GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L04709, doi:10.1029/2005GL025465, 2006

Monsoon drought over Java, Indonesia, during the past two centuries

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Received 12 December 2005; revised 17 January 2006; accepted 19 January 2006; published 24 February 2006.

[1] Monsoon droughts, which often coincide with El Niño warm events, can have profound impacts on the populations of Southeast Asia. Improved understanding and prediction of such events can be aided by high-resolution proxy climate records, but these are scarce for the tropics. Here we reconstruct the boreal autumn (October–November) Palmer Drought Severity Index (PDSI) for Java, Indonesia (1787–1988). This reconstruction is based on nine ring-width chronologies derived from living teak trees growing on the islands of Java and Sulawesi, and one coral $\delta^{18}O$ series from Lombok. The PDSI reconstruction correlates significantly with El Niño-Southern Oscillation (ENSO)-related sea surface temperatures and other historical and instrumental records of tropical climate, reflecting the strong coupling between the climate of Indonesia and the large scale tropical Indo-Pacific climate system.

Citation: D'Arrigo, R., R. Wilson, J. Palmer, P. Krusic, A. Curtis, J. Sakulich, S. Bijaksana, S. Zulaikah, and L. O. Ngkoimani (2006), Monsoon drought over Java, Indonesia, during the past two centuries, *Geophys. Res. Lett.*, *33*, L04709, doi:10.1029/2005GL025465.

1. Introduction

[2] Droughts can have devastating effects on the peoples of largely agrarian areas of monsoon Asia, including Indonesia. Indonesian drought results from the failure of the east monsoon, and tends to be linked to ENSO warm events [*Hastenrath*, 1987; *Harger*, 1995]. During such times the Walker Circulation weakens as the Indonesian Low migrates eastward into the tropical Pacific, resulting in drought over much of the country [*Allan*, 2000]. Indonesia is, therefore, particularly relevant to the study of the Indo-Pacific climate system [*Hackert and Hastenrath*, 1986; *Hastenrath*, 1987; *Nicholls*, 1995]. The correspondence between Indonesian climate and ENSO may be the most intense of any land area worldwide, with correlations between ENSO indices and Indonesian rainfall ranging from 0.7–0.8 for some periods [*Moore*, 1995; *van Oldenborgh*, 2002].

[3] Land-based rainfall proxies can considerably improve our understanding of past drought variability [e.g., *Cook and Krusic*, 2004], yet are scarce for Indonesia and the tropics as a whole. A network of ring-width chronologies has been derived from living teak (*Tectona grandis* L. F.) trees in Java and Sulawesi [*D'Arrigo et al.*, 1994]. The development of these records follows pioneering efforts by *Berlage* [1931], who produced the first such record for Java. In Java and Sulawesi, annual growth rings can form in teak during the dry, east monsoon season which extends from ~June to November [*Hastenrath*, 1987]. Here we use the teak records, along with one coral oxygen isotope series, to develop a reconstruction of a drought index for Java, and describe its relation to past monsoon and ENSO variability.

2. Data and Methods

2.1. Climate Data

[4] We use the updated global monthly Palmer Drought Severity Index (PDSI) data set (1870–2002) [*Dai et al.*, 2004] (http://www.cdc.noaa.gov; v. 2). An index of meteorological drought, the PDSI is a proxy for soil moisture and streamflow [*Dai et al.*, 2004]. The PDSI is based on temperature and precipitation data for global land areas, on a 2.5° grid. It was averaged over 5–10°S, 105–115°E, representing Java and vicinity (Figure 1). The Javanese PDSI series are compared to several tropical climate records, including El Niño sea surface temperature (SST) indices [*Kaplan et al.*, 1998], the Southern Oscillation Index (SOI) [*Ropelewski and Jones*, 1987], and station records of precipitation for Jakarta, Indonesia (Global Historical Climate Network) [*Peterson and Vose*, 1997], and sea-level pressure (SLP) data for Darwin, Australia [*Basnett and Parker*, 1997].

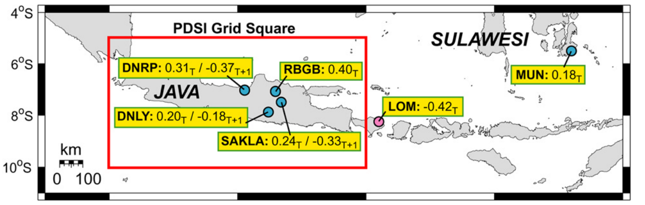

Figure 1. Map of Java and vicinity showing PDSI grid (5-10°S-105-115°E) and tree-ring (blue, *D'Arrigo et al.* [1994]) and coral $\delta^{18}O$ records (pink, *Moore* [1995]) used as predictors in PDSI regression model over 1870–1988 [*Cook and Kairiukstis*, 1990]. Values show significant (90% C.L.) correlations between each proxy (at lag T and/or T+1) and Oct–Nov PDSI.

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0094-8276/06/2005GL025465$05.00

Table 1. Description of Teak Chronologies Used to Reconstruct Java PDSI[a]

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
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
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
			Composite Series				
SAKLA	SAKLA	-	-	1689–2004	45	0.46	1759–2004
RBGB	RBGB	-	-	1668–2004	71	0.36	1834–2004
			Coral Data				
Lombok Strait	LOM	8.15 S	115.30 E	1782–1989	-	-	-

[a]Mean r = mean inter-series correlation derived from program COFECHA, and is an indication of common signal among tree-ring series within a chronology [*Holmes*, 1983]. Period > 10 series is an arbitrary cutoff for acceptable replication. SAKLA = composite of KLA and SAR; RBGB = composite of RAN, BEK, GUB and BIG. Series used in final reconstruction are: (tree rings): DNLY, DNRP, MUNA, SAKLA, and RBGB; (coral): Lombok δ^{18}O [*Moore*, 1995].

2.2. Tree-Ring and Coral Data

[5] Nine individual Indonesian tree-ring series were used (Table 1 and Figure 1). Due to low replication at some locations, some sites were composited to develop more robust time series (Table 1 and Figure 1). Some of these records were previously shown to correlate with ENSO indices [*D'Arrigo et al.*, 1994]. A few of these chronologies were included in previous ENSO reconstructions [*Stahle et al.*, 1998; *Mann et al.*, 2000], and several of the teak series, along with coral records, were used to reconstruct Indonesian SSTs (R. D'Arrigo et al., Reconstructed Indonesian warm pool SSTs from tree rings and corals: Linkages to the Asian monsoon and ENSO, submitted to *Paleoceanography,* 2005, hereinafter referred to as D'Arrigo et al., submitted manuscript, 2005). The coral series is a monthly skeletal δ^{18}O record from Lombok Strait (composited to create an annual series), which also relates to local SSTs (Table 1 and Figure 1) [*Moore*, 1995; D'Arrigo et al., submitted manuscript, 2005]. After compositing some of the chronologies, 5 tree-ring series and 1 coral series were used to develop the reconstruction.

3. The Java PDSI Reconstruction

[6] The October-November season optimized the PDSI signal in the combined proxies. These months fall within the period when rainfall over Java is best linked to ENSO [*Haylock and McBride*, 2001; *van Oldenborgh*, 2002; *Aldrian and Susanto*, 2003]. Variability in precipitation over Java is due in part to orographic effects, and there is a moisture gradient with drier conditions in eastern Java. This variability can complicate efforts to reconstruct drought and pinpoints the need for more diverse proxy data coverage. Our reconstruction is thus best representative of conditions in central-east Java and vicinity. Details on reconstruction methodology are provided as auxiliary material[1].

[7] The PDSI reconstruction explains 38% of the variance for the most replicated (1840–1988) period, dropping to 26% for the least replicated (1787–1819) period (Figure 2). Although these values are not very high, the statistical results (Figure 2) demonstrate that the model is

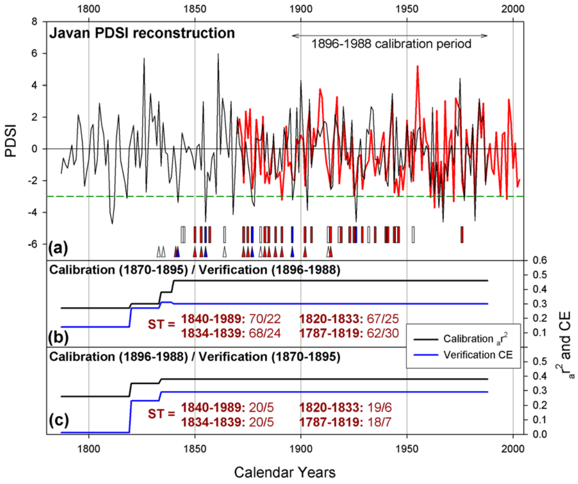

Figure 2. (a) Reconstructed (black) and instrumental (red) Oct–Nov Java PDSI over 1787–1988 and 1870–2004, respectively. Reconstruction scaled to instrumental data over the calibration period. Historical droughts identified from sea salt records (vertical bars, *Quinn et al.* [1978], 1844–1976) and planter's records and rain measurements (triangles, *van Bemmelen* [1916], 1833–1914) are highlighted. White = reconstructed PDSI > 0; red = PDSI between 0 and −3, blue = PDSI values < −3.0. Horizontal green dashed line highlights −3.0 PDSI level. (b) and (c) Calibration and verification statistics for nested reconstruction models. aR^2 = square of multiple correlation coefficient adjusted for loss of degrees of freedom; CE = Coefficient of Efficiency. CE's greater than zero indicate model skill [*Cook and Kairiukstis*, 1990]. ST = Sign test [*Fritts*, 1976] shows ratio of agreement/disagreement; all values are significant above 99% level.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL025465.

Table 2. Comparison of Reconstructed and Instrumental Java PDSI With Tropical Indices for Seasons of Optimum Correlation[a]

Index	Reconstruction	Years	Instrumental	Years	Reference
NINO4	−0.50 (Dec–Jan)	132 yr	−0.56 (Oct–Nov)	130 yr	5S–5N, 160E–150W
NINO3.4	−0.56 (Dec–Jan)	132 yr	−0.56 (Nov–Dec)	130 yr	5S–5N, 120W–170W
NINO3	−0.56 (Dec–Jan)	132 yr	−0.55 (Nov–Dec)	130 yr	5S–5N, 90–150W
NINO12	−0.43 (Dec–Jan)	132 yr	−0.44 (Oct–Nov)	130 yr	0–10S, 80W–90W
SOI	0.40 (Dec–Jan)	122 yr	0.61 (Jul–Aug)	130 yr	*Ropelewski and Jones* [1987]
Darwin SLP	−0.42 (Aug–Sep)	117 yr	−0.64 (Aug–Sep)	122 yr	*Basnett and Parker* [1997]
Jakarta PPT	0.32 (Aug–Sep)	125 yr,	0.59 (Sep–Oct)	121 yr,	GHCN

[a] Niño-SSTs from *Kaplan et al.* [1998]. All correlations significant above 99% confidence limit.

reasonably robust over its length. The reconstruction reveals PDSI variations during the past two centuries, with good agreement between instrumental and reconstructed values (Figure 2). The reconstructed PDSI ranges from −4.7 to 6.0. Analysis of the frequency of extreme dry/wet events per decade (exceeding ±1 std. dev. or SD) did not indicate any significant trends over the past two centuries. The PDSI series correlate significantly with several tropical climate indices (Table 2). The strongest correlations with the reconstruction are found with Niño-3 and 3.4 SSTs (for both, $r = -0.56$, 99.9% level). Consistent with these observations, the strongest coherence between the reconstructed and actual PDSI is within the 5–6 year ENSO bandwidth (Figure 3a). Evidence for a large-scale ENSO signal is further supported by multi-taper method spectral analysis [*Mann and Lees*, 1996], which also shows peaks consistent with ENSO (e.g., at ∼5–6 and 2–3 years; Figures 3b and 3c). Peaks in the coherency spectrum and full reconstruction at ∼10 years (Figures 3a and 3c) may correspond to ENSO-like quasi-decadal variability [*Allan*, 2000].

4. Comparison With Javanese Historical Records

[8] The PDSI reconstruction was compared to a historical record of Jakarta rain days [*Konnen et al.*, 1998]. This record begins in 1829 (with a gap from 1851–1863) and has been extended using modern data. Correlation is strongest for June to October ($r = 0.56$, 99.9% level). This coherence is good considering that rainfall in Jakarta, northwestern Java, can display differences from conditions at the tree sites (mainly in central and east Java). We also compare our reconstruction to two independent listings of drought for (1) 1844–1976 identified in Javanese sea salt records (Figure 2a) [*Quinn et al.*, 1978], and (2) 1827–1914, compiled by *van Bemmelen* [1916] based on planter's records and rain measurements (Figure 2a). Of the 36 *Quinn et al.* [1978] events, 22 coincide with reconstructed PDSI between 0 and −3, while 4 coincide with reconstructed values <−3. Similar results are obtained with the 20 *van Bemmelen* [1916] events, with 11 and 4 coinciding with reconstructed PDSI values of 0 to −3 and <−3 respectively. The overall reconstructed PDSI during the 20 [*van Bemmelen*, 1916] and 36 [*Quinn et al.*, 1978] (Figure 2) defined drought years is −1.11 (SD 1.93) and −1.05 (SD 1.63], respectively. There are also years in which the response in the reconstruction is lagged. For example, the Quinn and Bemmelen data state that 1902 was a drought year - the reconstruction shows a value of −3.87 in 1903 (similarly for Quinn years 1913, 1914 and 1976). These comparisons further confirm the representativeness of the climate signal in the proxy reconstruction.

[9] Reconstructed anomalies are at times associated with volcanic forcing, as well as ENSO and monsoon variability. The most negative departures follow the 1809 unknown volcanic event [*Dai et al.*, 1991], [1810 (−4.0), 1811 (−4.72) and 1812 (−3.54)] which has been linked with unusual tropical cooling [*Chenoweth*, 2001; D'Arrigo et al., submitted manuscript, 2005; R. Wilson et al., 250 years of reconstructed and modeled tropical temperatures, submitted to *Journal of Geophysical Research*, 2005]. There is a negative response following the Tambora, Indonesia 1815 eruption [1816 (−1.48), 1817 (−2.10), 1818 (−3.12)]. Reconstructed values following such events may relate to the proxies' response to cooling as well as drought. However, ENSO warm events may have also occurred during

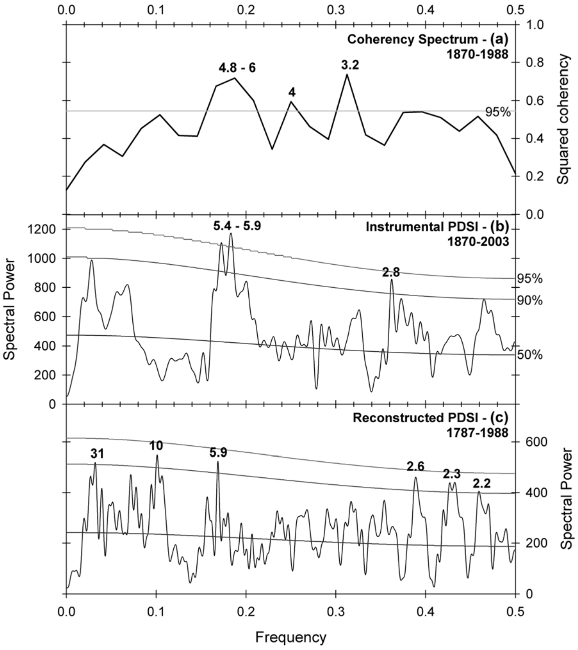

Figure 3. Spectral analysis results. (a) Coherency spectrum between reconstructed and instrumental PDSI. (b) and (c) Multi-taper method (MTM) spectral analysis of instrumental (1870–2003, Figure 3b) and reconstructed (1787–1988, Figure 3c) Javanese PDSI. Note dominant peak in ENSO bandwidth at 5–6 yr. There are also peaks at biennial and decadal time scales in both series. There are periods during which low proxy values may be related to volcanic-induced cooling rather than, or in addition, to drought effects, possibly impacting the spectral results.

these periods [*Ortlieb*, 2000]. Only weakly negative departures are reconstructed during the severe 1790s ENSO and drought, which impacted much of Asia [*Grove*, 1998]. These values are prolonged, however spanning five years (1787–1791, mean PDSI −0.95; SD 0.46; this event falls in the early, weakest part of the reconstruction). Drought is reconstructed during moderate-strong warm events of the 19th century: in ∼1855 (−4.60), 1868 (−4.14), and 1877–78 (−3.31, −3.62) [*Ortlieb*, 2000] (Figure 2). These values are comparable to, or exceed, those during intense warm events of recent decades: in 1982 (−4.54), 1994 (−2.95), 1997 (−3.17) and 2002 (−2.39). Two of these (1855 and 1877–78) are also identified by *Quinn et al.* [1978] and *van Bemmelen* [1916] (Figure 2a). Except for departures during the unknown volcanic event (1810–12), the 1877–78 event is the only one in which reconstructed values fall below −3.0 for two consecutive years.

[10] The greatest positive anomaly occurs in 1861, when the reconstructed value is 5.99; it falls within one of the wettest decades in the reconstruction (1856–1865). This decade coincides with the persistent "Civil War Drought" observed in tree-ring data over much of the USA, attributed to the effects of "La Niña"-like cold tropical Pacific SSTs [*Cook and Krusic*, 2004; *Herweijer et al.*, 2006] (Figure 2).

5. Summary

[11] Few high-resolution proxies exist for monsoon Asia. We have developed a reconstruction of PDSI for Java, Indonesia, that reflects past monsoon drought variability and the influence of ENSO in this region. Although short, spanning only two centuries, the reconstruction extends the available instrumental PDSI record, which is more uncertain in its early decades. Our results suggest strong coupling between Javanese drought and ENSO-related variability. This reconstruction should prove useful in future efforts to model Indonesian drought relationships with the Asian monsoon and ENSO over the past several centuries.

[12] **Acknowledgments.** This project was funded by the National Science Foundation (grant OCE 04-02474). We thank M. Moore, B. Lyon and M. Bell for data and assistance, and the Indonesian Institute of Sciences (LIPI). We also thank G. J. van Oldenborgh and one anonymous reviewer for helpful comments. We acknowledge KNMI Climate Explorer. LDEO contribution number 6870.

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