Reconstructed Indonesian Warm Pool SSTs from Tree Rings and Corals: Linkages to Asian Monsoon Drought and ENSO

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Abstract

The West Pacific warm pool is the heat engine for the globe's climate system. Its vast moisture and heat exchange profoundly impact conditions in the tropics and higher latitudes. Here, September-November SST variability is reconstructed for the warm pool region (15°S-5°N, 110-160°E) surrounding Indonesia using annually-resolved teak-ring-width and coral $\delta^{18}O$ records. The reconstruction dates from AD 1782-1992 and accounts for 52% of the SST variance over the most replicated period. Significant correlations are found with ENSO and monsoon indices at interannual to decadal frequency bands. Negative reconstructed SST anomalies coincide with major volcanic eruptions, while other noteworthy extremes are at times synchronous with Indian and Indonesian monsoon drought, particularly during major warm ENSO episodes. While the reconstruction adds to the sparse network of proxy reconstructions available for the tropical Indo-Pacific, additional proxies are needed to clarify how warm pool dynamics have interacted with global climate in past centuries to millennia.

Introduction

Ocean-atmosphere variability associated with the equatorial Western Pacific warm pool impacts climate worldwide [*Wang and Xie*, 1998, *Barlow et al.*, 2002, *Sun,* 2003]. Tropical warm pool waters surrounding the Indonesian Maritime Continent feature some of the highest (>28.5°C) sea surface temperatures (SSTs) on earth. Heat and water vapor are transported from the warm pool to higher latitudes via deep convective clouds and the prevailing atmosphere-ocean circulation. Even small changes in warm pool SST can have substantial consequences for global climate (e.g. for tropical cyclone activity; *Emanuel*, 2005). Warm pool conditions, modulated by the El Niño-Southern Oscillation (ENSO) system, reverberate around the globe. Recent central and southwest Asian drought, for example, was attributed to an enhanced signal in the warm pool region associated with ENSO [*Barlow et al.*, 2002]. In turn, shifts in warm pool SST can modulate ENSO variability [*Sun*, 2003]. However, these relationships are very complex and a partial decoupling of warm pool conditions from the ENSO system can occur due to a variety of influences [*Schneider*, 1998, *Hoerling, et al.* 2001].

Increasingly, paleoclimatic records are being applied to extend our understanding of tropical climate variability, including ENSO, into the past. For example, reconstructions based primarily on tree rings have been developed for ENSO indices [*Stahle et al.*, 1998, *Mann et al.*, 2000, *D'Arrigo et al.*, 2005a]. However, much of the data on which these reconstructions are based originate from subtropical North America, and therefore rely on teleconnected relationships with ENSO rather than a direct influence from the tropics.

Coral-based climate records have been used to reconstruct ENSO-related changes in SST and salinity in the Indo-Pacific [*Charles et al*., 1997, *Cole et al*., 2000, *Evans et al.,* 2002, Cobb *et al*., 2003, *Linsley et al*., 2004] and for the West Pacific warm pool during glacial and interglacial time periods [*Tudhope et al*., 2001]. Coral records have also been related to Pacific decadal variability [*Linsley et al*., 2000, *Cobb et al*., 2001, *Evans et al*., 2001, *D'Arrigo et al*., 2005b], and used to assess dynamics between the Indian and Pacific Oceans [*Cole et al*., 2000, *Charles et al*., 2003]. However large-scale, continuous tropical climate reconstructions are still relatively rare [*Evans et al.,* 2002, *Wilson et al*., submitted]. Below we describe a reconstruction of Indonesian warm pool SSTs that is derived from tree-ring and coral proxies, and evaluate its relation to other features of the tropical climate system.

Warm pool SST reconstruction from tree rings and corals

Monthly gridded SST data were extracted from the *Kaplan et al.* [1998] data set for the warm pool region in the vicinity of Indonesia, and averaged over the area bounded by the coordinates 15°S-5°N; 110°-160°E (i.e. an average of 40 grids - **Figure 1**). This area was selected because it encompasses much of the warm pool region associated with the Indonesian Low (a center of action of the ENSO system), while also optimizing the signal between the SST and proxy data. It should be noted, however, that the spatial extent of the warm pool waxes and wanes for a variety of reasons (http://earthobservatory.nasa.gov/Study/WarmPool/), and that here we reconstruct SSTs for an area within the warm pool region rather than for the warm pool per se.

A data set of 12 teak (*Tectona grandis*) ring-width records has been developed for Indonesia over the past two decades (**Table 1**, *D'Arrigo et al.*, 1994, *Cook et al.*, 2000). The teak chronologies were processed by detrending the raw ring-width series, after they had been power transformed [*Cook and Peters*, 1997], with negative exponential or linear negative/zero slope functions. Many of these teak records correlate significantly with indices of ENSO, consistent with the tendency for warm ENSO events to be linked with drought and decreased teak growth in Indonesia [*D'Arrigo et al.*, 1994, *Cook et al.*, 2000]. One of the teak records, Saradan, was previously included in a tree-ring reconstruction of the Southern Oscillation Index (SOI; *Stahle et al.*, 1998). Many of the teak ring-width series represent new or updated chronologies, and due to low replication at some of the sites (**Table 1**) and the close proximity of these sites, regional clusters of tree-ring data were composited together to develop more robust mean functions. Screening the teak chronologies against the gridded warm pool SST data identified four chronologies (two of which are composites - **Figures 1 and 2, Table 1**) that express significant (99% confidence limit (C.L.)) correlations, at high frequencies, with the instrumental data and were considered for further analysis.

In the vicinity of the Western Pacific warm pool (from Indonesia, New Guinea and the Cape York region of Australia), there exist nine 100-year long, annually resolved coral records (4 skeletal $\delta^{18}O$ and 5 calcification series) measured from massive *Porites* with a maximum age uncertainty of ± 2 years in their early portions. Of these, the four $\delta^{18}O$ records (annualized but otherwise unprocessed) showed significant high frequency

correlations (99% C.L.) with warm pool SSTs and were selected for use in this study (**Figure 1**).

As with the teak chronologies, these coral records - from Bunaken (Sulawesi Sea) and Lombok Strait [*Moore*, 1995, *Charles et al.*, 2003]; and Laing Island and Madang Lagoon (New Guinea, *Tudhope et al.*, 2001) - demonstrate significant relationships with ENSO, but are also subject to local effects; it is important to note that we are only reconstructing SSTs rather than ENSO or other indices specifically.

Reflecting the general spatially heterogeneous signal of SSTs through our defined warm pool grid, the Lombok series is more sensitive to easternmost Indian Ocean conditions, while the Bunaken, Laing and Madang sites display strong correlations with both warm pool SSTs and Darwin, Australia sea-level pressure (SLP), and are sensitive to local as well as regional-scale western Pacific conditions (**Figures 1 and 2**; *Moore*, 1995; *Tudhope et al.*, 2001). We should note, however, that coral isotopic $\delta^{18}O$ portrays a mixture of temperature and water composition (salinity) changes - although in the warm pool these variables often correlate positively with each other since most of the rainfall is related to deep atmospheric convection consequent on heating from below [*Charles et al.*, 2003, *Lough*, 2004]. Our own analyses (not shown) indicate that the relationships between the coral $\delta^{18}O$ records, SST and salinity are reasonably consistent at the frequencies defined herein, implying that temperature is the dominating control on $\delta^{18}O$ for those records used.

To try and identify potential biases in the frequency domain from conflicting influences of SST and salinity, the correlations undertaken to screen the data were calculated for three frequency bands (<10, 10-30 and > 30 years - **Figure 1**). For the coral records, the sign of the correlations is the same at each frequency band, with the strongest correlations generally at lower frequencies. We should note though that when the degrees of freedom are corrected for 1st order autocorrelation in the smoothed series [*Dawdy and Matalas* 1964], correlations at time-scales >30-years are not significant even at the 90% C.L.. However, at the mid-frequencies (10-30 years), significant correlations (> 90% C.L.) are noted for Lombok, Bunaken and Laing. The frequency-dependent correlations derived for the tree-ring data are more variable, suggesting that more care is needed in using these (land-based) data for a reconstruction of warm pool SSTs. This is addressed in more detail below.

Due to the relatively small number of proxy time series and the relatively low inter-series correlations (**Table 2**), rather than using principal component regression, stepwise multiple regression (F-to-enter = 0.05; F-to-remove = 0.10) was used to develop the reconstruction. This approach allows only those proxy series that most significantly represent the instrumental data to enter the regression model. The tree-ring and coral data were input as potential predictor series in the regression. Only those series that most significantly correlated with the WP SST series entered the final model. Calibration trials (not shown) indicated that the September-November season optimized the SST signal in the combined proxies. These autumn months are an important time for reconstructing

SST because they fall within the June to November period when monsoon rainfall over much of Indonesia is most strongly impacted by ENSO, and when this relationship is most spatially coherent [*Aldrian and Susanto*, 2003, *Chang et al.*, 2004].

A variant of a nesting procedure [e.g. Meko 1997, *Cook et al.,* 2002] was employed to maximize the length of the reconstruction. Using this method, iterative stepwise regression-generated nested models of different lengths (due to the loss of the shorter series leaving the data matrix) were generated and the relevant sections spliced together following normalization and scaling to the mean and standard deviation of the most replicated nest. Two nested models were developed, beginning in 1782 (LOM and SAKLA), and 1860 (BUN, LOM and SAKLA); with a further model to extend the reconstruction to 1992 (LNG and SAKLA). The final nest reconstructions are effectively linear weighted averages of the original series that entered that particular nest model.

Calibration-verification statistics commonly used in dendroclimatology [*Cook and Kairiukstis*, 1990] were performed separately for each nest and utilized to quantify the robustness of the reconstruction over time. These statistics are the Reduction of Error (RE), Coefficient of Efficiency (CE), Product Means (PM), Sign Test (ST), and Pearson's correlation coefficient [*Cook and Kairiukstis*, 1990]. A split period calibration-verification scheme was applied over the periods 1885-1936 and 1937-1989, with the final reconstruction based on the full calibration model from 1885-1989. The full spliced reconstruction time-series (1782-1992) was scaled (same mean and variance - [*Esper at al*. 2005]) to the instrumental data over the 1885-1989 period to account for the possible

bias from using OLS regression for calibrating linear relationships, which results in predicted data with lower variance than the original instrumental data [von Storch et al. 2004].

The reconstruction and associated calibration and verification results are presented in **Figure 3** and **Table 3** respectively. Due to the stepwise approach used to develop the reconstruction, some of the proxy series, despite being significantly correlated with warm pool SSTs, were not included in the final model. The statistical results, which include positive RE and CE values (indications of predictive model skill), reveal that the model is reasonably robust over the full length of the record. Both the CE and Sign Test results are weak for the earliest nest but the RE is still positive, indicating some useful model skill. In addition, and perhaps most importantly due to the weak mid-to-low frequency correlations for the tree-ring data (**Figure 1**), there is no significant trend in the model residuals for the various nests based on either the Durbin-Watson test statistic or the linear trend in the model residuals (**Table 3**). The reconstruction (1782-1992) explains 52% of the variance for the most replicated (1860-1989) nest, with this value dropping to 30% prior to this period (**Table 3**). As the proxy series are inter-correlated (**Table 2**), we tested for potential multicollinearity using the variance inflation factor (VIF; Fox 1997). All VIF values (not shown) are well below the defined threshold of Fox (1997), indicating that the amount of explained variance was not artificially inflated due to multicollinearity [*Cook et al.*, 1994]. It should be noted, however, that the coherence between the instrumental data and the reconstruction weakens markedly prior to the mid 1870s (**Figure 3b**). This may partly reflect the 'quality' of the instrumental data, which is

based on relatively few observations during this time [*Kaplan et al.*, 1998]. Some additional confirmation of the earlier period of the reconstruction, however, is provided below through comparison with other climate records. For example, **Figure 3c** compares the entirely independent coral-based tropical temperature reconstruction of Wilson et al. (submitted), which shows agreement with the warm pool reconstruction at lower frequencies as well as expressing a common response to some volcanic events (see later).

Warming is evident over the past century in both the instrumental and reconstructed warm pool series (**Figure 3a -** both series increase by 0.2°C/100 yrs over the 1856-1992 period). Similarly, warming has been observed for Indonesia [*Harger*, 1995] and over the tropics (30°S-30°N) as a whole (Wilson et al. submitted, **Figure 3c**), although over the same period, the rate of increase of mean tropical annual SSTs is marginally greater at 0.3°C/100 yrs. The famed 1976 climate shift is not clearly evident in either the actual or reconstructed warm pool SST records for the September-November season analyzed herein, despite its presence in a number of climate indices over the equatorial Indo-Pacific as well as the Pacific basin [*Graham*, 1994, *Deser et al.*, 2004]. This finding is consistent with some analyses of Pacific climate that indicate little or no climatic shift at this time over Indonesia [*Graham*, 1994]. Despite the reasonable empirically derived modeling of the warm pool SSTs, we should note that the reconstruction may reflect an unquantifiable salinity bias from the δ^{18}O records, as well as inconsistencies with regards to trend in some of these series [*D'Arrigo et al.*, 1994, *Moore*, 1995 - see **Figure 2**]. The multi-proxy approach that we have used, however, should minimize these biases to some degree.The correlations with local and large-scale SSTs indicate that the proxies are

doing well at correlating the large-scale climate signal. This was also observed by Moore (1995) in his thesis and in other relevant coral papers cited herein. The verification statistics would also fail if local site effects dominated the signal in the proxies. Although corals can record changing temperature, light and salinity effects as they grow to the surface, this is really only an issue for corals living in very shallow water that grow up to the intertidal zone (where the gradients are very steep). The corals used in this study were all substantially sub-tidal even when cored and did not grow up through any major vertical gradients in their lifespan.

Spatial correlation maps compare the actual and reconstructed warm pool series to the global SST field for the instrumental period (**Figure 4;** *Kaplan et al.*, 1998). Over the calibration period, the proxy estimates, based on both unfiltered and first differenced data, capture the large-scale features seen in the instrumental warm pool SST correlation field, which is dominated by the characteristic ENSO pattern. Interestingly, correlations with Indian Ocean SSTs are only significant for the first-difference comparisons (**Figures 4c and 4d**), suggesting some differences in low-frequency signals between the Indian Ocean and Indonesian warm pool regions. Evaluation of the instrumental data and reconstruction with the global SLP field (Hadley Centre data set, *Basnett and Parker*, 1997) shows positive correlations over the eastern Pacific, with pronounced negative correlations over Asia in areas impacted by the Australian-Asian and Indian monsoons (**Figure 5**). These relationships are consistent with the tendency for the Indonesian Low

pressure cell to be associated with greater rainfall and warmer SSTs over these regions [*Allan*, 2000].

Multi-taper method [*Mann and Lees*, 1996)] spectral analysis of the warm pool reconstruction reveals significant spectral peaks at >50 years, and in the ENSO band at 5.3-6.3 years (**Figure 6a**). The ~5-6 year spectral mode is consistent with those found in previous instrumental studies of ENSO [e.g. *Tourre et al.*, 2001] and in coral data from across the Indo-Pacific [*Moore*, 1995, *Cole et al.*, 2000, *Cobb et al.*, 2001, *Charles et al.*, 2003] and the tropics as a whole [*Wilson et al.* submitted]. Coherency spectral analysis was performed between the warm pool reconstruction and instrumental warm pool SSTs, Niño-3 SSTs, and Darwin, Australia SLP (**Figures 6b-d**). All three analyses demonstrate highly significant (95% level or higher) coherency at periods of ~2-10 years. The comparison of instrumental and reconstructed warm pool SSTs (**Figure 6b**) reveals coherency that extends across much of this interval, whereas the coherency is concentrated at ~ 4-5 years for Niño-3 SST (**Figure 6c**) and at ~ 3 years for Darwin SLP (**Figure 6d**).

Based on the range of variability shown in these spectral results, we divided the warm pool SST reconstruction into three filtered frequency bands (<10, 10-30 and >30 years) for further analysis. **Table 4** presents correlations between the actual and reconstructed warm pool SST series for these frequency bands and a suite of relevant instrumental and proxy climate indices for the tropical Indo-Pacific and vicinity. We focus herein on results for the two higher-frequency bands, and only include the >30 year results for

comparison with a coral-based temperature reconstruction for tropical latitudes [*Wilson et al.*, submitted]. Correlations using the instrumental warm pool SST data are significant (99% C.L.) with instrumental ENSO indices for the past century, as well as with the PDO and an Indian monsoon rainfall index, although with the latter indices, the correlations are weak and non significant at the 10-30 year time-scale (**Table 4a**, *Sontakke and Singh*, 1996). Similar results are obtained using the warm pool reconstruction, although correlations with the Pacific Decadal Oscillation (PDO) appear stronger than for the warm pool SST data (r = -0.49 vs -0.38 respectively; these two correlations are not statistically different from each other; **Table 4b**). Correlations are also significant with several proxy reconstructions of ENSO (**Tables 4c and 4d,** *Stahle et al.*, 1998, *Mann et al.*, 2000, *D'Arrigo et al.*, 2005a). It is perhaps noteworthy to highlight the high correlations with the independent tropical temperature reconstruction noted above (**Table 4**; *Wilson et al.,* submitted). However, observe that correlations are negative at higher frequencies and positive at lower frequencies (see below).

Warm pool SST reconstruction and extreme climate events

The warm pool reconstruction shows a pronounced decade-long cool period between ~1808 and 1818 (**Figure 3**). This period corresponds to, and is likely forced by two major volcanic episodes: an unknown event in 1809 [*Dai et al.*, 1991, inferred from sulfate data from Greenland and Antarctic ice cores] and the eruption of Tambora, Indonesia in April, 1815 [*Simkin and Siebert*, 1994]. Recent ice core results more precisely date the former eruption, which of the two, shows the greatest impact on reconstructed warm pool SSTs, at March-July, 1808 [*Cole-Dai and Thompson*, unpublished data]. Both of these eruptions

produced highly significant cooling over some tropical regions, including the warm pool area, according to an early data set of global marine air temperature for 1807-1827 [*Chenoweth*, 2001]. Annual marine air temperature anomalies in the tropics (20°N-20°S) were -0.84 (+/- 0.20°C) in 1809 and -0.81 (+/- 0.17°C) in 1816 [*Chenoweth*, 2001]. Reconstructed warm pool anomalies from 1809-1812 are -0.28, -0.73, -0.76 and -0.79°C; and -0.30, -0.51 and -.51°C for 1815-17 (95% standard error confidence range for each annual value is (+/- 0.46°C). An ENSO warm event ~1817 may have contributed to some of the cooling after Tambora [*Ortlieb*, 2000, *Chenoweth*, 2001]. The cooling observed by *Chenoweth* [2001] during the early 1800s supports the case that much of the shift in the warm pool reconstruction is due to temperature rather than salinity.

Elsewhere in Asia, pre- and post-monsoon temperature reconstructions for Nepal show conditions around the time of the Tambora event to be the coldest in the past six centuries [*Cook et al.*, 2003]. Madras, India temperatures were also cold, falling from above to well below average by June 1815 [*Chenoweth*, 2001]. There are also pronounced negative anomalies in the warm pool reconstruction following other volcanic events, including the Coseguina, Nicaragua (1835; reconstructed values in 1836-1838 are -0.46, -0.49, and -0.59°C) and Krakatoa, Indonesia eruptions (1883; values for 1883-1885 are -0.11, -0.32, and -0.64°C; **Figure 3,** *Simkin and Siebert*, 1994). Several ENSO events in the 1830s [*Ortlieb*, 2000] could also help explain the cold reconstructed SSTs around the time of the Coseguina event.

In addition to volcanism, the warm pool SST reconstruction shows close correspondence with ENSO and monsoon rainfall indices and extremes (**Table 4, Figure 7** below).

However, it appears insensitive to the severe 1789-1793 episode of warm ENSO conditions and reported monsoon drought over India and Java (reconstructed SST value for mean of 1789-1793 = -0.05). There is a more negative anomaly during the major 1877 ENSO and monsoon drought episode [*Grove*, 1998; -0.42°C].

The warm pool reconstruction - after high pass filtering (10 years) and normalizing - was also compared to a listing of east monsoon droughts for Java, Indonesia, compiled from historical sea salt records from Dutch estates (1844-1976, **Figure 7**, *Quinn et al.*, 1978). This comparison allows some additional evaluation of the reconstruction using land-based historical data. During periods when ENSO variability is low (based on *D'Arrigo et al.*, 2005a Niño-3 SST reconstruction), there appears to be little relationship between drought events [*Quinn et al.*, 1978] and warm pool reconstructed SSTs. For example, over the periods ~1844-1875 and ~1929-1960 - periods with relatively low interannual variance in ENSO (**Figure 7b**; *Allan*, 2000, *D'Arrigo et al.*, 2005b) - the median normalized SST departures are 0.03 (standard deviation 0.84, 9 cases) and -0.04 (standard deviation 1.37, 9 cases) respectively. However, the reconstruction is more consistent with the sea salt record from 1877-1926, a period of greater variability with several relatively strong ENSO warm events, when the reconstructed normalized departure is -1.11 (standard deviation 0.80, 17 cases). Agreement during the relatively weak early and late periods is better for some individual ENSO events - e.g. in 1941 when the normalized SST departure is -2.14. The year 1868, coincident with a moderate to strong ENSO warm event [*Ortlieb*, 2000], has one of the years of lowest reconstructed warm pool SSTs on record; however it is not listed as a drought year in the historical sea salt information.

There is also good agreement in the recent instrumental period when the warm pool reconstruction is compared to an instrumental drought index for Java and vicinity (Palmer Drought Severity Index or PDSI; Dai *et al.* 2004; see *D'Arrigo et al.* 2006 for a description of a PDSI reconstruction for Java, Indonesia) *Dai et al.,* 2004). These results suggest that there is greater coupling of Javan drought and warm pool SSTs during periods of strong ENSO variability.

With regards to other tropical proxies, significant departures are also evident in the Malindi coral $\delta^{18}O$ record from the far western Indian Ocean during both the unknown and Tambora early 1800s episodes, as well as other volcanic events [*Cole et al.,* 2000]. Responses to volcanism are also noted in an independent coral-based reconstruction of tropical SSTs [*Wilson et al.,* submitted, **Figure 3c**]. This latter record shows significant cooling in tropical SSTs related to the 1808 and 1883 events. Little response is noted however, to the 1815 event, possibly because the ENSO warm episode ~1817 may have counteracted some of the cooling after Tambora in some areas of the tropics [*Ortlieb,* 2000, *Chenoweth,* 2001]. Most of the coral records utilized by *Wilson et al.* are situated in the central Pacific (although Malindi was also included), and therefore express a strong positive response to high frequency ENSO variability. The relationship between the warm pool and tropical temperature reconstructions is thus inverse at high frequencies (despite the common response to some volcanic events - **Figure 3c**), due to their inverse high-frequency response to ENSO (**Table 4**). The mid to high frequency information in the warm pool reconstruction, at least recently, appears to also be controlled by ENSO, and/or PDO-related dynamics. However, the fact that the low frequency (>30 year) mode

is positively correlated between the warm pool and tropical temperature reconstructions begs the question as to what is the ultimate control (possibly solar or anthropogenic forcing) at these secular frequencies.

Summary

We have described a reconstruction of SST for the Indonesian warm pool region based on tree-ring and coral data. This study is among the first to reconstruct high-resolution tropical climate variability based on combined terrestrial and marine proxies from the equatorial tropics. Both proxies contribute important, independent information to the reconstruction. The reconstruction is robust, capturing 52% of the instrumental variance over the most replicated period, with significant calibration and verification statistics. It demonstrates both interannual and decadal fluctuations that appear related to ENSO and/or Pacific decadal variability. There is highly significant coherency between the reconstruction, instrumental warm pool SSTs, Niño-3 SST and Darwin SLP data. When separated into three frequency bands, we observe correspondence between the warm pool series and both instrumental and proxy indices of Indo-Pacific and Pacific basin climate. Coincidence between anomalously cold warm pool temperatures in the early 1800s and major volcanic events confirms previous findings of pronounced lowering of tropical marine air temperatures in early instrumental observations [*Chenoweth*, 2001], and helps quantify the impact of these events on the warm pool region. There is some agreement between anomalous years in the reconstruction and those found in records of Asian monsoon rainfall during major ENSO episodes. However, we caution that the reconstruction is based on relatively few proxy series and extends back for little more

than two centuries. There are efforts underway to extend the living teak record back in time using subfossil wood, although the degree to which this is possible is constrained by the date at which teak was introduced to Indonesia (possibly as much as 1000 years ago). Living corals are also limited in their longevity, although there has been success using subfossil samples to reconstruct selected time slices [e.g. *Cobb et al*. 2003]. Trends are also somewhat uncertain as there are local factors at play in addition to the regional signals. Consequently, additional records are needed to improve our understanding of the behavior of the Indonesian warm pool and the factors, including ENSO, that impact its variability.

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Table and Figure Captions

Table 1: Description of the teak ring-width chronologies and coral series. Mean r = is the mean inter-series correlation between the series as derived from program COFECHA [*Holmes*, 1983]. SAKLA = composite of KLA and SAR; RBGB = composite of RAN, BEK, GUB and BIG.

Table 2: Correlation matrix between the teak and coral unfiltered series that express a significant relationship with warm pool SSTs. Upper value in each box is the correlation, and the lower value the significance. Correlations not significant at the 95% C.L. are shaded.

Table 3. Calibration and verification statistics for nested reconstruction models (these results can be used to assess the skill gained by the addition of each proxy predictor). r = correlation coefficient; aR^2 = square of the multiple correlation coefficient following adjustment for loss of degrees of freedom; RE = Reduction of Error statistic; CE = Coefficient of Efficiency statistic; RE and CE values greater than zero indicate good model skill; there is no significance level per se [*Cook and Kairiukstis*, 1990]. PM = Product means test [*Fritts*, 1991]; ST = Sign test [*Fritts*, 1976], showing ratio of agreement/disagreement; values are significant at the 95% confidence level except those that are highlighted by shading; DW = Durbin-Watson statistic for residual autocorrelation; Linear r = correlation of linear trend in residual series. The proxy variables included in each model nest are also listed.

Table 4. Correlations of warm pool temperature actual and reconstructed data with various instrumental and proxy climate indices for three frequency bands (see text). Correlations with Niño-3 SSTs [*Kaplan et al.*, 1998)] PDO [*Mantua et al.*, 1997], and All-India monsoon index [*Sontakke and Singh*, 1996] are indicated. Niño-3 season = September-November; PDO season = August-October. Proxy ENSO reconstructions: Cook: *D'Arrigo et al.*, 2005a, Stahle: *Stahle et al.*, 1998, and Mann: *Mann et al.*, 2000. Sign of the *Stahle* record has been inverted. TROP = coral tropical reconstruction [*Wilson et al.*, submitted]. The degrees of freedom have been adjusted to account for the 1st order autocorrelation in the time series [Dawdy and Matalas 1964]. The resultant significance of the correlations is denoted by *, ** and *** for the 90%, 95% and 99% confidence limits respectively.

Figure 1. Map of Indonesian warm pool region (15°S-5°N, 110-160°E) showing locations of four tree-ring [*D'Arrigo et al.*, 1994] and four coral δ^{18}O records [*Moore*, 1995; *Charles et al.*, 2003, *Tudhope et al.*, 2001] that were used as candidate predictors for the warm pool reconstruction. These coral records are independent of those used in a recent reconstruction of tropical temperatures (see text; *Wilson et al.*, submitted). The chronologies of individual corals are based on annual banding in skeletal density and geochemistry. The excellent zero-lag match between the coral δ^{18}O records and ENSO indices throughout their length suggests that they are precise to within a year, but, conservatively, we could assess the maximum age uncertainty as ±2 years over the length of each record.

The values show the correlations, calculated over 1885-1989, between the proxy and the September-November season of the warm pool SSTs for three frequency bands (<10, 10-30 and > 30 years). The degrees of freedom have been adjusted to account for the 1st order autocorrelation in the time-series [Dawdy and Matalas 1964]. The resultant significance of the correlations is denoted by *, ** and *** for the 90%, 95% and 99% confidence limits respectively.

Figure 2. Teak and coral records that correlate significantly with warm pool SSTs (**Figure 1**). The series were normalized to the common period (Note: the sign of the coral series is reversed). The smoothed function is a 15-year spline. Upper (lower) panel - proxy records used (not used) for the warm pool reconstruction.

Figure 3. The warm pool reconstruction. **A.** Actual (red) and reconstructed (black) September-November Indonesian warm pool SSTs. Volcanic episodes are indicated with arrows; see text. The reconstructed values have been scaled (same mean and variance - [Esper at al. 2005]) to the instrumental data over the 1885-1989 period to account for the possible bias from using OLS regression for calibrating linear relationships, which results in predicted data with lower variance than the original instrumental data [von Storch et al. 2004]**.** The regression of the proxies against SST calibrates the time-series to SST values **B.** Running 31 year correlation plots between the reconstruction and instrumental data. Correlations are calculated for both the unfiltered data (green) and 1st differenced transforms (blue). **C**. and **D**.: As in **A** and **B**, but for Wilson et al. (submitted) tropical SST reconstruction.

Figure 4. Spatial correlation fields (1885-1989) of actual (A and C) and estimated (B and D) Sept-Oct Indonesian warm pool and global SSTs [*Kaplan et al.*, 1998]. Correlations are slightly higher for this season than Sept-Nov. A and B generated using unfiltered data, while C and D were calculated from 1st difference transformed time-series.

Figure 5. Spatial correlations (1885-1989) of warm pool instrumental (A) and reconstructed (B) Sept-Oct warm pool SSTs with Hadley Centre SLP [*Basnett and Parker*, 1997].

Figure 6: Multi-taper method (MTM, *Mann and Lees*, 1996) spectral analysis of warm pool SST reconstruction (A) and coherency spectra with three instrumental climate indices (B-D).

Figure 7: Comparison between the warm pool reconstruction and the sea salt drought record [*Quinn et al.*, 1978]. **A.** High pass filtered (10 year) normalized warm pool reconstruction. The sea salt events are highlighted with circles and colored relative to the standard deviation values of the coincident year in the reconstruction. Dry years for the recent period are defined using Palmer Drought Severity Index (PDSI) data   averaged over Java and vicinity [*Dai et al.*, 2004]. Only extreme (< -3) years are shown. **B.** Moving 31-year variance windows of the *D'Arrigo et al.* [2005a] Niño-3 SST reconstruction and instrumental data.

Site Name	Site code	Latitude	Longitude	Full period	No of series	Mean r	period > 10 series
Individual Chronologies							
Randublatung	RAN	7.06 S	111.22 E	1925-2004	13	0.47	1938-2004
Bekutuk	BEK	7.07 S	111.22 E	1668-2004	20	0.40	1834-2004
Gubug Payung	GUB	7.05 S	111.29 E	1864-2004	18	0.34	1879-2004
Pangaran Natural Forest	PGR	7.29 S	111.48 E	1815-2004	9	0.46	-
Donoloyo Cagar Alam	DNLY	7.52 S	111.12 E	1714-2004	13	0.39	1746-2004
Pagerwunung Darupono	DNRP	7.02 S	110.16 E	1776-2004	19	0.39	1820-2004
Klangon Natural Forest	KLA	7.30 S	111.47 E	1707-2004	15	0.49	1812-2004
Saradan	SAR	7.29 S	111.42 E	1689-2000	30	0.46	1812-2000
Sepanjang	SPJ	7.00 E	115.30 E	1760-2000	35	0.49	1834-2000
Bigin	BIG	7.10 S	111.34 E	1839-1995	20	0.59	1853-1995
Muna	MUN	5.30 S	123.00 E	1564-1995	39	0.42	1673-1994
Cepu	CEP	7.30 S	110.00 E	1870-1991	13	0.45	1896-1991
Composite Series							
SAKLA	SAKLA	-	-	1689-2004	45	0.46	1759-2004
RBGB	RBGB	-	-	1668-2004	71	0.36	1834-2004
Coral Series							
Lombok Strait	LOM	8.15 S	115.30 E	1782-1990	-	-	-
Bunaken	BUN	1.30 N	124.50 E	1860-1989	-	-	-
Madang Lagoon	MAD	5.13 S	145.49 E	1881-1992	-	-	-
Laing Island	LNG	4.09 S	144.53 E	1885-1992	-	-	-

Table 1.

	SAKLA	DNRP	RBGB	LOM	BUN	MAD	LNG
DNLY	**0.35**	**0.23**	0.06	**-0.24**	**-0.26**	**-0.36**	**-0.35**
p	*0.00*	*0.02*	*0.54*	*0.02*	*0.01*	*0.00*	*0.00*
SAKLA		**0.60**	**0.39**	-0.16	**-0.18**	-0.15	**-0.20**
p		*0.00*	*0.00*	*0.10*	*0.07*	*0.12*	*0.04*
DNRP			**0.62**	-0.14	**-0.26**	-0.10	**-0.22**
p			*0.00*	*0.14*	*0.01*	*0.31*	*0.02*
RBGB				0.08	**-0.21**	-0.09	**-0.24**
p				*0.44*	*0.03*	*0.38*	*0.01*
LOM					**0.32**	**0.34**	**0.33**
p					*0.00*	*0.00*	*0.00*
BUN						**0.39**	**0.65**
p						*0.00*	*0.00*
MAD							**0.64**
p							*0.00*

Table 2.

Splice Period	Calibration			Verification					
	Period	**r**	**aR2**	**Period**	**r**	**RE**	**CE**	**PM**	**ST**
1990-1992	**1885-1936**	0.55	0.30	**1937-1989**	0.46	0.30	0.06	4.19	36/17
	1937-1989	0.60	0.33	**1885-1936**	0.47	0.37	0.19	3.67	32/20
	1885-1989	0.58	0.33						
	DW = 1.75; Linear r = -0.09			Variables: LNG, SAKLA					

	Period	**r**	**aR2**	**Period**	**r**	**RE**	**CE**	**PM**	**ST**
1860-1989	**1885-1936**	0.70	0.46	**1937-1989**	0.66	0.51	0.34	4.50	43/10
	1937-1989	0.73	0.50	**1885-1936**	0.66	0.56	0.44	3.89	37/15
	1885-1989	0.73	0.52						
	DW = 1.87; Linear r = -0.05			Variables: BUN, LOM, SAKLA					

	Period	**r**	**aR2**	**Period**	**r**	**RE**	**CE**	**PM**	**ST**
1782-1859	**1885-1936**	0.57	0.30	**1937-1989**	0.37	0.25	0.00	3.42	40/13
	1937-1989	0.54	0.27	**1885-1936**	0.42	0.30	0.10	3.89	31/21
	1885-1989	0.56	0.30						
	DW = 1.64; Linear r = 0.12			Variables: LOM, SAKLA					

Table 3.

A. Instrumental correlations - 1900-2000

	NINO3	PDO	ALL India
<10	-0.77***	-0.38***	0.37***
10-30	-0.64***	-0.26	0.23

B. Reconstruction correlations - 1900-1992

	NINO3	PDO	ALL India
<10	-0.60***	-0.49***	0.32***
10-30	-0.49**	-0.50**	0.34

C. Reconstruction correlation - 1900-1976

	Cook	Stahle	Mann	Trop
<10	-0.57***	-0.63***	-0.44***	-0.63***
10-30	-0.46**	-0.51**	-0.45*	-0.44*
>30	–	–	–	0.88

D. Reconstruction correlation - 1782-1976

	Cook	Stahle	Mann	Trop
<10	-0.41***	-0.47***	-0.27***	-0.38***
10-30	-0.24	-0.35**	-0.22	0.09
>30	–	–	–	0.56

Table 4.

Figures
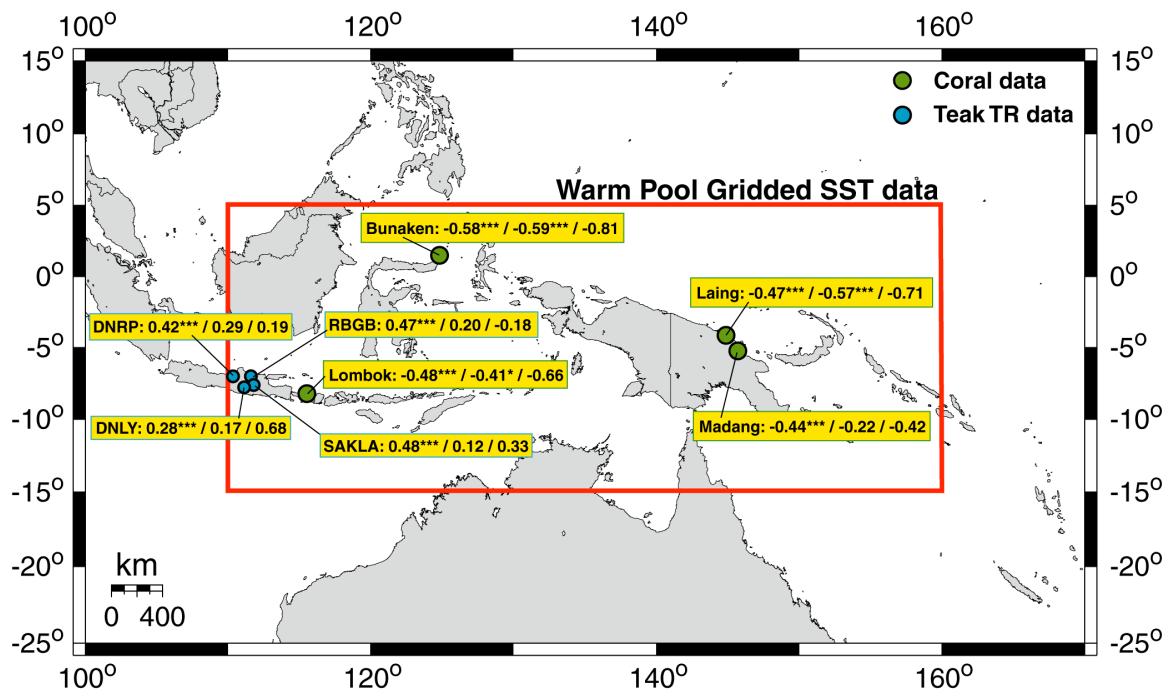
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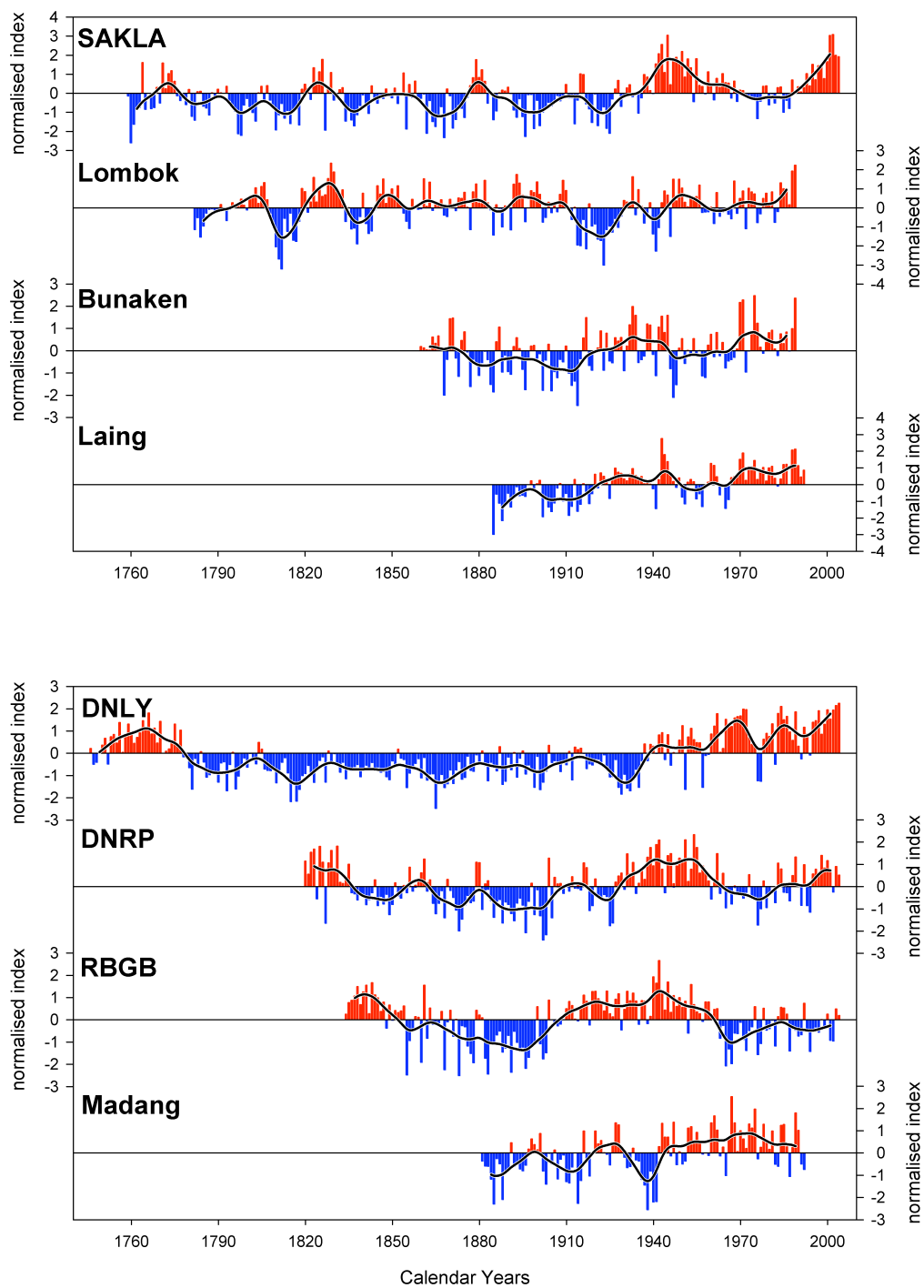
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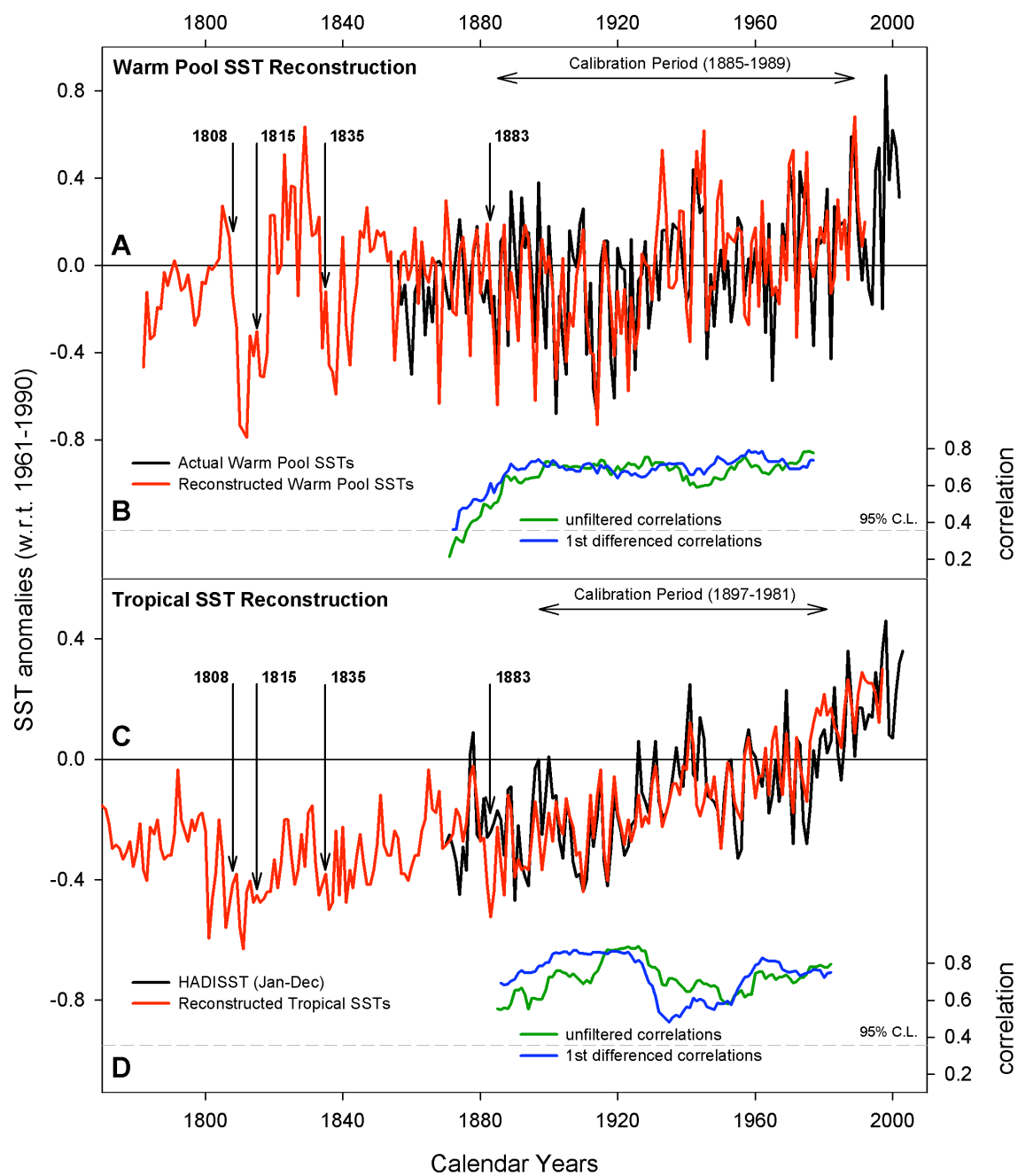
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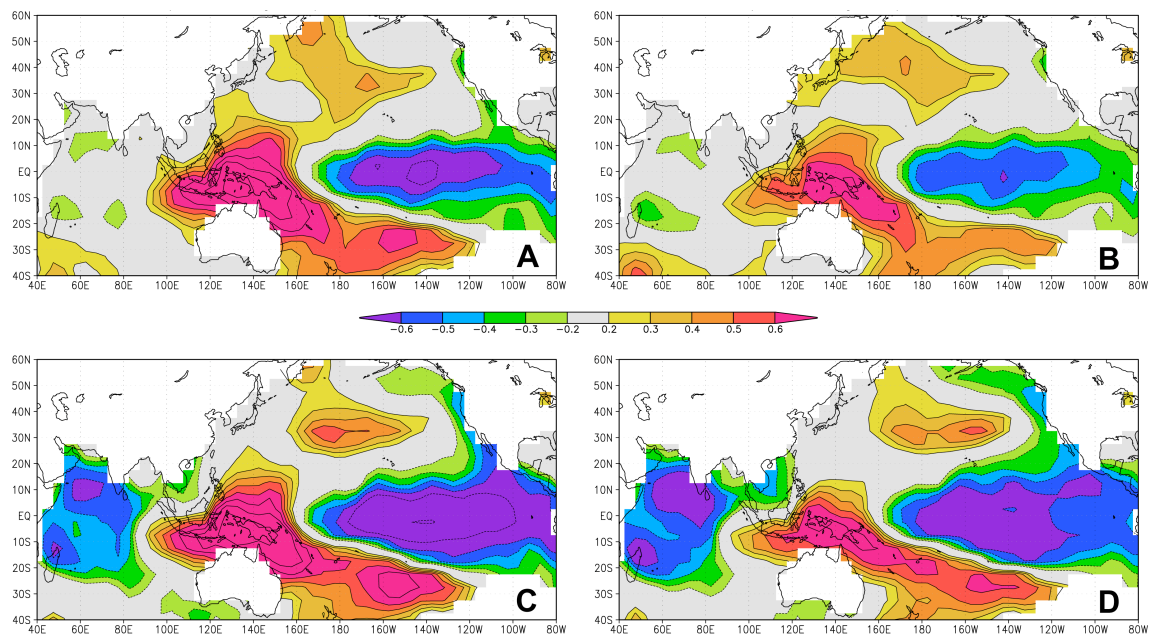
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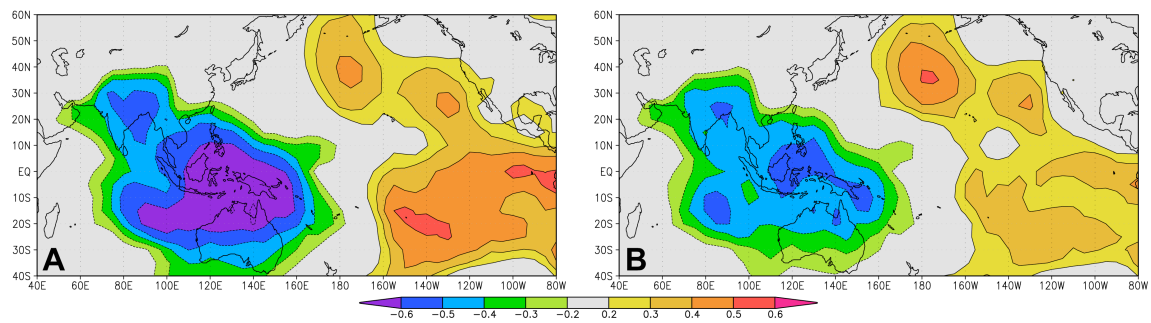
Figure 5.

Figure 6.

Figure 7.