ice core records going back in time. Even a dating error of only one year will affect the correlation and Kalman filter analysis substantially.
3. For the TEL, TEXMEX and MANN reconstructions, the teleconnected relationship between the central/eastern Pacific and the regions where the different proxy records are located may not be time stable.
Spectral analysis can be employed to ascertain whether the four ENSO reconstructions do portray consistent power within the ‘classic’ ENSO bandwidth over time. Firstly, to highlight any potential seasonal differences that the reconstructions may show, a multi-taper method (MTM - Mann and Lees 1996) analysis was first performed upon the instrumental data over the 1925-1979 period. Significant peaks were identified at 4.6-6.0 years for both the DJF and previous Dec-November seasons as well as a further peak at 3.8-3.9 years for the annual season.

MTM spectral analysis was made for each of the reconstructions of the three independent periods 1925-1979, 1850-1924 and 1650-1849 (Figure 7). Over the 1925-1979 period, COA, TEL and TEXMEX express similar spectral properties to the instrumental data. Interestingly, however, the MANN series does not show any significant peaks at the 95% C.L. over this period. Over the 1850-1923 period, the spectra for COA and TEL are again quite similar with a common peak at 3.5-4.0 years (as does MANN). COA also expresses significant power at 9.7-10.3 years which is not quite significant in TEL, possibly reflecting the quasidecadal mode identified by Allan and D’Arrigo (1999). Ault et al. (submitted) also identified similar decadal variability since 1850 in the 1st principal component derived from 23 coral oxygen isotope records. The TEXMEX series shows no significant peaks during this period. Over the longer extended 1650-1850 period, the spectral properties of the series generally express much stronger multi-decadal variability. Despite the fact that COA is represented by only one series (URV), it does still portray some ‘ENSO-like’ variability with peaks around 4.1-4.8 years which is similar to peaks ranging from 3.9-4.8 years in the TEXMEX and MANN series. COA also shows a marked multi-decadal peak ~32-57 years which coincides with similar peaks in TEL (38-49 years) and MANN (34-35 years). The TEXMEX series does not appear to express any multi-decadal signal over this period however. Finally, TEL expresses more higher frequency ‘ENSO-like’ variability at 2.8-2.9 years which is also observed in the TEXMEX reconstruction.

Exploring ENSO’s post volcanic response

Despite a weakening in inter-series coherence during the early/mid 19th century compared to the 20th century (Table 2 and Figure 6), MTM spectral analysis (Figure 7) indicates that all four reconstructions express ‘ENSO-like’ characteristics. Although dating errors could affect the RBAR (Figure 2) and Kalman filter analyses (Figure 6), the spectral analysis results do appear to indicate that all the reconstructions portray some aspect of past ENSO variability, but it may be different in each time-series related to the locations of the original constituent proxy sources used. This
observation also agrees with Kao and Yu (in press) who identified distinct ‘types’ of ENSO depending on location within in the tropical Pacific. If each of the reconstructions therefore portray slightly different “flavours” of past ENSO behaviour, what are the implications of this observation upon the hypothesis that there is an increased probability of warm El Niños after major volcanic events (Adams et al. 2003, Mann et al. 2005 and Emile-Geay et al. in press)? To test this, we undertook a Superposed Epoch Analysis (SEA) on each time-series after they had been normalised to z-scores over the 1800-1980 period. The 10 strongest and most significant tropical volcanic events were identified between 1800 and 1998 (see Table 3) using a variety of volcanic indices (Crowley 2000; Robertson et al. 2001; Ammann and Naveau 2003; Adams et al. 2003; Mann et al. 2005) and relative mean departures for each reconstruction were calculated for the 5 years preceding and 10 years following an event. As the COA reconstruction is likely not particularly robust prior to 1840 (Figure 3) and the TEXMEX and MANN records only go to 1980 (so reducing the number of events in the analysis to eight), a reduced SEA analysis was also made targeting the four events (1883, 1902, 1963 and 1968) common to all four records.

The SEA results (Figure 8) show that both COA and MANN do not show a post-event ‘El Niño-like’ warming. This is a surprising result with respect to the MANN record as Adams et al. (2003) clearly showed, using the same series, an increased probability of warmer SSTs after strong volcanic events. Ultimately, this disparity in results likely reflects the sensitivity of the SEA method to differing periods of analysis and different volcanic events used. For example, the results for the four event analysis do indicate significant warming in year T+1 for both COA and MANN.

For the full SEA analysis both TEL and TEXMEX show significant mean ‘El Niño-like’ warming for the 1st and 2nd years after the volcanic events. Caution however is advised for the TEL results as most of the proxies utilised for this reconstruction are located in regions where local SSTs are inversely correlated with NINO3.4 SSTs (Figure 1, see also D’Arrigo et al (in review)) and so their time-series entered into the regression models with negative weighting (in the CPR approach). Therefore, the reconstructed local cooling after a volcanic event is transformed in the NINO3.4 reconstructions to a warming which in actual fact may not reflect a ‘real’ warming in the central Pacific, but an overall cooling in the regions where the TEL proxy records came from.

Another interesting observation from the SEA is that there appears to be an apparent shift to negative SST (La Niña-like) conditions at T+7 (COA and TEL) and T+4 (TEXMEX and MANN) years. A similar observation was noted by Adams et al. (2003) where they hypothesised that after the initial post volcanic event warming in T+1, a rebound to ‘La Niña-like’ conditions occurred during years T+4, T+5 and T+6, possibly to “synchronise the internal clock of ENSO”. We feel that such an observation overstates the results and the noted ‘La Niña-like’ conditions are likely
simply related to the mean period of ENSO variability and again highlights that all the reconstructions portray some aspect of the ENSO system.

Discussion and Conclusion

There is potentially a large data-set of annually resolved proxy archives from tropical and extra-tropical locations that will continue to be amassed, which can be used to infer information on past ENSO activity. It is however crucial to understand the limitations of these series with respect to (1) the temporal stability of the climatic teleconnections between the tropical Pacific and the regions where these archives are located and (2) potential dating errors in the time-series. Ignoring these two issues may result in erroneous conclusions about past ENSO activity when such large data-sets are utilised to reconstruct the dynamics of the ENSO system.

Although a certain degree of understanding can be gleaned from the instrumental data (Allan 2000), they are essentially too short to examine ENSO teleconnections over more than a century and explore longer term variability at decadal and multi-decadal scales. Palaeoclimatic archives therefore, which can be used to extend our climatic knowledge well beyond the period covered by the instrumental data, are crucial to improve our understanding of past climate variability in the tropics. However, it should be noted that ongoing data activities led by the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (http://brohan.org/hadobs/acre/acre.html) will markedly improve late 18th-early 19th century instrumental records in the coming years.

In this study, annually resolved proxy records from the tropics were screened for an ENSO signal and divided into two data-sets: records that were located within the central and eastern Pacific (COA) and records that were located in regions that are climatically teleconnected with the central Pacific (TEL). Using three different reconstruction methods (CPR, PCR and RegEM) two independent reconstructions of annual previous December-November NINO3.4 SSTs were developed. Both reconstructions are strongly calibrated and well verified (Figure 3 and 4). The COA reconstruction (1607-1998) is in fact exceptional, in palaeoclimate terms, as ~80% of the instrumental variance is explained over the most replicated period during calibration. Unfortunately, due to the sparse nature of proxy records from the central Pacific, the COA record weakens markedly and can only be interpreted as being robust since 1840. The TEL reconstruction (1540-1998), although not as strongly calibrated as COA ($r^2 = 0.67$) is still highly robust and well verified back to 1727. Of the three reconstruction methods tested, little statistical difference between the results was noted, although the RegEM approach appears to inflate the variance of the reconstruction relative to the CPR and PCR ‘flavours’ when replication is low.
The COA and TEL series were compared to a new tree-ring based TEXMEX reconstruction of DJF NINO3.4 SSTs (Cook et al. 2008) as well as a multi-proxy based NINO3 reconstruction (Mann et al. 2000). Overall, using a Kalman filter analysis, inter-proxy coherence breaks down completely around the early-mid 19th century (Figure 6) which suggests either a problem in some of the constituent proxy records or a breakdown in the spatial teleconnections. Interestingly, however, despite the differences in the four reconstructions, a superposed epoch analysis (Figure 8) identifies a generally consistent ‘El-Niño-like’ response to major volcanic events in the following year (although this analysis appears sensitive to the number of volcanic events studied), while during years T+4 to T+7, ‘La Niña-like’ conditions are noted. This observation generally agrees with results of Adams et al. (2003). MTM spectral analysis undertaken on the four reconstructions over the periods 1925-1979, 1850-1924 and 1650-1849 identified ENSO-like ‘behaviour’ in all the time-series. This ‘behaviour’ however does not appear to be spatially or temporally consistent. For example, although the spectra of COA and TEL are arguably quite similar (Figure 7), the COA record expresses stronger decadal variability prior to 1925 than TEL. This observation is consistent with results detailed in Ault et al. (submitted). Significant multi-decadal variability (30-60 years) is also noted prior to 1850 in the COA, TEL and MANN records, but not in the TEXMEX series.

Folland et al (1999), Trenberth and Stepaniak (2001), Trenberth et al. (2002) and Kao and Yu (in press) identified distinct ‘types’ of ENSO variability depending on location within the tropical Pacific. The results of these studies have major implications for the reconstruction of past ENSO variability. Are NINO3.4 SSTs, for example, an appropriate index for ENSO as a whole, or just one aspect of it? There are a variety of ENSO indices (NINO 1+2, NINO3, NINO3.4, NINO4, SOI and the Multivariate ENSO index (Wolter and Timlin 1993)), with no consensus within the scientific community as to which index best defines ENSO. Hanley et al. (2003) explore this issue and state that the choice of which ENSO index to use is dependent upon the phase of ENSO that is to be studied. This is also suggested in Allan et al. (1996) and Allan (2000). Of course, spatial field reconstructions (e.g. Evans et al, 2002) are the optimal answer to this problem, but such an approach must rely on teleconnections between proxy records and SSTs which, as has been suggested, may not be time-stable. A more ideal approach is the so called “point-by-point regression” approach, utilised by Cook et al. (1999; 2004) for their North American drought reconstructions. This method works on the premise that only proxy records that are proximal to a given climate grid will likely be true predictors of a particular climate parameter with a greater probability that the modelled relationship will be stable through time. Unfortunately, in the tropics, such a methodological approach is not practical due to the sparse network of relevant proxy records, especially further back in time.
So, how can future research improve upon earlier studies (Stahle et al. 1998; Mann et al. 2000; Evans et al. 2002. D’Arrigo et al. 2005a)? Ultimately, the central and eastern Pacific are the key locations where new annually resolved proxy records need to be developed. Unfortunately, there are only relatively few locations in this region where relevant coral colonies could theoretically exist (Evans et al. 1998). However, as has been shown with the COA reconstruction (see also Evans et al. 1998), due to the relatively homogenous nature of the central/eastern tropical Pacific climate, only a few key coral records would be needed to derive a robust ENSO reconstruction. Future work therefore needs to focus on sampling new, and extending old, coral records from this region. Importantly, and mirroring recommendations made by Lough (2004), dating control on coral proxy records could be verified and improved if a minimum of three coral heads were sampled for each location and the dendrochronological practise of “crossdating” was employed. The extension of living coral records using fossil material (e.g. Cobb et al. 2003) also provides an exciting possibility for extending short but climatically sensitive records.

Currently, for the simple reasons of dating control and proxy record replication, the TEXMEX (D’Arrigo et al. 2005a; Cook et al. 2008) ENSO based reconstructions are likely the most robust representations of ENSO variability over recent centuries. However, it cannot yet be tested whether this is a temporally consistent representation of central Pacific SSTs, or whether it merely represents the teleconnected relationship between the central Pacific and the American southwest which may vary over time. However, with the development of longer exactly dated coral based records from this crucial region in the Pacific, it would be statistically simple to assess the temporal stability of teleconnected links.

Acknowledgements

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References


Solomon, S. et al. 2007. *Climate change 2007: the physical science basis*. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.


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<th>Latitude</th>
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<th>TEL reconstruction</th>
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Table 1: Summary information of annually resolved proxy archives used in this study. Bolded correlations are significant at the 95% confidence limit. # = URV is composite of Urvina Bay (1607–1953/1962 – 1981 (Dunbar et al., 1994)) and Punta Pitt (1936–1981 (Shen et al., 1992)). See Wilson et al. (2006 – Table 1) for details. @ = DSM is a composite record of three teak ring-width chronologies (Pagarwunung Darupono, Saradan and Muna). See D’Arrigo et al. (2006a) for more details.
### Table 2: Correlation matrix (calculated over the 1800-1870 and 1871-1980 periods) between the four ENSO reconstructions. Values with grey shading are not significant at the 95% confidence limit.

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### Table 3: Summary list of the major tropical volcanic events identified for the SEA. The last column denotes the Volcanic Explosivity Index (VEI – Newhall and Self (1982)) for each volcanic event. The VEI values were taken from: http://www.volcano.si.edu/world/largeeruptions.cfm

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Figure 1: Correlations (1925-1979) between NINO3.4 SSTs and local HADISST 1 x 1 degree grid squares for the annualised (previous December- November) season. Locations of annually resolved proxy records (see Table 1 for details on each series) utilised in this study are shown. The spatial correlation base map was generated using the KNMI Climate Explorer (van Oldenborgh and Burgers 2005).
Figure 2: Running 31-year RBAR time-series (with 2-sigma error envelopes) for both the COA and TEL data-sets. The RBAR values are centred on the central year of each 31-year window. Error estimates can only be calculated for those periods were replication is greater than three proxy series. See Figures 3 and 4 for proxy replication for each data-set.
Figure 3: COA reconstruction: A: Comparison of the CPR, PCR and REGEM time-series with 2-sigma error plots. Legend relevant for all panels; B: Calibration r² results and replication histogram of proxies used; C: Verification r²; D: Verification RE; E: Verification CE.
Figure 4: As for Figure 3 but for the TEL reconstruction.
**Figure 5:** Time-series plots of each ENSO reconstruction. The data have been normalised to the 1900-1980 period. Thick smoothed line is a 10-year smoothing spline. The lower time-series (grey) in each panel represents a sliding 31-year variance plot for each reconstruction. The vertical lines for COA and TEL delineate the start of the ‘robust’ period (1840 and 1727 respectively).
Figure 6: Kalman filter analysis between each ENSO reconstruction. Grey shading denotes 2-sigma error bars.
Figure 7: MTM spectra for each proxy over three different periods: 1925-1979, 1840-1924 and 1650-1849. The dashed grey line denotes the 95% C.L.
Figure 8: Superposed Epoch Analysis results for the four ENSO reconstructions. The black line (with grey 2-sigma error envelope) denotes the relative departures for each series averaged over 10 major volcanic events (see Table 3). The red line (with associated 2-sigma error bars) details the relative departures averaged over four common volcanic events (1883, 1902, 1963, and 1968).