On the variability of ENSO over the past six centuries

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[1] The instrumental record is too brief for evaluation of the El Niño-Southern Oscillation (ENSO) system and its long-term response to climate forcing. To supplement these data, we use a new reconstruction of December–February Niño-3 sea surface temperatures based on subtropical North American tree-ring records to investigate aspects of ENSO variability over the past six centuries (AD 1408–1978). Spectral analyses reveal that the reconstruction best resolves variability within the "classical" ENSO band of 2–8 years. A low amplitude ENSO epoch in the 17th to 18th centuries broadly coincides with "Little Ice Age" conditions over much of the globe. The detailed behavior shows good agreement with shorter tree-ring reconstructions of ENSO over the past few centuries, but differs at times from other longer coral ENSO records and recent model simulations of past ENSO behavior. We discuss possible reasons for these discrepancies. **Citation:** D'Arrigo, R., E. R. Cook, R. J. Wilson, R. Allan, and M. E. Mann (2005), On the variability of ENSO over the past six centuries, *Geophys. Res. Lett.*, *32*, L03711, doi:10.1029/2004GL022055.

1. Introduction

[2] Although paleoclimatic records provide one of the few means available for assessing the long-term variability of the El Niño-Southern Oscillation (ENSO) system, relatively few have been used to directly reconstruct ENSO indices. Two recent efforts in this regard are a tree-ring reconstruction of the Dec-Feb Southern Oscillation Index (SOI) (*Stahle et al.* [1998], 1706–1977; hereinafter referred to as the ST98 reconstruction), and a multiproxy reconstruction of Oct-Mar Niño-3 sea surface temperatures (SSTs) (*Mann et al.* [2000], 1650–1980; hereinafter referred to as the MBH00 reconstruction). These reconstructions, which employ different methodologies and nearly independent data sets, provide complementary information on key variables used to measure the ENSO system. The ST98 series is based almost entirely on subtropical North American tree-ring data, and as such best reflects the ENSO teleconnection to that region. The MBH00 series incorporates multiproxy data from various locations around the globe, both within and outside the ENSO domain in the Indo-Pacific. While the ST98 series (due to autoregressive modeling) generally lacks decadal and longer-term information on ENSO, the MBH00 series exhibits more lower-frequency variability. Here we evaluate past ENSO variability using a new tree-ring reconstruction of Niño-3 SST. It is based on a subtropical North American tree-ring width data set that largely overlaps with that used in the ST98 reconstruction, and to a lesser extent the data used in the MBH00 series. However, the new reconstruction is considerably longer than these previous series, spanning six centuries. Below, we analyze this reconstruction and compare our results to these other studies.

2. The Tree-Ring Based Niño-3 SST Reconstruction

[3] The new reconstruction is calibrated on Niño-3 Pacific SSTs [*Kaplan et al.*, 1998] (5°N–5°S, 90–150°W) and covers 1408–1978 (Figures 1a–1b) (*Cook* [2000] hereinafter referred to as the Cook reconstruction]. The ring-width records used are all from moisture-sensitive sites in the southwestern USA and Mexico. Such records from this "Tex-Mex" region of North America have the strongest ENSO signal yet detected in tree-ring data worldwide (ST98). An important caveat, however, is that this signal is communicated through extratropical ENSO teleconnections (which could change over time), rather than actual underlying tropical Indo-Pacific climate changes associated with ENSO. 175 chronologies were screened as potential predictors (lags t; t + 1) of the instrumental Niño-3 data in principal component regression [*Cook and Kairiukstis*, 1990]. Both the tree-ring and instrumental data were prewhitened using autoregressive modeling, with instrumental persistence added back in to the reconstruction [*Cook and Kairiukstis*, 1990]. Series significantly correlated (>0.05 level) with the instrumental record were used to reconstruct Niño-3 SSTs. Calibration/verification testing (Figures 1c–1d) strongly support the reconstruction's validity. A nested procedure (in which the number of chronologies declines back in time) was used to develop the longest possible reconstruction, with iterative nests beginning in 1408, 1507, 1608 and 1709. The final reconstruction was developed by averaging early and late calibration reconstructions within each nest, and splicing these series together after their variance and mean had been adjusted to that of the 1709–1978 nest. The fidelity of the signal decreases back in time (Figure 1). The r^2 values range from 52% to 43% between the most and least-replicated models, similar to skill levels established in the shorter ST98 and MBH00 reconstructions.

[4] The Cook reconstruction models the boreal winter (Dec–Feb) season of greatest ENSO variability [*Allan*, 2000]. Positive values are typically associated with warm (El Niño) events and negative values with cold (La Niña) events. Although instrumental persistence has been added back in, low-frequency variability may still be less strongly

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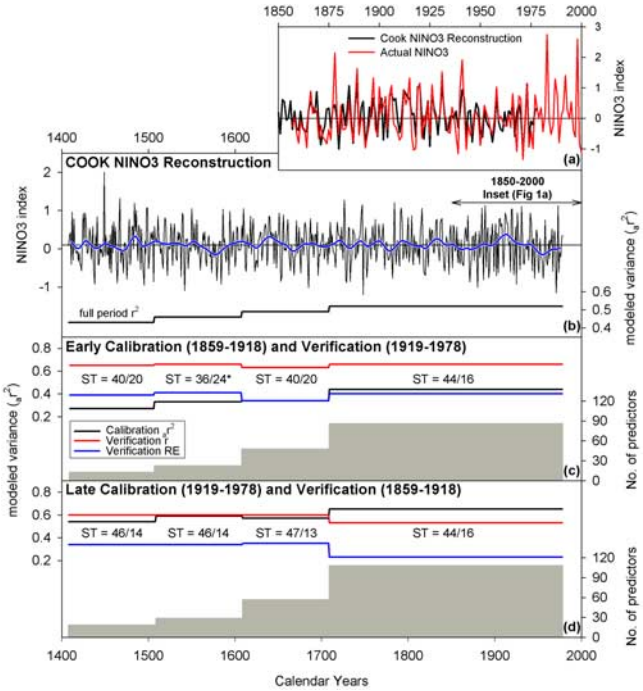

Figure 1. (a) Actual and estimated indices. (b) Niño-3 SST reconstruction, plus full period calibration r^2 (AD 1408–1978). Horizontal line = mean; heavy line is 25-yr cubic smoothing spline. (c) Calibration ($_ar^2$, 1859–1918) and verification (Pearson's correlation r, Reduction of Error (RE) and Sign Test (ST), 1919–1978). * = ST not significant at 95% CL (p = 0.08). Grey = number of predictors entered into each nested model. (d) As in (c) but for 1919–1978 and 1859–1918. The RE measures common variance between actual and estimated series; positive values indicating regression skill. ST measures how well estimates track yr-yr changes in instrumental data [*Cook and Kairiukstis*, 1990].

expressed than in the instrumental record. Thus, this reconstruction best reflects the "classical" band of ENSO variability of ~2–8 yr [*Allan*, 2000]. It correlates with the ST98 record at r = −0.77 (1706–1977) and with the MBH00 record at r = 0.55 (1650–1978). Stronger correlation with the former at least partly arises through greater overlap in predictors used.

3. Results and Discussion

[5] The spectral properties of the Cook reconstruction were compared to those of the instrumental record using the multi-taper method [*Mann and Lees*, 1996] for 1859–1978. The reconstruction reproduces the main spectral features of the instrumental record, displaying peaks within the 3.5–4 year period band that exceed the 95% confidence limit (Figures 2a and 2b). A weaker decadal peak is consistent with identification of lower-frequency modes in the instrumental record [*Allan*, 2000]. Recent global analyses of joint SST and mean sea-level pressure (MSLP) signals on interannual to multidecadal timescales [*Meinke et al.*, 2005] indicate that there does not appear to be a distinct decadal (9–13 yr) ENSO band in Tex-Mex rainfall data, and thus this frequency band might not be expected in the Cook series in any case. Interestingly, a coral-based reconstruction from the tropical Indo-Pacific does reflect such lower-frequency variability (R. D'Arrigo et al., Tropical-North Pacific climate linkages over the past four centuries, submitted to *Journal of Climate*, 2004, hereinafter referred to as D'Arrigo et al., submitted manuscript, 2004). The reconstruction spectrum for the Cook preinstrumental period (1408–1858; Figure 2c) generally indicates periodicities consistent with those in the instrumental period, with strong peaks in all three series at ~3.5–4 and 5.5–6 years (Figures 2a–2c).

[6] Morlet wavelet analysis [*Torrence and Compo*, 1998] was performed to assess significant spectral changes over time in the Cook record (Figure 3a). Results are broadly consistent with peaks identified above, but show considerable amplitude modulation within the "classical" ENSO bandwidth. One noteworthy feature is an episode of low variability during the generally globally-cold "Little Ice Age" interval [*Grove*, 1988; *Mann et al.*, 1999] of the later 1600s-early 1700s (Figure 3), coincident with the latter part of the Maunder Minimum (MM) period of low solar irradiance [*Eddy*, 1976] discussed further below. Low amplitude at this time is also evident using singular spectrum analysis [*Vautard*, 1995].

[7] To further investigate possible evidence for a relation between ENSO variability and climate forcing, we plotted variance over time (sliding 31-year window) for the three ENSO-related reconstructions and instrumental Niño-3 record (Figure 3b). We also show variance plots from two coral records that correlate significantly with ENSO [*Cobb et al.*, 2003; D'Arrigo et al., submitted manuscript, 2004]. Figure 3c shows the variance of Niño-3 model estimates based on volcanic and solar forcing [*Mann et al.*, 2005], and

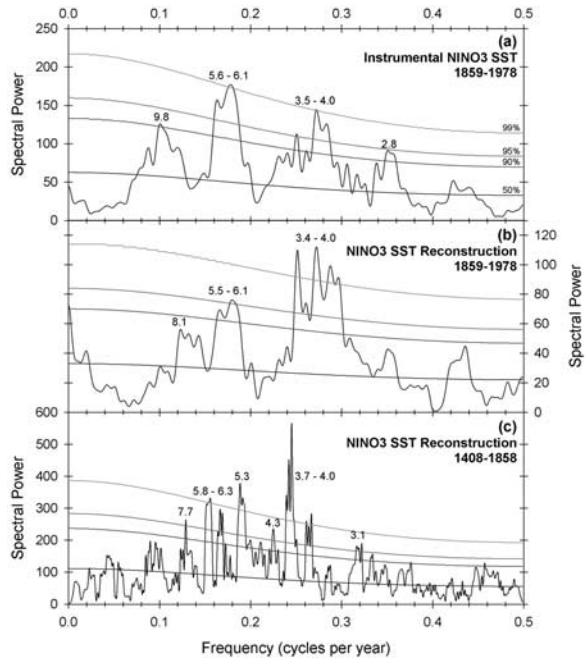

Figure 2. Multi-taper method spectral analysis [*Mann and Lees*, 1996] of instrumental (a) and reconstructed (b) Niño-3 SST over 1859–1978. Significance lines indicate 50, 90, 95 and 99% confidence limits. (c) Reconstruction spectrum for preinstrumental 1408–1858 period. Important peaks are labeled.

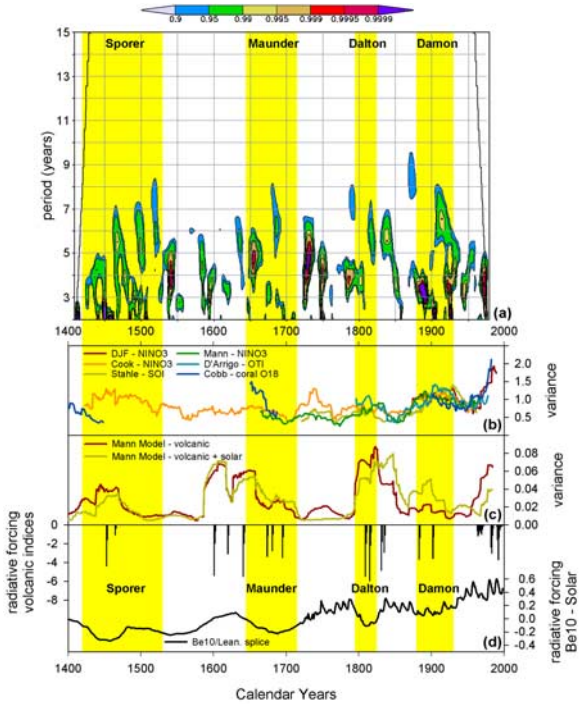

Figure 3. (a) Morlet wavelet analysis of Cook series. (b) Sliding 31-yr variance of 3 reconstructions and actual NINO3 record, coral O18 record [*Cobb et al.*, 2003], and coral tropical reconstruction (D'Arrigo et al., submitted manuscript, 2004) (normalized 1886–1977). (c) Sliding 31-yr variance of Niño-3 SST estimates of *Zebiak and Cane* [1987] model to estimate tropical forcing [*Mann et al.*, 2005]. Ensemble-mean response has less variance than individual realizations, representing average of many realizations of model's internal variability. Amplitude of internal variability averages to 0, leaving only estimated forced response. This results in a ~ factor of 5 scale mismatch between model and reconstructions (Figures 3b–3c). (d) *Crowley* [2000, also personal communication] forcing series. Volcanic series adjusted for tropical latitudes; there are uncertainties in past estimates of solar forcing.

Figure 3d shows time series of solar and volcanic forcing [*Crowley*, 2000, also personal communication]. The *Cobb* record, from the western fringe of the Niño-3 central Pacific region, shows intense ENSO activity during the early MM (mid 17th century) coinciding with a spectral peak in the Cook series (Figure 3a). These observations are in agreement with the *Mann et al.* [2005] (Figure 3c) study for this period, which indicates that low radiative forcing is associated with warm, "El Niño-like" conditions and increased variability in eastern tropical Pacific SSTs based on experiments using the *Zebiak and Cane* [1987] ENSO model forced with estimated changes in natural (solar + volcanic) radiative forcing over the past 1000 years. The Cook reconstruction is generally in good agreement with regards to some of these variance changes over time (e.g., higher variance in the early 19th and late 20th centuries; Figure 3b). Lower variability (the lowest on record for the series in fact), however, is observed in the Cook series during the later MM (late 1600s-early 1700s). Although the *Cobb* coral record and *Mann et al.* [2005] model simulations show higher variance in the early MM period (mid 17th century), they show decline in the later MM period, in agreement with the tree-ring data. Over the length of the Cook reconstruction (1408–1978) the variance is 0.40, decreasing to 0.31 during the MM (~1645–1715) [*Eddy*, 1976], and to 0.18 for the later MM (1690–1715). In the MBH00 reconstruction the variance is 0.25 for 1650–1715 vs. a long-term mean of 0.37. For the brief overlap with the ST98 series, the variance is 0.14 for 1706–1715 vs. a long term mean of 0.36. The early 1800s, another period of widespread cold conditions [e.g., *Mann et al.*, 1999], was associated with diminished solar irradiance (Dalton Minimum) [*Eddy*, 1977] and enhanced volcanic activity. Figure 3b indicates slightly higher ENSO variability in the early 1800s [but no strong spectral peak], followed by decreased variability in the middle 1800s, when other evidence suggests a breakdown in the ENSO teleconnection [*Mann et al.*, 2000; *Urban et al.*, 2000; D'Arrigo et al., submitted manuscript, 2004]. Reconstructed ENSO variance is also higher during two other solar minima (Sporer and Damon), which were also associated with increased volcanic activity (Figure 3b) [*Eddy*, 1976, 1977]. The above comparisons, along with previous studies [*Waple et al.*, 2002; *Adams et al.*, 2003; *Mann et al.*, 2005], suggest a connection between decreased (increased) radiative forcing and greater (lesser) ENSO variability via the thermostat mechanism of *Clement et al.* [1996]. The low variability evident in the present reconstruction during the later MM (latter 17th century and early 18th century) (Figure 3b) would appear to be less consistent with this mechanism, due to the decreased solar activity at this time. However, the model results also indicate low variability in the later MM, likely in association with a relative absence of negative volcanic radiative forcing events. Discrepancies between the present reconstruction and the model simulations are also observed. An example is the higher variability in the Cook series in the middle 1700s, a time not associated with anomalous forcing in the model (Figure 3). One possible explanation is that both ENSO intensity and its extratropical teleconnections were changing during such periods. In any case, it is clear that the ENSO/radiative forcing relationship is still not fully understood, and deserves further investigation through appropriate climate modeling experiments [e.g., *Collins*, 2004; *Mann et al.*, 2005]. Finally, it is interesting to highlight that the instrumental variance in recent decades exceeds the values of all three tree-ring reconstructions over their length, possibly reflecting a combination of natural radiative forcing and anthropogenic influences [*Clement et al.*, 1996].

4. Conclusions

[8] We have examined past ENSO variability using a new reconstruction of Niño-3 SST. The reconstruction is well verified and captures the dominant spectral properties in the instrumental record for the classical ENSO bandwidth. We thus consider this record to be a valid expression of ENSO variability with the caveats noted above. The longest such record of its kind, the Cook reconstruction extends information on Niño-3 SSTs back to the early 1400s. Comparison with other ENSO series shows remarkably good agreement in variance changes in recent centuries (Figure 3)]. This result appears to indicate stationarity in this aspect of ENSO

behavior between the equatorial Pacific and its teleconnection to subtropical North America, though other evidence does suggest some degree of breakdown in this teleconnection during certain periods, such as the mid 19th century [*Mann et al.*, 2000; *Urban et al.*, 2000; D'Arrigo et al., submitted manuscript, 2004]. We have also evaluated the Cook and other reconstructions for a proposed ENSO-radiative forcing connection. In general, ENSO variability appears to be somewhat modulated by external forcing - higher variance in the ENSO-related tree-ring and coral series coincides during some intervals with decreased radiative forcing, in broad agreement with previous coral [*Cobb et al.*, 2003] and modeling [*Mann et al.*, 2005] studies. One possible exception, however, is the low reconstructed variance during the later 17th to early 18th centuries, a period of low solar irradiance in the MM, considered to represent a "crucible" for understanding of climate change [*Rind et al.*, 2004]. Additional proxy investigations from the tropical Pacific and ENSO teleconnection regions, along with modeling studies, should further refine how ENSO amplitude has varied on a range of time scales.

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