Pacific and Indian Ocean climate signals in a tree-ring record of Java monsoon drought

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ABSTRACT: Extreme climate conditions have dramatic socio-economic impacts on human populations across the tropics. In Indonesia, severe drought and floods have been associated with El Niño-Southern Oscillation (ENSO) events that originate in the tropical Indo-Pacific region. Recently, an Indian Ocean dipole mode (IOD) in sea surface temperature (SST) has been proposed as another potential cause of drought and flood extremes in western Indonesia and elsewhere around the Indian Ocean rim. The nature of such variability and its degree of independence from the ENSO system are topics of recent debate, but understanding is hampered by the scarcity of long instrumental records for the tropics. Here, we describe a tree-ring reconstruction of the Palmer Drought Severity Index (PDSI) for Java, Indonesia, that preserves a history of ENSO and IOD-related extremes over the past 217 years. Extreme Javan droughts correspond well to known ENSO and IOD events in recent decades, and most extreme droughts before this recent period can be explained by known ENSO episodes. Coral proxies from regions near or within the two poles of the IOD show good agreement with Javan PDSI extremes over the past ∼150 years. The El Niño of 1877, in conjunction with a positive IOD, was one of the most intense and widespread episodes of the past two centuries, based on instrumental and proxy data from across the tropical Indo-Pacific and Asian monsoon regions. Although Java droughts typically show the expected association with El Niño-like conditions and failed Indian monsoons, others (mainly linked to positive IOD conditions) co-occur with a strengthened Indian monsoon, suggesting linkages between the Indian monsoon, Indonesian drought and Indian Ocean climatic variability. The close associations between the Java PDSI, ENSO and Indian Ocean climate are consistent with the hypothesis that interannual ENSO to decadal ENSO-like modes interact to generate dipole-like Indian Ocean variability. Copyright © 2008 Royal Meteorological Society

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1. Introduction

The core physical ocean–atmosphere interactions underlying the El Niño-Southern Oscillation (ENSO) phenomenon are centered on the Indo-Pacific region, but its climatic impacts can be of global extent (Allan et al., 2003). The dominant influence of ENSO on the Indian Ocean does not preclude, however, the possible existence of more independent modes of Indian Ocean variability. It has been proposed that an Indian Ocean dipole mode (IOD) exists that is largely distinct from ENSO and contributes significantly to climate around the Indian Ocean rim (Saji et al., 1999; Webster et al., 1999; Behera et al., 2006) and the globe (Saji and Yamagata, 2003). The Dipole Mode Index (DMI) is defined as the sea surface temperature (SST) difference between the western (50°–70°E, 10°S–10°N, off Kenya) and eastern (90°–110°E, 0°–10°S, off Java/Sumatra) Indian Ocean. During what have been described as positive IOD events, a cold SST anomaly forms in the eastern Indian Ocean during the boreal summer and fall, contributing to drought conditions over western Indonesia. These cold SSTs are linked, via various positive feedbacks, to intensified southeasterly trade winds, shallowing of the thermocline and other physical changes in the eastern Indian Ocean (Saji et al., 1999). Meanwhile, warm SST anomalies occur in the western Indian Ocean, intensifying rainfall in eastern Africa. Opposite patterns are typically observed during negative IODs, although anomalies are not typically as strong as those during the positive IOD mode. Over Java/Sumatra, positive (negative) IODs tend to result in intense drought (wet) extremes, with anomalies of the same sign as those
that occur during El Niño (La Niña) episodes. Equatorial Indian Ocean zonal wind anomalies (EQWIN) are another closely related atmospheric component of Indian Ocean variability linked to the IOD and the Indian monsoon (Gadgil et al., 2004; Ihara et al., 2007), and are closely linked to ENSO variability (Wright et al., 1985).

Other researchers have argued that the IOD in its evolution, frequency spectrum, SST pattern and proposed near-global influence is simply another phase of the ocean–atmosphere interactions underlying Indo-Pacific ENSO variability, that results from the interaction of quasi-biennial, ‘classical’ ENSO and quasi-decadal ENSO-like signals in SST and sea level pressure (SLP) (Allan et al., 2001; Baquero-Bernal et al., 2002; Dommenget and Latif, 2002; Allan et al., 2003). These modes can combine and interact to produce protracted ENSO conditions, with negative or positive phasing, over the Indian Ocean sector (Allan and D’Arrigo, 1999; Allan, 2000; Allan et al., 2003). Allan et al. (2003) have indicated that the bulk of IOD events of either sign occur in conjunction with some type of El Niño or La Niña event or episode. In this view, there are a range of different types of ENSO events and episodes which can be strong to weak in magnitude, short to ‘protracted’ in temporal extent, or even of abortive nature. Additionally, Allan et al. (2001, 2003) stress that the interpretation of Indian Ocean domain-only empirical orthogonal function (EOF) analysis in IOD studies fails to recognize that, though orthogonal at zero lag, the first two EOF modes are confounded and have considerable shared variance, being significantly correlated at leads and lags of around nine months. Thus, the second EOF mode (the IOD) is simply representative of another phase of the first EOF mode (ENSO). Similar restricted domain EOF and singular value decomposition (SVD) analyses in the Pacific Ocean by Trenberth and Stepaniak (2001) and Kumar et al. (2006) have encountered a similar situation to the Indian Ocean, but report that their first and second EOF/SVD modes are simply different ‘flavours’ of the ENSO response in that ocean basin. Alternatively, ENSO may be only one of several potential triggers for dipole-type conditions in the Indian Ocean (Fischer et al., 2005).

A better understanding of the complex interactions between ENSO and Indian Ocean climate requires longer time series for analysis than those presently available from instrumental data. High-resolution tropical proxy records, mainly derived from tree rings, corals and ice cores, yield valuable information on past climate, but such records are relatively rare for the Indian Ocean and surrounding land areas. Among such proxies, coral records of SST for the western Indian Ocean (Figure 1) have been published for Malindi, Kenya (Cole et al., 2000; Kayanne et al., 2006) and for the Seychelles (Charles et al., 1997; Pfeiffer and Dullo, 2006). Both sites lie within or near the western pole of the IOD and have been used in these studies to demonstrate annual to decadal-scale impacts of ENSO on Indian Ocean climate. A combined Seychelles coral record (Charles et al., 1997; Pfeiffer and Dullo, 2006) produced seasonal correlations with ENSO that were basically stationary over time, with cross-spectral analyses indicating coherency between the coral index and ENSO, supporting the concept that decadal ENSO variability influences the Indian Ocean. Elsewhere in the Indian Ocean, coral series exist for sites near Madagascar (Zinke et al., 2004, 2005), the Chagos Archipelago (Pfeiffer et al., 2004) and other locations (Chakraborty, 2006). Of these published Indian Ocean coral records, only one extends back further than ~150 years (for the Ifaty site off southwestern Madagascar; 1659–1995). A tree-ring chronology for Zimbabwe, one of the few land-based high-resolution records for the western Indian Ocean rim, begins in the late 18th century and indicates drought and wet extremes that correlate well, although intermittently, with ENSO (Therrell et al., 2006).

The eastern Indian Ocean, just west of the islands of Java and Sumatra, is considered to be the more robust of the two poles of IOD variability and is also where such events tend to originate (Saji and Yamagata, 2003; Meyers et al., 2007). From within the actual region of peak SST anomaly off Java/Sumatra used to define the IOD, coral δ18O and Sr/Ca records for the Mentawai Islands (Figure 1) reveal cold and dry SST anomalies in response to positive IODs (Abram et al., 2003, 2005, 2007). Mentawai fossil corals were used to suggest that the magnitude of the very strong 1997–1998 IOD (also a severe ENSO) was not unique relative to events earlier in the Holocene (Abram et al., 2003, 2007). Abram et al. (2003; pers. comm. 2006) argue that the cold SSTs off Sumatra during positive IODs distinguish such events from the Indian Ocean basin-wide warming signal during El Niños. On the other hand, Baquero-Bernal et al. (2002) point out that El Niños can also help force dipole-type structure and cold SSTs in the eastern Indian Ocean. Charles et al. (2003) used a network of Indian Ocean coral records to investigate ENSO and the IOD, finding that their zonal isotopic gradient was significantly


Note overlap of Java PDSI gridcell with that of the eastern pole of the IOD. Also indicated in green is the gridcell used to develop the EQWIN index of equatorial zonal winds for the central Indian Ocean (Gadgil et al., 2004; Ihara et al., 2007). Also shown are locations of coral proxies mentioned in the text – in the western Indian Ocean, for the Seychelles (Charles et al., 1997) and Malindi (Cole et al., 2000); in the eastern Indian Ocean, for the Mentawai Islands (Abram et al., 2003). This figure is available in colour online at www.interscience.wiley.com/joc

Figure 1. Map showing location of gridcell (in red) used to develop Java PDSI reconstruction (D’Arrigo et al., 2006a) and the two gridcells of SST (blue boxes) used to define the DMI (Saji et al., 1999).
correlated with central Pacific SSTs, and that this coral
dipole resulted from strong ENSO-like teleconnections in
the Indian Ocean, as opposed to being the result of unique
Indian Ocean or monsoonal dynamics. More importantly,
Allan et al. (2001, 2003) and Reason et al. (2000) have
shown that the austral spring Indian Ocean SST pattern of
the IOD is identical to that of ENSO events in that season
and ocean basin, and that the basin-wide SST response
across the Indian Ocean reported above is only seen at
the peak ENSO phase in the austral summer.

Here we use a tree-ring-based reconstruction of the
boreal fall (Oct–Nov) Palmer Drought Severity Index
(PDSI) for Java, Indonesia (D’Arrigo et al., 2006a) to
investigate drought and wetness extremes, and their
relation to Indian Ocean and ENSO variability over the
past two centuries. Positive (negative) PDSI indicates wet
(dry) conditions. Because Indonesia is uniquely situated
between the Pacific and Indian Oceans, its rainfall is
impacted by SST variability in both basins (Aldrian
and Susanto, 2003). Java, along with the island of
Sumatra and the adjacent smaller islands, experiences
the greatest Indian Ocean-related climate impacts in all
of Indonesia (Saji and Yamagata, 2003). Indonesian tree-
ring and coral records were used previously to reconstruct
western Pacific warm pool SSTs in relation to ENSO
(D’Arrigo et al., 2006b). We demonstrate that the Java
PDSI reconstruction, derived from a land area that
overlaps the eastern pole of the IOD (Figure 1), also
captures features of Indian Ocean climate. At 217 years
in length, it is one of the longest continuous, high-
resolution records available for investigating rainfall
variability in the tropical Indo-Pacific. We also compare
the PDSI reconstruction to other high-resolution proxies
from the Indian Ocean to assess spatial variations in IOD
and ENSO-related impacts over the past two centuries.
The conceptual framework of the paper is, therefore, to
assess the interrelationships between ENSO, the IOD, and
the Indian monsoon, using both instrumental and high-
resolution proxy climate records for the tropical Indo-
Pacific region.

2. Data and methods

2.1. Instrumental data:

We use the monthly DMI of Saji et al. (1999; http://www.
jamstec.go.jp/frsge/research/d1/iod/), defined in the
Introduction, which begins in 1958. The two SST boxes
used to define the DMI are indicated in Figure 1. Decadal
periodicities (longer than 7 years) were removed by Saji
et al. (1999) in calculating their index. We also use the
global SST dataset of Kaplan et al. (1998), as well as an
extended DMI (1869–2002) based on these data (from
the IOD website cited above). The extended record, how-
ever, includes early periods of relatively sparse data
coverage (with possibly spurious values) for which data
was interpolated (Kaplan et al., 1998). For compar-
ison, a version of the DMI was also created from the
HADSSST2 dataset (Rayner et al., 2006). A monthly index
of zonal surface wind anomalies for EQWIN is used from
ICOADS data for averaged anomalies over 62°–90°E,
4°N–4°S, for 1881–1997 (Worley et al., 2005). Rain-
fall data were obtained from the Global Precipitation
Climatology Centre (GPCC) Variability Analysis of Sur-
face Climate Observations (version Vascim-0 0.5, Beck
et al., 2005) precipitation dataset from 1951 to 2000.
Also used in this study are standard ENSO indices
(http://www.cpc.noaa.gov), including Niño-3.4 SSTs; the
Jakarta rain days record (Konnen et al., 1998), the all-
India monsoon index (http://www.tropmet.res.in/) and
the Indian monsoon index of Sontakke et al. (1993), Son-
takke and Singh (1996). An index of the Southern Oscil-
lation (SOI) was developed from the gridcells represent-
ing Tahiti and Darwin from the HADSLP2 dataset (Allan
and Ansell, 2006).

2.2. Proxy data

The boreal fall PDSI reconstruction, described in detail
in D’Arrigo et al. (2006a), spans the interval from 1787
to 2003 (instrumental values were spliced onto the PDSI
reconstruction after 1988 following adjustment for mean
and variance). The PDSI incorporates parameters of both
rainfall and temperature and is a proxy for soil moisture
and streamflow (Dai et al., 2004; see D’Arrigo et al.,
2006a for further details). Based on nine Javan tree-
ring records of teak (Tectona grandis) and one coral
series, the reconstruction is reasonably well validated and
is used herein to evaluate Indian Ocean-related PDSI
variability for the eastern pole of the IOD (Figure 1),
complementing the eastern Indian Ocean coral data
(Abram et al., 2003, time series not available). This
Java reconstruction is most sensitive to adverse climatic
events such as drought (rather than more favorable
wetter conditions), as has been found for other tree-
ring series (Fritts, 1976). For the western Indian Ocean,
we compare the PDSI reconstruction to the Seychelles
coral δ18O record (Charles et al., 1997; 1846–1994;
detrended for the boreal fall season), which is available
at monthly resolution, unlike the Malindi, Kenya series.
Note, however, that the Seychelles and Mentawai records
date back only a few decades prior to the extended
DMI. We also evaluate the proxy data in relation to
other Indian Ocean, Indian monsoon and ENSO-related
indices (Table I, Figure 1). See Table II for a listing of
acronyms and data used in this study. Instrumental data-
based listings of IODs and ENSO events in Saji and
Yamagata (2003), and the consensus ENSO listings of
two sources:

1. J. Null (2004; http://ggweather.com/enso/years.htm);
El Niño and La Niña Years: A consensus listing,
using events that appear on 3/4 of the following 4
widely used lists: Western Region Climate Center, Cli-
mate Diagnostics Center, Climate Prediction Center,
Multivariate ENSO Index from Climate Diagnostics
Center; and

au/Help/ElNinoSouthernOscillation/
Table I. Correlation matrices of Java PDSI reconstruction, instrumental indices of IOD and ENSO, and other records for tropical Indo-Pacific for September–October season. Matrix A is for common 1958–1994 period. 90% = >0.27 and 95% = >0.32; matrix B for full period of common overlap between each series. Significance values and degrees of freedom (N) shown; shaded correlations not significant at these levels.

(a) KAP DMI SAJI DMI HAD DMI EQWIN SST EAST SST WEST NINO3 SOI JAK SEY ALL IND SINGH

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(b) KAP DMI SAJI DMI HAD DMI EQWIN SST EAST SST WEST NINO3 SOI JAK SEY ALL IND SINGH

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3. Results

To test the ability of the PDSI reconstruction to provide information on past Indian Ocean climate, this record was first correlated to theIOD indices (DMI) of Saji et al. (1999; http://www.jamstec.go.jp/frsgc/research/d1/iod/) and those derived from Kaplan et al. (1998) and Rayner et al. (2006) during the latter half of the 20th century (since 1958), when theIOD indices are considered most reliable (Table I(a), Figure 2(a)). The PDSI reconstruction is most strongly correlated with theDMI ($r = -0.64$ using the Kaplan series from 1958 to 1994) for the boreal fall months (Sept–Oct) of peakIOD variability. Correlation over the full interval of Kaplan extended SST dipole data since 1869 is $r = -0.45$ (Table I(b)). Correlations between the reconstructed PDSI and SST data for the two gridcells representing the poles of theIOD are statistically significant ($p \leq 0.05$) and of opposite sign. The negative correlation between the reconstructed PDSI andDMI is consistent with the tendency for drier conditions over western Indonesia to occur during positiveIOD episodes. A significant correlation is also found with the EQWIN index ($r = 0.73$, $p < 0.05$, 1958–1994, Figure 2(b)). Statistically significant correlations are also found with the boreal fall Niño-3.4 SSTs and other indices of tropical Indo-Pacific climate (Table I). These findings indicate that the PDSI reconstruction reflects Indian Ocean as well as tropical Pacific Ocean-related climatic variability (D’Arrigo et al., 2006a,b).

Additional evidence for a relationship between the Java PDSI and Indian Ocean SSTs is presented in Figure 3, which shows spatial correlation fields between Indo-Pacific SSTs, the KaplanDMI, HADSLP2SOI and the PDSI reconstruction for the boreal fall season for both recent (post-1958) and century-long (post-1880) time series. Both theDMI and PDSI correlation patterns reveal dipole-like structure in Indian Ocean SSTs over recent decades as well as over the full length of instrumental record (Figure 3(a)–(d)). This is also the case for Niño-3.4 SST (Figure 3(e) and (f)) and the SOI (Figure 3(g) and (h)). This finding is consistent with Allan et al. (2001) and Baquero-Bernal et al. (2002), both of whom observed that ENSO can also cause dipole-like patterns in the Indian Ocean. Figure 3(a)–(h) all show coincident and coherentIOD and ENSO structures in SST during the boreal autumn season that are very similar to the SST composites in Allan et al. (2003). Spatial correlation fields of the Java PDSI reconstruction with precipitation reveal the strong opposing relationship between rainfall over eastern Africa/Arabia versus Indonesia/Australia andenso data since 1869 is $r = -0.45$ (Table I(b)). Correlations between the reconstructed PDSI and SST data for the two gridcells representing the poles of the IOD are statistically significant ($p \leq 0.05$) and of opposite sign. The negative correlation between the reconstructed PDSI and DMI is consistent with the tendency for drier conditions over western Indonesia to occur during positive IOD episodes. A significant correlation is also found with the EQWIN index ($r = 0.73$, $p < 0.05$, 1958–1994, Figure 2(b)). Statistically significant correlations are also found with the boreal fall Niño-3.4 SSTs and other indices of tropical Indo-Pacific climate (Table I). These findings indicate that the PDSI reconstruction reflects Indian Ocean as well as tropical Pacific Ocean-related climatic variability (D’Arrigo et al., 2006a,b).

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To further investigate the correspondence between the Javan PDSI and climate anomalies related to Indian and Pacific Ocean variability, PDSI values below and above 1 standard deviation (representing drought and wet periods) were identified over the length of the reconstruction (1787–2003). In Figure 4(a), PDSI drought years are compared to the instrumental, historical and proxy records of positiveIOD and ENSO warm events (see ‘Data and Methods’). Since 1787, of the 29 drought years ($> -1$ standard deviation), 19 (66%) coincide with El Niños. With the 47 ENSO warm events identified since 1787 (see Figure 4), the probability that 19 coincident years are identified by chance (i.e. relative to using random time series) is extremely low ($p < 0.000$). However, this relationship appears to break down prior to 1850 (shown by open diamonds in Figure 4(a); only 25% (1812 and 1838–$p = 0.28$) coincide). Since 1850, of the 21 drought events (relative to 37 ENSO warm events), 17 (81%; $p < 0.0000$) coincide with El Niños. The relationship with ENSO is not as coherent when wet events are examined. Of the 31 reconstructed wet years since
1850, only 7 (22%; \( p = 0.15 \)) coincide with La Niña events. Additionally, seven of these wet years actually coincide with El Niño events. A similar situation exists when the wet/dry years are compared to IODs since 1960, when such events appear to have increased in frequency (Saji and Yamagata, 2003). Of the nine droughts over this period, seven (78%; \( p < 0.0000 \)) coincide with positive IOD events, while only one (17%; \( p = 0.40 \)) of the 6 wet years coincides with a negative IOD (not shown). As noted previously, the negative IOD is also a less robust pattern than the positive IOD mode. Thus, while many of these comparisons of extreme events (and the correlations in Table I) are highly significant statistically, and together account for a sizeable proportion of the PDSI variance (e.g. as we demonstrated in R. D’Arrigo and R. Wilson (in press)), it is clear that there is additional variance not accounted for by the variables analysed herein. This fact reflects, at least in part, quality issues and varying spatial representation in the early historical records as well as the proxy records themselves, such that they are not perfect measures of the phenomena that we are examining. There are also other factors forcing climate in these regions (e.g. volcanism in the early 1800s).

Reconstructed Java droughts thus correspond reasonably well with the positive IODs and ENSO warm events identified in instrumental, historical or proxy records, reflecting their links to both tropical Indian Ocean as well as Pacific Ocean SSTs (Figure 4(a)). Before 1961, only one major positive IOD has been identified over the past few centuries (in 1877, also an El Niño; noted in the Mentawai corals – Abram et al., 2003). Variance in the early part of the extended DMI reflects this low IOD activity: for 1878–1960 the average variance is 0.08, versus 0.21 for 1961–2002. Ihara et al. (in press) describe different regimes in the instrumental period, related to differential warming in the Indian Ocean, in which there are different frequencies of positive and negative dipole events. Most droughts can be explained by ENSO events...
Figure 3. Spatial correlation fields computed for the recent period since 1958 (left panels) and since the late 19th century (right panels), comparing the Kaplan dipole index (a), (b), Java PDSI reconstruction (c), (d), Nino 3.4 SST (e), (f), and HADSLP2 SOI (Allan and Ansell, 2006; (g), (h)) with global SSTs from the Kaplan et al. (1998) dataset for the boreal fall (Sept–Oct). Note that all SST fields show dipole structure in the Indian Ocean as well as ENSO signatures in the Pacific Ocean. Figure 3(i)–(j) shows spatial correlations of the Java PDSI reconstruction with boreal fall precipitation data ((i): Sept–Oct and (j): Oct–Nov) for 1951–2000, illustrating the strong opposing relationship of rainfall between eastern Africa/Arabia versus Australasia, as well as linkages between Indian and Indonesian drought. This figure is available in colour online at www.interscience.wiley.com/joc

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Figure 4. Analysis of extreme drought years in tropical Indian Ocean proxies. (a) In Java, PDSI reconstruction from 1787 to 2003. Positive (negative) PDSI values indicate wetter (drier) conditions. Horizontal dashed lines indicate ±1 standard deviation from the mean. Pink diamonds denote El Niño warm events coincident with negative PDSI (T or T+1) values. Also labeled are positive IOD years from Saji and Yamagata (2003; blue arrows) and from the Abram et al. (2003) coral δ18O record for the Mentawai Islands, eastern Indian Ocean (labeled as green ‘M’s). PDSI drought events were previously linked to historical sea salt and rainfall measurements for Java (D’Arrigo et al., 2006a). El Niño anomalies are interpreted as being ‘coincident’ with the proxy data when the proxies show negative values in either the concurrent (year t) or following year (t+1). Arrows at 1809 and 1815 indicate timing of two major volcanic eruptions (1809 unknown and 1815 Tambora events) that caused cold SSTs, and possibly, droughts for Indonesia and vicinity. (b) As for a, but using the detrended Seychelles coral δ18O record (Charles et al., 1997) for the boreal fall season showing low δ18O years and warmer SSTs inferred for positive IOD and El Niño events. Red diamonds denote El Niño warm events coincident with negative MAH (T or T+1) values. This figure is available in colour online at www.interscience.wiley.com/joc

identified in instrumental and historical data prior to the recent period, from 1787 to 1960 (Figure 4(a)). Low PDSI values from 1810 to 1812 may be partly a result of El Niños (Ortlieb, 2000), but may also reflect cold SSTs (and related drought) in the tropical Indo-Pacific following volcanic activity (Figure 4(a); Chenoweth, 2001; D’Arrigo et al., 2006a,b; Wilson et al., 2006). The magnitude of recent PDSI events does not appear to be particularly unique relative to previous events over the past two centuries.

Although the Java PDSI reconstruction indicates both Indian and Pacific Ocean SST extremes over the past two centuries, it is not sufficient by itself for generating a history of IOD events, since both positive IODs and El Niños result in the same signal (drought) over Java. Comparison of the PDSI reconstruction to other high-resolution proxies provides additional information on past Indian Ocean and ENSO variability (Figure 4). For example, extreme isotopic values in the Mentawai coral record (Abram et al., 2003, Figure 4(a)) from the eastern pole of the IOD result from cool SSTs (and dry conditions) during major positive dipole events in 1877, 1961, 1994 and 1997. These IODs agree well with Java droughts: the normalized PDSI value is −1.4 averaged over these 4 years.

The Seychelles coral series is a logical candidate for representing the western arm of the IOD (Figures 1, 4(b); Charles et al., 1997). Correlation between the boreal fall Seychelles coral series and the Sep–Oct western Indian Ocean SST gridcell off Kenya used to identify the IOD is $r = -0.47$ (139 years); and $r = -0.44$ with the extended Kaplan Sept–Oct DMI (126 years). These results are consistent with the expectation that low δ18O values in the western Indian Ocean should be linked to warm SSTs (and wet conditions), positive IODs and El Niño-type conditions. The Seychelles record reveals good agreement with IOD and ENSO events in the recent period, and back in time when compared to the PDSI reconstruction as well as the listings of ENSO events. As for the Java reconstruction, however, there are some
years that do not show the expected relationships: of the 29 negative values in the Seychelles record (related to warm SSTs), 20 (69%; \( p < 0.0000 \)) coincide with El Nino events. On the other hand, only 50% of the negative events coincide with positive IODs since 1960. As with the PDSI reconstruction, the coherence with La Nina and negative IOD events is relatively weak.

Both the Abram et al. (2003) and Charles et al. (1997) corals indicate extreme \( \delta^{18}O \) values around the time of the 1877 ENSO episode, which was coincident with a positive IOD. The 1877 event was one of the most widespread and intense episodes in the tropical Indo-Pacific in recent centuries. It shows the lowest \( \delta^{18}O \) value over the length of the original annual Seychelles record (Charles et al., 1997). It is also one of the most persistent autumn droughts in the Jakarta rain days record (values were consistently zero from Aug to Oct; Konnen et al. 1998). The 1877 event also coincides with a major DMI anomaly, drought in the Javan PDSI record, a very strong El Niño (Ortlieb, 2000; Allan et al., 2003), an IOD in the Mentawai coral data (not shown) and the second greatest Indian monsoon failure over the past millennium as documented in the Dasuopu, Tibet ice core record (Thompson et al., 2000; and see Grove, 1998) (Figure 5).

A composite analysis (Figure 6(a)) reveals that seven cases of Javan PDSI droughts over the common period with the monsoon record of Sontakke and Singh (1996; 1813–1995) show the expected relationship with a weakened Indian monsoon, typically associated with El Niño’s. However, four other major Java PDSI droughts actually coincide with a strengthened Indian monsoon (Sontakke and Singh, 1996). Three of these latter events have been identified as positive IODs [in 1877 (following the catastrophic 1877–1878 ENSO), 1961 and 1994]; the fourth, in 1842, may be another candidate. Figure 6(b) and (c) shows SST composites for the years of Java drought during strong and weak Indian monsoon seasons, with the strengthened Indian monsoon case having a more pronounced dipole pattern (Figure 6(b)). This result, although based on a limited number of cases, suggests an association between the Indian monsoon, Indian Ocean SSTs and Java drought that differs from the expected ENSO-Indian monsoon–Java drought relationship (see Discussion and Conclusions below).

We have performed several spectral analyses of the PDSI reconstruction to further investigate the expression of ENSO variability. MTM spectral analysis reveals spectral peaks at 2–3 and 5–6 years in the full reconstructed Javan PDSI (1787–2003), which fall within the classical ENSO bandwidth (Allan, 2000). Pronounced decadal-to-multidecadal variability is also noted in the reconstruction (Figure 7(a); D’Arrigo et al., 2006a). Morlet wavelet analysis (Figure 7(b); Grinsted et al., 2004) indicates that the strength of variability in the PDSI series at the ENSO and decadal-to-multidecadal bands has varied in time, with a period of quiescence occurring during the middle part of the 20th century. Furthermore, the coherence between the PDSI reconstruction and Niño3-4 SSTs has varied in time across most spectral bands (Figure 7(c), Grinsted et al., 2004). The periods of greatest coherency, however, occur on interannual timescales spanning the classical ENSO bandwidth. Additionally, normalized, scale-average time series (not shown) between the 2–8 year bands in the PDSI reconstruction and Niño3-4 SSTs are significantly correlated with each other (\( r = 0.273, p = 0.0018 \)).

Figure 5. Time series of the catastrophic combined 1877 El Niño and positive IOD episode. Plot of normalized instrumental and proxy time series for 1850–1900 time period, emphasizing the 1877 event. Time series include the Sept–Oct Kaplan DMI (inverted) (Kaplan et al., 1998), Nino 3.4 SSTs (http://www.cpc.noaa.gov), Seychelles coral \( \delta^{18}O \) (Charles et al., 1997), Indian monsoon index (Sontakke et al., 1993; Sontakke and Singh, 1996), HADSLP2 SOI and PDSI reconstruction (D’Arrigo et al., 2006a). This event is also present in the Mentawai corals (see Figure 4(a)). This figure is available in colour online at www.interscience.wiley.com/joc
4. Discussion and conclusions

We have used a multiproxy reconstruction of the PDSI drought index to demonstrate that rainfall over Java and Indonesia is impacted by both tropical Indian Ocean and Pacific Ocean SSTs over the past two centuries. Reconstructed drought years over Java were found to agree reasonably well with both ENSO and IOD episodes identified in instrumental and documentary data, particularly after ∼1850. The PDSI reconstruction is thus one useful indicator of Indian Ocean-related SST and rainfall extremes for the eastern pole of the IOD adjacent to Java/Sumatra. Before recent decades, major drought events in Java can largely be accounted for by known El Niño episodes. This finding, along with the documentation of IODs indicated for the Mentawai corals (Abram et al., 2003, 2007) and the apparent hiatus of major IODs in the extended DMI from 1878 to 1960, suggests that IOD activity was relatively infrequent over the past two centuries, prior to recent decades. Indian Ocean coral data from the two poles of the IOD (Charles et al., 1997; Abram et al., 2003) reveal reasonably good agreement with the PDSI reconstruction. In future investigations, transects of these and other coral and tree-ring records (e.g. Moore, 1995; Cole et al., 2000; Abram et al., 2003; Pfeiffer et al., 2004; Zinke et al., 2004; Therrell et al., 2006) could be used to develop a more detailed, continuous spatial history of tropical Indian and Pacific Ocean climate and its relation to ENSO and the Asian monsoon.

While we have shown that the Javan PDSI record is reflective of tropical Indian Ocean SST variability, we do not mean to imply that IODs are necessarily distinct from the ENSO system. In fact, evidence in this paper suggests that the opposite is true. One consideration is that the PDSI reconstruction demonstrates statistically significant...
correlations with ENSO on interannual to decadal time scales, as has been found for the Indian Ocean coral proxies (Charles et al., 1997; Cole et al., 2000). Like these coral series, the Java PDSI indicates spectral activity at \( \sim5–6 \) and \( 10–14 \) years (Figure 7). Such annual to decadal (as well as multidecadal) variability in the Javan PDSI appears to be best explained by ENSO (as was found for the Malindi coral by Cole et al., 2000) rather than specifically by dipole (Saji et al., 1999) or Asian monsoon (Charles et al., 1997) related effects. Our observations thus lend support to the concept that Indian Ocean SST activity related to IODs results from the interaction of quasi-biennial, ‘classical’ ENSO and decadal-scale ENSO-like modes of variability and their expression across the Indian Ocean basin (Allan and D’Arrigo, 1999; Allan, 2000; Allan et al., 2001, 2003).

The coincidence of some major Javan droughts with a strengthened monsoon over India suggests a monsoon–Indian Ocean climate (including SSTs and winds) relationship, although this observation is based on limited data. In a related study, Ihara et al. (2007; and see Gadgil et al., 2004) found that the state of the Indian Ocean modulates the ENSO-monsoon relationship, with a negative EQWIN increasing the likelihood of a stronger Indian monsoon despite the presence of El Niño. Although not well understood, it appears that in such cases a negative EQWIN state may weaken the impact of ENSO on the Indian monsoon by inducing anomalous surface divergence in the eastern tropical Indian Ocean, subsequently stimulating convection that propagates northward causing anomalous ascent and surplus rainfall over India. A stronger monsoon can, in turn, generate easterly wind anomalies that cool the eastern Indian Ocean, stimulating upwelling of cool deep waters and positive dipole conditions, with decreased convergence of moist air and ensuing drought in Java/Sumatra (Gadgil et al., 2004; Ihara et al., 2007). These two studies also found that a better model of Indian monsoon rainfall could be obtained using both the EQWIN index and Niño-3 SSTs as predictors, rather than either index alone (Gadgil et al., 2004; Ihara et al., 2007). It is also worth noting that other phenomena may potentially contribute to irregularities in expected ENSO patterns and teleconnections (such as the Madden–Julian Oscillation, or MJO, Zhang et al., 2001).

Here we have shown that stronger Indian monsoons can also be linked to drought (a failed Indonesian monsoon) in Java during positive IOD-type conditions over the past two centuries. Similar to the results of Gadgil et al. (2004) and Ihara et al. (2007) noted above, analysis reveals that a better regression model of the Java PDSI reconstruction can be obtained using both Niño-3.4 SSTs and the EQWIN index than either index alone, with over 54% of the variance accounted for in the PDSI estimates (see D’Arrigo et al. in press, U Clim for a more detailed analysis). The strong correlation between the Java PDSI reconstruction and EQWIN, and possible links to the Indian monsoon, are intriguing, and will be investigated in more detail in a future study. Improved spatial coverage of proxy data, modeling and

Figure 7. Spectral analyses of Java PDSI reconstruction. (a) MTM analysis (Mann and Lees, 1996) of full Java PDSI reconstruction from 1787 to 2003 (instrumental data spliced onto reconstruction for 1989–2003 period). Thin solid lines in MTM plot indicate significance at 50, 90 and 95% levels. (b) The continuous wavelet power spectrum for the PDSI reconstruction from 1787 to 2003. Black contours bind regions that are significant against a red noise null hypothesis. Lighter shaded regions indicate the cone of influence where edge effects are likely and the results should not be interpreted. (c) Squared wavelet coherence between the PDSI reconstruction and Niño-3.4 SST. Arrows indicate the phase of the coherence, where right is in phase and left is antiphase; note that significant regions all show an in-phase relationship, which supports the idea that there may be a simple cause and effect relationship between the two phenomena. Otherwise as in (b). Note decadal-to-multidecadal variability in both the MTM and wavelet analyses (interpreted as being indicative of protracted and low-frequency ENSO variability), in addition to spectral activity in more classical ENSO bandwidth of 2–7 years. This figure is available in colour online at www.interscience.wiley.com/joc

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other analyses will further aid our understanding of the nature and origin of Indian Ocean climatic variability, its relation to ENSO and the Asian monsoon, and how such activity may be modulated by future greenhouse warming.

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