Experimental reconstruction of monsoon drought variability for Australasia using tree rings and corals

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[1] An experimental reconstruction uses three well-dated, annually-resolved proxies from Australasia (0–40°S, 95–155°E) to provide large-scale information on Sep–Jan Australasian monsoon variability based on the Palmer Drought Severity Index (PDSI) for 1787–2002. The proxies are: (1) a ring width chronology of Callitris intratropica for northern Australia (1847–2006); (2) a tree-ring and coral–based reconstruction of the Oct–Nov PDSI (1787–2003) for Java, Indonesia; and (3) a rainfall reconstruction for northeastern Australia (1631–2002) based on Great Barrier Reef coral luminescence. All three proxies show considerable explanatory value for reconstructing monsoon rainfall variability over much of Australia and environs, which will improve as additional records become available. The success of this “proof of concept” experiment largely reflects the highly significant, spatially-coherent correlations between austral spring and summer PDSI, Australasian climate and ENSO. Citation: D’Arrigo, R., P. Baker, J. Palmer, K. Anchukaitis, and G. Cook (2008), Experimental reconstruction of monsoon drought variability for Australasia using tree rings and corals, Geophys. Res. Lett., 35, L12709, doi:10.1029/2008GL034393.

1. Introduction

[2] Instrumental records reveal patterns of monsoonal rainfall across Australasia that are often spatially coherent and strongly impacted by the El Niño-Southern Oscillation (ENSO), particularly during austral spring and summer [Allan, 2000]. Typical El Niño warm events are linked with drought conditions across much of Australia and Indonesia, with the reverse during La Niñas [Allan, 2000; Lough, 2007]. Greater coherency of Australian rainfall with ENSO has been found during cool phases of the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation (PDO/IPO) [Lough, 2007]. Other factors contributing to climate variability over Australasia (herein this term refers to Australia and Indonesia only) include Indian Ocean climate variability [Saji et al., 1999] and the Antarctic Oscillation (AO), also termed the Southern Annular Mode or SAM; Mo [2000]; Shi et al. [2008]).

[3] Understanding of longer-term Australasian monsoon variability and its linkages to large-scale features of the atmosphere-ocean circulation (such as ENSO and the PDO/IPO) is restricted by the limited length and spatial coverage of instrumental observations. Proxy records are also scarce over Australasia, with few exactly-dated, high resolution paleoclimatic records (mainly tree rings and corals) developed to date. This is largely due to the difficulty of identifying suitable tropical tree species that have defined annual rings and can be cross-dated [Worbes, 2002].

[4] In particular, relatively little is known of the dendrochronological potential of the native tree flora of tropical and subtropical Australia. Ash [1983a, 1983b] examined anatomical features and climate sensitivity of three conifers from north Queensland. Heinrich and Banks [2005, 2006] have shown Toona ciliata, a native timber species from eastern Australia to be useful for dendroclimatology. Early efforts to cross-date Australian trees focused primarily on a limited number of mainland species (none from tropical monsoonal Australia), and conifers in Tasmania [LaMarche et al., 1979; Dunwiddie and LaMarche, 1980]. However, these studies have sampled only a fraction of the hundreds of tree species in Australia. Recently, a broad survey of forest trees in northern Australia has examined the dendrochronological potential of >300 native tropical/subtropical tree species [Baker et al., 2008]. One of the most promising to emerge from this survey is the conifer, Callitris intratropica (Cupressaceae), which has distinct annual growth rings and can be successfully cross dated to produce a high-quality chronology [Baker et al., 2008]. See Baker et al. [2008] for a review of tree species in Australia and their dendroclimatic potential. Coral isotopic and fluorescence data also yield valuable high-resolution proxy records of climate, and have been developed for a number of low latitude sites [e.g., Gagan et al., 2000; Hendy et al., 2003; Lough, 2006, 2007]. Like tree-ring data, the coral records are very limited in length and spatial coverage across Australasia.

[5] Here, we present an experimental reconstruction of an index of monsoon drought and wetness variations for Australia and vicinity using three proxies. This reconstruction is preliminary but is used herein to demonstrate the potential of such series to reconstruct past climate in the region. We also present a preliminary spatiotemporal field reconstruction of drought for this same region. These reconstructions will improve as additional records become available.
Table 1. Information on Proxy Records Used in This Study

<table>
<thead>
<tr>
<th>Site</th>
<th>Proxy</th>
<th>Site</th>
<th>Years</th>
<th>Correlation</th>
<th>Beta</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Callitris</td>
<td>Tree Rings</td>
<td>northern Australia</td>
<td>1847–2006</td>
<td>0.29</td>
<td>0.29</td>
<td>Baker et al. [2008]</td>
</tr>
<tr>
<td>Java PDSI</td>
<td>Tree Rings, Coral</td>
<td>Java, Indonesia</td>
<td>1787–2003</td>
<td>0.61</td>
<td>0.36</td>
<td>D’Arrigo et al. [2006]</td>
</tr>
<tr>
<td>QLD Rain</td>
<td>Coral luminescence</td>
<td>Great Barrier Reef</td>
<td>1631–2005</td>
<td>0.38</td>
<td>0.38</td>
<td>Lough [2007]</td>
</tr>
</tbody>
</table>

*Correlations are with Australasian PDSI over 1925–2002 calibration period. Correlation and beta regression coefficients significant above 0.05 level.

2. Data and Methods

[6] The monthly gridded (2.5° × 2.5°) Palmer Drought Severity Index (PDSI) [Palmer, 1965] data set of Dai et al. [2004] was used to generate the experimental reconstruction for mainland Australia and adjacent Indonesia (averaged over 0–40°S, 95–155°E). The PDSI is a widely-used metric of hydrological variability derived from both temperature and precipitation data that has less noise than individual station records. The overall PDSI data set covers 1870–2003, but there are varying amounts of missing data and lower data quality in early years. It extends from 1880–2003 for the region of interest. Tree rings have been successfully used to reconstruct PDSI for locations around the globe, including the USA [Cook et al., 2004]. Principal components regression analysis [Cook and Kairiukstis, 1990] was used to develop the experimental reconstruction of Australasian PDSI.

[7] We compare the actual and reconstructed PDSI to gridded large-scale monthly climatic data sets, including rainfall (Vasclim analysis) [Beck et al., 2005], and sea surface temperature (SST) data from Kaplan et al. [1998]. Spatial correlation fields were generated between the actual and reconstructed PDSI and the PDSI, rainfall and SST gridded data sets in KNMI Climate Explorer (http://climexp.knmi.nl/). The PDSI series were compared to climate indices relevant to the region, including indices of ENSO: Niño-4 SST [Kaplan et al., 1998] and Southern Oscillation Index or SOI [Koenen et al., 1998], All-India monsoon rainfall [Parthasarathy et al., 1995], the Dipole Mode SST Index (DMI) for the Indian Ocean [Kaplan et al., 1998; Saji et al., 1999], an index of Jakarta rain days [Koenen et al., 1998], the PDO Index [Mantua et al., 1997], the AAO index (AAO, NOAA) [Mo, 2000]: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aoa/aoa.shtml and the Madden-Julien Oscillation (MJO) index (140°E, NOAA Climate Prediction Center, http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_mjo_index/mjo_index.html).

[8] The first proxy used herein is a ring-width chronology derived from Callitris intratropica trees sampled in northern Australia (Table 1, 1847–2006 [Baker et al., 2008]). As noted, few tree-ring chronologies exist for mainland Australia and this record is among the first documented for this species [Baker et al., 2008]. The chronology is a composite of three sites: Pine Creek 1 (PC1), Pine Creek 2 (PC2) and Edith Farm (EDF), all within the region from ca. 13–14°S, 131–132°E. Combined ring width measurements for these sites show a strong common signal using COFECHA [Holmes, 1983], with a series intercorrelation of 0.66. These ring width measurements were processed using 20-year spline curve fits and standardized using the ARSTAN program [Cook, 1985, also personal communication, 2008]. Different detrending methods [e.g., 67% spline] yielded similar results.

[9] The second proxy is a tree-ring and coral 0₁⁸O-based reconstruction of Oct–Nov PDSI for Java, Indonesia (Table 1) [D’Arrigo et al., 2006]. Spanning 1787–2006, it reflects monsoon fluctuations related to ENSO and Indian-Pacific Ocean climate over this period [D’Arrigo et al., 2006, 2008]. During the Oct–Nov season, relationships between ENSO and tropical rainfall and SST are among the most coherent and active over much of the tropical western Pacific and Indian Oceans [Adrian and Susanto, 2003]. It is also during these months that the strongest correlations are observed between the Java PDSI reconstruction and rainfall in adjacent land areas.

[10] The third record is a reconstruction of an Oct–Sept rainfall index for Queensland, northeastern Australia based on coral fluorescence data from the Great Barrier Reef (GBR) [Hendy et al., 2003; Lough, 2007] (Table 1), spanning 1631–2003. This record was also used to reconstruct river flow for four rivers in the region, and showed relationships with ENSO and the PDO [Lough, 2007].

3. Results

[11] Table 2 and Figures 1 and 2 present results for the PDSI reconstruction for Australasia and its correlations with climate. Preliminary screening of proxies with the instrumental PDSI revealed that the Sept–Jan season showed the strongest overall correlations when all three proxies were considered together. As noted, this season typically coincides with the period of most spatial coherence with ENSO [Allan, 2000]. The calibration period used is 1925–2002, with verification performed on 1880–1924 [Cook and...
Kairiukstis, 1990]. Reconstruction validity was assessed using the Reduction of Error (RE) and Coefficient of Efficiency (CE) statistics. For the RE and CE, positive value indicates model skill, with the CE being the more rigorous of the two [Cook and Kairiukstis, 1990]. Two nested reconstructions were developed to optimize the length of the reconstruction, after correcting for differences in mean and variance so that different segments are scaled to the instrumental record [e.g., Wilson et al., 2006]: one nest from 1847–2002 based on all three proxies and the second from 1787–1846 based on only the Java and GBR proxies. A third nest, using only the longer GBR proxy, could not be successfully validated. The Sign Test, an indication of the ability of the regression estimates to correctly track the sign of yr-to-yr climatic observations, and the Pearson coefficient were also utilized in verification tests (Table 2).

[12] The proxy records together account for 40% of the variance in the instrumental PDSI during the calibration period. The RE and CE are positive for both nested models, indicating considerable skill (Table 2). They are weaker, as expected, for the longer nest based on only two proxies (Java and GBR). Sign Test and other results are significant at or above the 0.05 level. The Australasian PDSI reconstruction reveals annual to decadal variability over the past several centuries, and indicates that useful information about monsoon drought over a sizeable area of Australasia can be gleaned using proxy data.

[13] Spatial correlation fields compare the actual and reconstructed PDSI to large-scale patterns of PDSI, rainfall and SSTs over Australasia and the Indo-Pacific sector (Figure 2). Moisture-related correlations are generally stronger over eastern Australia and areas of Indonesia, indicating the best potential for reconstruction in these regions. The relatively low correlations in areas of central and western Australia may partly reflect the relative scarcity of climate stations in these areas [e.g., Peterson and Vose, 1997].

[14] A spatial field reconstruction was also generated for comparison to the PDSI reconstruction generated above. In Figure 3, the reconstructed mean Indo-Australia drought index is correlated with (1) the Dai et al. [2004] PDSI field, and (2) the $0.5^\circ \times 0.5^\circ$ self-calibrating PDSI field derived following van der Schrier et al. [2005]. Figure 3 shows point-to-point correlations between an experimental reconstruction of the leading spatiotemporal mode of drought (EOF1, 33% explained variance, 0 to 40$^\circ$S, 95 to 155$^\circ$E) and the full field from Dai et al. [2004]. Increased skill over eastern Australia, Papua New Guinea, and Indonesia indicates that a spatially-complete climate field reconstruction using an expanded network of proxy sites could improve estimates of spatial variability of drought over Australasia.

[15] Correlations between the actual and reconstructed PDSI and large-scale Indo-Pacific climate and monsoon indices are indicated in Table 3. Results reveal significant correlations between the Australian PDSI series and several of these indices, including those representing ENSO and the Indian monsoon. Normalized negative departures in the actual and reconstructed PDSI are often linked to major droughts during El Niños, as in 1877–78 and 1982 [Allan, 2000] (Figure 2). Significant correlations are observed with Jakarta rain days and the Indian Ocean DMI. Correlations with indices of the PDO, which has been shown to impact Australian climate [Power et al., 2006], AAO and MJO are also significant for the periods of overlapping record.

4. Discussion and Conclusions

[16] An experimental reconstruction for Australasia has been presented which reveals annual to decadal variability in PDSI over recent centuries, using Australian proxies and Indonesian proxies. It was developed to test whether presently-available proxies could prove useful in reconstructing large-scale drought and wetness conditions prior to the instrumental period. The results are promising and suggest that available climatic information may be significantly increased in length using proxies for Australasia, and that there is potential to improve such reconstructions using additional proxy data. The season selected for analysis (Sep–Jan) represents a period of relatively high coherency in climate across much of the area studied. Australasia is a vast region, however, and there is considerable diversity in climate, as well as non-stationarities in the impacts of ENSO and other factors [e.g., Robertson et al., 2005; Shi et al., 2008]. Other proxies for monsoon Asia can be utilized to improve the experimental reconstructions described herein, including tree-ring data recently generated for elsewhere in monsoon Asia and Australia [e.g., Buckley et al., 2006; Heinrich and Banks, 2006], and additional coral records for the region. More formal, spatially comprehensive field reconstructions of monsoon-related PDSI and SST variability are planned, expanding on the preliminary analysis shown in Figure 3. The results justify
Figure 2. Spatial correlation fields comparing actual (left) and reconstructed (right) Sep–Jan Australasian PDSI with gridded data sets of (a) PDSI (1925–2002), (b) rainfall (1951–2000) and (c) SST (1925–2002) for the Sept–Jan season.
Figure 3. Climate field correlation of the reconstructed mean Indo-Australia drought index with (a) the Dai et al. [2004] PDSI field, and (b) 0.5 × 0.5 degree self-calibrating PDSI field following van der Schrier et al. [2005]. (c) Point-to-point correlations between an experimental reconstruction of the leading spatiotemporal mode of drought (EOF1, 33% explained variance, 0 to 45S, 95 to 155E) and the full field from Dai et al. [2004]. Enhanced skill over both eastern and western Australia and Papua New Guinea indicates that a spatially-complete climate field reconstruction using an expanded network of proxy sites could improve estimates of spatial variability of regional drought.

Table 3. Correlations of Actual and Reconstructed Australasian Sep-Jan PDSI With Selected Large-Scale Climate Indices

<table>
<thead>
<tr>
<th></th>
<th>Niño-4 SST</th>
<th>SOI</th>
<th>All-India Monsoon</th>
<th>Jakarta Rain Days</th>
<th>DMI</th>
<th>PDO</th>
<th>AAO</th>
<th>MJO4 140°E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual PDSI</td>
<td>-0.73 (123)</td>
<td>0.69 (123)</td>
<td>0.40 (120)</td>
<td>0.64 (108)</td>
<td>-0.54 (123)</td>
<td>-0.33 (102)</td>
<td>0.59 (24)</td>
<td>-0.56 (25)</td>
</tr>
<tr>
<td>Estimated PDSI</td>
<td>-0.56 (147)</td>
<td>0.42 (138)</td>
<td>0.32 (128)</td>
<td>0.50 (126)</td>
<td>-0.42 (134)</td>
<td>-0.22 (102)</td>
<td>0.45 (24)</td>
<td>-0.48 (26)</td>
</tr>
</tbody>
</table>

*N values in parentheses. All results are statistically significant above the 0.05 level. Correlations are for optimal seasons of comparison.
continued development of tree-ring and coral records from Australia for paleoclimatic studies.

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References


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