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# Tropical climate influences on drought variability over Java, Indonesia

Rosanne D'Arrigo[1] and Jason E. Smerdon[1]

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[1] We investigate relationships between Indonesian drought, the state of the equatorial Indian Ocean, and ENSO using three instrumental indices spanning 1884–1997 A.D.: 1. EQWIN, a zonal wind index for the equatorial Indian Ocean; 2. the Dipole Mode Index (DMI), an indicator of the Indian Ocean SST gradient; and 3. tropical Pacific Niño-3.4 SSTs. A regression model of the Java Sep–Dec Palmer Drought Severity Index (PDSI) using a combination of these indices provides significant predictive skill ($ar^2 = 0.50$). Both the DMI and EQWIN correlate strongly with Java droughts ($r = 0.71$ and 0.66, respectively), but weakly with wet events ($r = 0.21$ and 0.18, respectively), while the Niño SST index correlates moderately with both dry and wet events ($r = 0.31$ and 0.36, respectively). Our findings indicate that Java droughts are intensified during El Niños that coincide with negative EQWIN conditions, which are also linked to a strengthened Indian monsoon.

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## 1. Introduction

[2] The Indonesian Archipelago is situated squarely at the crossroads of the Indian and Pacific Oceans. Severe drought and flood events, which cause much hardship for populations that occupy this vast region, are strongly impacted by conditions in both ocean areas: the El Niño-Southern Oscillation or ENSO that originates in the tropical Pacific [*Allan*, 2000] and tropical Indian Ocean variability associated with the Indian Ocean dipole mode [*Gadgil et al.*, 2003, 2004; *Abram et al.*, 2003; *Saji et al.*, 1999; *Webster et al.*, 1999]. El Niño warm events (La Niña cold events) and positive (negative) Indian Ocean dipole episodes tend to be associated with western Indonesian drought (wet) conditions [*Saji et al.*, 1999; *Webster et al.*, 1999]. Measures of the strength and polarity of these ocean and atmosphere conditions have been developed into several well-established indices. El Niño-sea surface temperatures (SSTs), and the Southern Oscillation Index (SOI) are key indices used to represent the state of the tropical Pacific [*Allan*, 2000]. The Indian Ocean Dipole Mode Index (DMI), based on the SST anomaly gradient over the equatorial Indian Ocean, and the equatorial zonal wind anomaly index (EQWIN) together represent the state of the Indian Ocean atmosphere-ocean system [*Saji et al.*, 1999; *Ihara et al.*, 2007]. The relationships between these three climate indices and Indonesian rainfall are strongest in boreal autumn when there is the greatest coherency between Indonesian climate and large-scale Indo-Pacific Ocean variability [*Haylock and McBride*, 2001; *Aldrian and Susanto*, 2003]. The extent to which these indices are closely related will not be considered here, where for convenience we will refer to the Indian Ocean and Pacific Ocean climate indices as though they are distinct entities [*Saji et al.*, 1999; *Allan et al.*, 2001]. We note, however, that Indian Ocean SST anomalies have been closely linked to ENSO [e.g., *Allan et al.*, 2001; *Wu and Kirtman*, 2007].

[3] In addition to studies that have focused on hydrologic variability in Indonesia, the links between Indian summer (Jun–Sept) monsoon rainfall (ISMR), ENSO, and the Indian Ocean dipole have also been investigated [*Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007]. When combined, ENSO and EQWIN indices were found to provide a significantly better model of the ISMR over recent decades (since 1979) than Niño SSTs alone, reflecting the important role played by the Indian Ocean in determining ISMR variability [*Gadgil et al.*, 2003, 2004]. Similarly, *Ihara et al.* [2007] recently used longer data sets of these variables from 1881–1998 A.D., finding that although El Niños are generally linked to failed Indian monsoons, excess ISMR can still occur if a negative EQWIN phase occurs together with an El Niño event. Comparable associations were not found with the DMI or with La Niñas.

[4] A three-way link between ENSO, the ISMR and the Indian Ocean dipole has been used to explain the absence of ISMR droughts during some El Niño years, such that when the ENSO-ISMR link weakens, the Indian Ocean influence on ISMR strengthens [*Ashok et al.*, 2001]. Although the precise mechanism is not well understood, a northward shift in westerlies can occur during El Niños coupled with negative EQWIN conditions (although not necessarily a negative DMI, the other major indication of a positive IOD state). During such conditions, warm waters in the western Indian Ocean are linked to anomalous ascent over India [*Ashok et al.*, 2001; *Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007]. This negative EQWIN state (also linked with drought in western Indonesia) may weaken the impact of ENSO on the ISMR by inducing anomalous surface divergence in the eastern tropical Indian Ocean, stimulating convection that propagates northward causing anomalous ascent and surplus rainfall over India. A stronger ISMR 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. The proposed link between ISMR and the Indian Ocean may therefore operate in both directions.

[5] In previous studies, we investigated relationships between the boreal autumn Java Palmer Drought Severity Index (PDSI [*Dai et al.*, 2004]), Indian Ocean dipole and tropical Pacific ENSO indices for recent decades (since 1958 [*D'Arrigo and Wilson*, 2008]), and for earlier intervals

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[1] Lamont-Doherty Earth Observatory, Palisades, New York, USA.

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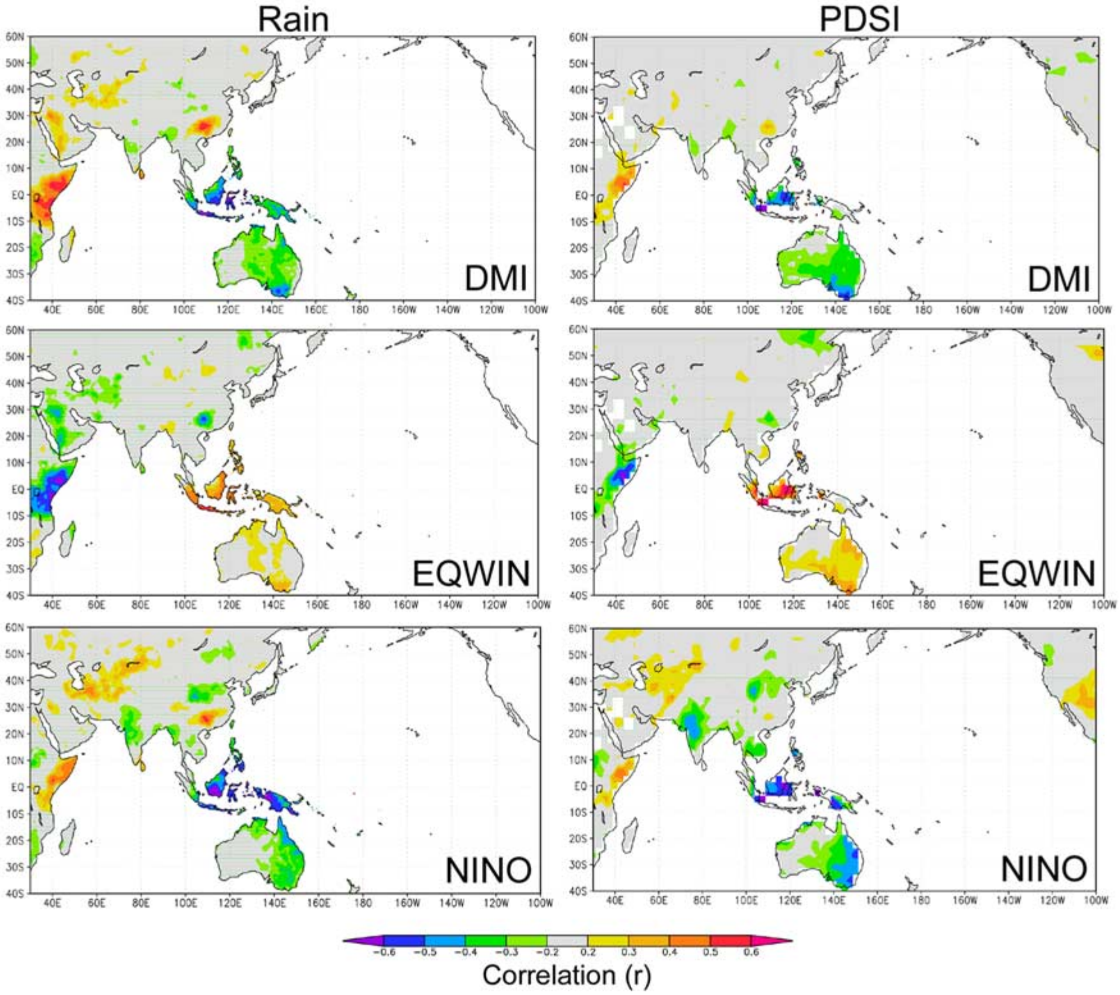

**Figure 1.** Sep–Dec DMI, EQWIN and NINO indices vs same-season rainfall [*Mitchell and Jones*, 2005] and PDSI [*Dai et al.*, 2004] for the tropical Indo-Pacific sector for 1901–1997. The 95% level of statistical significance for this interval applies for correlations exceeding ±0.168, given the associated degrees of freedom.

beginning in 1787 using proxy data [*D'Arrigo et al.*, 2008]. In the work by *D'Arrigo and Wilson* [2008], the best regression model of boreal autumn Java PDSI for the post-1958 period was found using all three variables as predictors (EQWIN, DMI and NINO-SST; ar$^2$ 0.71). Here, we further explore the spatial relationships between the Indian and Pacific Ocean climate indices and Indonesian rainfall using longer instrumental records available since the late 19th century. We also examine aspects of the multivariate influence of ENSO and the Indian Ocean on Java PDSI and the Indian monsoon.

## 2. Data

[6] We use the monthly PDSI [*Dai et al.*, 2004] from 1879–2003 A.D., which integrates both surface air temperature and precipitation and is considered a more sensitive, less noisy indicator of drought than rainfall station data. The gridded PDSI data were averaged over the island of Java, Indonesia (5–10°S, 105–115°E). We focused herein on the Sept–Dec season that includes the end of the dry monsoon and onset of the wet monsoon in Java, when rainfall is most coherent with large scale Indo-Pacific climate [*Haylock and McBride*, 2001; *Aldrian and Susanto*, 2003]. We use the extended monthly DMI of *Saji et al.* [1999] (http://www.jamstec.go.jp/frsgc/research/d1/iod/), which spans 1869–2002 and is based on the global SST data set of *Kaplan et al.* [1998]. A monthly index of zonal surface wind anomalies for the equatorial Indian Ocean (EQWIN) was derived from ICOADS data for which anomalies were averaged over 62–90°E, 4°N–4°S, from 1884–1997 [*Worley et al.*, 2005]. Rainfall data were obtained from the GPCC Variability Analysis of Surface Climate Observations data set from 1951–2000 (Vasclim-0 0.5 [*Beck et al.*, 2005]), and the CRU Ts 2.1 0.5° analysis data set (1901–2002) [*Mitchell and Jones*, 2005]. Also used are standard ENSO indices (http://www.cpc.noaa.gov), including Niño-3.4 SSTs and the ISMR index of *Sontakke et al.* [1993] and *Sontakke and Singh* [1996].

## 3. Empirical Predictors of Java Drought

[7] Spatial correlation fields (Figure 1) are used to demonstrate the linkages between Indian Ocean and ENSO indices with rainfall and PDSI over Indonesia and other land areas around the Indian Ocean Rim for 1901–1997. The

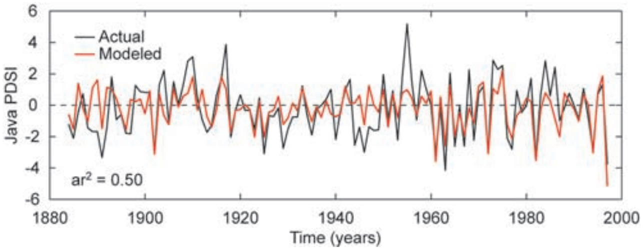

**Figure 2.** Actual Java Sep–Dec PDSI and optimal modeled time series based on Sep–Oct DMI-EQWIN-NINO model from 1884–1997 (ar$^2$ 0.50).

Indian Ocean DMI and EQWIN indices show stronger correlations with rainfall and PDSI over westernmost Indonesia, while correlations with Niño tropical Pacific SST are strongest over the eastern part of the country. Furthermore, the correlations over Indonesia are strong for both the rainfall and PDSI variables, while the patterns and strength of correlations can change for these variables in other land regions adjoining the Indian Ocean Rim. These robust features speak to the strength of the association between hydrologic variability in Indonesia and the collective state of the Indo-Pacific atmosphere-ocean system.

[8] To understand the predictive skill of the three climate indices of the tropical Indo-Pacific for the boreal autumn Java PDSI, we develop a series of regression models as in the work by *D'Arrigo and Wilson* [2008], but over a longer period of time. We assume multivariate linear models in which we employ individual indices as predictors of monthly/seasonal Java PDSI, or linear combinations of the three indices (Table S1[1]). The best model (ar$^2$ = 0.50) was found using the combined Sep–Oct DMI-EQWIN-NINO indices as predictors (the Oct model is virtually identical). Although this model is associative rather than predictive, note that a number of the models indicated in Table S1 based on earlier months/seasons have predictive skill. The success of the DMI-EQWIN-NINO model is consistent with the previous analysis performed for the post-1958 period only, in which these three indices were significant predictors (ar$^2$ = 0.71) of the Java PDSI [*D'Arrigo and Wilson*, 2008]. The adjusted r-squared value of this DMI-EQWIN-NINO model is significantly higher than for model versions based on any of these three variables alone for any month or season (Table S1). In particular, the NINO-only model accounts for only 0.30 of the PDSI variance, indicating that there is considerable improvement when the Indian Ocean variables are included.

[9] We plot the actual and modeled Java PDSI time series in Figure 2. The DMI-EQWIN-NINO model validates well using several calibration and verification statistics over the early and later halves of the common period used in the regression analysis [*Cook and Kairiukstis*, 1990] (Table S2); e.g. the Reduction of Error (RE) and Coefficient of Efficiency (CE) statistics are strongly positive in both cases: values for both statistics are 0.55 for the early calibration model and 0.35 for the late calibration model. These two statistics are useful measures of shared variance between actual and modeled series, with the CE providing the more rigorous test for validation [*Cook and Kairiukstis*, 1990]. Additionally, the variance inflation factor and Durbin Watson statistics indicate that there is little or not multicollinearity or autocorrelation in the models and residuals (Table S2; caption). These results indicate that inclusion of the Indian Ocean variables considerably improves the accuracy of ENSO-only based models of drought for Java [e.g., *Naylor et al.*, 2007], and that they can be used together with indices of ENSO to improve predictive models of drought over the region.

## 4. Extreme Drought and Wet Events in Java, Indonesia

[10] In order to examine relationships between the Indo-Pacific climate indices and drought and wetness years in Java, the three indices, along with the Sep–Dec PDSI record, were normalized over the 1884–1997 period of analysis. Normalized departures of Java PDSI for the dry (n = 59 yr) and wet (n = 55 yr) halves of the PDSI record were then compared with the values of the DMI, EQWIN and Niño-3 SST indices in corresponding years (Figure S1). The two Indian Ocean climate indices (DMI and EQWIN, inversely correlated at $r = -0.7$) display similar, asymmetric relationships with the Java PDSI. For both, strong correlations are observed with Java dry events, but much weaker correlations are found for wet events. One likely factor contributing to this asymmetry is that positive IOD events (i.e. those characterized by negative EQWIN and positive DMI values), which are linked to Java drought, tend to demonstrate more robust anomalies than negative IODs [*Saji et al.*, 1999; *Saji and Yamagata*, 2003]. Correlations between the Indian Ocean indices and the Javan droughts are stronger than those found for the Niño-3 SST index, which shows more moderate correlations consistent in magnitude between Java dry and wet events.

## 5. Java Drought and the Indian Monsoon

[11] We next investigate connections between Java drought, ENSO, the Indian Ocean dipole and the ISMR [*Ashok et al.*, 2001; *Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007]. There is a tendency for positive Niño-3 SST values, representing El Niño warm events, to coincide with drought conditions over both western Indonesia (including Java) and India [e.g., *Allan*, 2000]. The years 1961 and 1994 were two of only three exceptions to this expected pattern over the 1884–1995 period (the ISMR record ends in 1995). Both years featured positive IOD events, with strongly negative EQWIN and strongly positive DMI values (Table S3) [*Saji et al.*, 1999; *Abram et al.*, 2003; *Saji and Yamagata*, 2003]. El Niño conditions were only moderate in these years, coinciding with the expected *weakened* monsoon over Java but with a *strengthened* monsoon over India (Table S3) [*D'Arrigo et al.*, 2008]. Conversely, the year 1986 is the only El Niño over the study period with a *weakened* ISMR but a *strengthened* Java PDSI, the latter being the opposite of what is expected under strong El Niño conditions. This latter event coincided with a mildly positive EQWIN, which is consistent with a negative IOD state and wetter conditions over Indonesia. The DMI was positive in 1986, however, which would tend to favor drought in Java (Table S3). *Ihara et al.* [2007] note that at times EQWIN and the DMI behave in opposite ways, with this event being one possible

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032589.

example. These and previous results indicate that Indian Ocean dipole wind and SST anomalies can significantly impact Indian and Java monsoon conditions, at times overriding the tropical Pacific effects of ENSO.

[12] The ISMR record extends back to 1813 AD [*Sontakke et al.*, 1993; *Sontakke and Singh*, 1996], several decades prior to the common period we have used for analysis (1884–1997). In order to exploit this early part of the ISMR record (1813–1883), we compare it to a tree-ring and coral based reconstruction of the Java PDSI (1787–2003 [*D'Arrigo et al.*, 2006]) (Table S3). Comparison of these two extended records reveals three additional early years in which the ISMR and Java PDSI show anomalies of opposite sign, in contrast with the expected same-sign pattern of drought during El Niños. In two of these years (1842 and 1878), positive ISMRs contrast with negative Java PDSI; 1878 was also a time of very strong positive IOD and El Niño conditions [*Saji et al.*, 1999; *Abram et al.*, 2003] (Table S3). Thus, it appears that the ISMR-IOD link may have dominated over ISMR-El Niño dynamics in 1878. There is little supporting information for 1842, when positive Niño-SSTs would tend to support Java drought (although historical data do not indicate an El Niño at this time [*Ortlieb*, 2000]), while a negative EQWIN at this time would theoretically support an enhanced ISMR [*Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007]. 1864 is the one year in this early period with a negative ISMR but a positive Java PDSI. Although instrumental climate data is limited at this time, historical records of ENSO [*Ortlieb*, 2000] indicate that a major El Niño occurred in 1864.

[13] To summarize, during El Niños, the ISMR has been shown to be consistently deficient during a positive EQWIN state, but is often strengthened when EQWIN is negative [*Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007]. By comparison, drought over Java is consistently found during El Niños that coincide with a negative EQWIN state, but less so when EQWIN is positive, i.e. the average normalized departure of Java PDSI during El Niños with negative EQWIN is $-2.7$, considerably drier than for El Niños when EQWIN is positive ($-0.2$) (Table S3). Taken together, these and prior results [*Gadgil et al.*, 2003, 2004; *Ihara et al.*, 2007] suggest that a negative EQWIN state during El Niños contributes to a strengthened Indian monsoon (working against the expected pattern of a weakened Indian monsoon during El Niños), while at the same time contributing to an intensified Java drought (amplifying the expected pattern during El Niños).

## 6. Discussion and Conclusions

[14] Various combinations of three tropical Indo-Pacific climate indices were used in regression analyses of Java PDSI. The best model, yielding an $ar^2$ of 0.50, was obtained using the combined Indian Ocean (DMI and EQWIN) and Niño-3 SST indices as predictors. This result indicates the importance of climate conditions in both the Indian and Pacific Oceans in forcing monsoon rainfall over Java (Figure 2) and enhances understanding of the factors modifying Java climate for modeling and possibly predictive purposes. Previous studies have only used Niño-SSTs to model Java drought over the past few decades [e.g., *Naylor et al.*, 2007]. Our results confirm those of a similar study for the post-1958 period [*D'Arrigo and Wilson*, 2008], indicating that these relationships have held over the past century. The latter study also focused on a predictive model, using boreal summer climate predictors to estimate subsequent boreal autumn conditions. The results herein (Table S1) suggest similar predictive models, although we have focused on a concurrent (associative) one. The reduced predictive skill ($ar^2 = 0.50$ vs 0.71) for the longer time period at least partly reflects the lower data quality prior to recent decades. Additionally, the reduced predictive skill during the early period may also partly reflect the lower level of ENSO variability that has been observed for the mid-20th century [*Allan*, 2000]. Much of the remaining unexplained variance in Indonesian drought is likely related to local dynamical and orographic effects [*Haylock and McBride*, 2001; *Aldrian and Susanto*, 2003; *Wu and Kirtman*, 2007].

[15] Examination of extreme drought and wet years over the past century revealed that the association of Java PDSI with Indian Ocean atmosphere-ocean variability is much stronger during dry as opposed to wet events, while the correlations of Java PDSI with ENSO are more moderate and of comparable magnitude for both dry and wet events. We have extended this analysis back in time by comparing the early ISMR record of *Sontakke and Singh* [1996] and *Sontakke et al.* [1993] with a PDSI reconstruction for Java based on tree-ring and coral data [*D'Arrigo et al.*, 2006]. Analysis of extreme events showed that a strengthened ISMR and intensified Java drought can both occur during El Niños if the El Niño event coincides with negative EQWIN conditions. While some studies suggest that the ISMR can cause Java droughts by exciting a positive Indian Ocean dipole state [*Abram et al.*, 2007; *Overpeck and Cole*, 2007], others [*Ashok et al.*, 2001] contend that positive Indian Ocean dipole conditions can help force an enhanced ISMR, and Java drought. Either scenario points to enhanced (decreased) convection over India (Java) during El Niños with negative EQWIN conditions via the proposed mechanisms mentioned earlier. Analysis of corals from western Indonesia suggest that Java droughts were more intense/prolonged during the mid-Holocene, a time when there was a stronger Indian monsoon state that may have dominated over the presumably weaker El Niño conditions at this time [*Abram et al.*, 2007]. Determination of whether Indonesian droughts associated with present-day interannual ENSO variability and dipole events are similarly more severe as a direct result of strengthened Indian monsoon conditions will require further investigation [*Overpeck and Cole*, 2007].

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R. D'Arrigo and J. E. Smerdon, Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA. (rdd@ldeo.columbia.edu)