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Reconstructed streamflow for Citarum River, Java, Indonesia: linkages to tropical climate dynamics

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Abstract The Citarum river basin of western Java, Indonesia, which supplies water to 10 million residents in Jakarta, has become increasingly vulnerable to anthropogenic change. Citarum's streamflow record, only ~45 years in length (1963-present), is too short for understanding the full range of hydrometeorological variability in this important region. Here we present a tree-ring based reconstruction of September–November Citarum streamflow (AD 1759–2006), one of the first such records available for monsoon Asia. Close coupling is observed between decreased tree growth and low streamflow levels, which in turn are associated with drought caused by ENSO warm events in the tropical Pacific and Indian Ocean positive dipole-type variability. Over the full length of record, reconstructed variance was at its weakest during the interval from ~1905–1960, overlapping with a period of unusually-low variability (1920–1960) in the ENSO-Indian Ocean dipole systems. In subsequent decades, increased variance in both the streamflow anomalies and a coral-based SST reconstruction of the Indian Ocean Dipole Mode signal the potential for intensified drought activity and related consequences for water supply and crop productivity in western Java, where much of the country's rice is grown.

Keywords Streamflow · Java · Tree rings · ENSO · Dipole · Drought

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1 Introduction

Monsoonal droughts and floods in southeast Asia have profound impacts on human populations, particularly in rural settings where crop productivity is highly vulnerable to such extremes (Naylor et al. 2007). In such settings, the need for adequate and reliable water resources is of increasing concern. Some experts forecast severe water shortages, along with drought and flood extremes, for much of Asia in coming decades, with potentially profound impacts for human populations and the environment. One likely cause of such change is the release of anthropogenic greenhouse gases, which are expected to result in substantial alterations in the distribution and variability of rainfall (Bates et al. 2008). Circulation changes driven by expected warming are anticipated to impact the Intertropical Convergence Zone (ITCZ) and monsoonal rainfall patterns over much of southern Asia, although there is considerable uncertainty in future projections (Overpeck and Cole 2007; Abram et al. 2008; Vecchi et al. 2008). Water-related issues are thus of critical interest to those involved in sustainability and climate risk management efforts in drought and flood prone regions of the globe (e.g. Boer 2007).

In Indonesia, integrated action is needed by (local, regional, national) government, climate specialists and other planners to mitigate against the increased threats of extreme drought and related wildfires, as well as severe flood events, in areas where water demand, land use and development are rapidly on the rise (Aqil et al. 2007; Overpeck and Cole 2007; Abram et al. 2008; Field et al. 2009). Indonesia's most populated locations, including the island of Java (where much of the nation's rice is grown), are particularly vulnerable to extremes in rainfall and water shortages (Boer 2007).

The Citarum River basin (Figs. 1, 2) is one of the largest watersheds on the island of Java, Indonesia. It is highly vulnerable to environmental change and is already experiencing considerable water deficits due to severe pollution, land use and development (Boer et al. 2004). Streamflow in the Citarum basin comes mainly from rainfall during the Australasian monsoon wet season from November–April (Fig. 2). Java's monsoonal rainfall has its strongest climatic teleconnections associated with the atmosphere–ocean circulation phenomenon known as the El Niño-Southern Oscillation (ENSO) during the September–November months, at the onset of the wet season (Haylock and McBride 2001; Aldrian and Susanto 2003). Correlation of September–November and annual Citarum streamflow is 0.78, 1963–2006, means 122 vs 173 m^3, respectively. During El Niños, the low pressure cell over Indonesia and its associated rainfall activity moves eastward in the Pacific, causing drought across much of the country (Allan 2000). Cold sea surface temperature (SST) anomalies off Java-Sumatra linked to the positive phase of the Indian Ocean dipole (IOD) mode, an aperiodic oscillation in the Indian Ocean, can also contribute to drought over western Indonesia, and may be linked in a three-way interplay with the Asian monsoon and ENSO (Saji et al. 1999; Ashok et al. 2007; Abram et al. 2007, 2008; Field et al. 2009; Brown et al. 2009).

Historical records of streamflow are typically limited in length for many areas of Asia and the globe. The Citarum streamflow record (Figs. 1, 2), one of the longest such time series available across monsoon Asia, is only about 45 years in length. This is clearly insufficient for understanding the potential range of hydrological variability and extremes in this region, and how this variability may be changing in a warming world. There is therefore a need for additional information on the behavior of the Citarum River and other hydrologically-important locations in monsoon Asia. Long records of streamflow variability would thus be highly useful for assessing past activity, evaluating model simulations, and other applications relevant to climate risk management (Asian Institute of

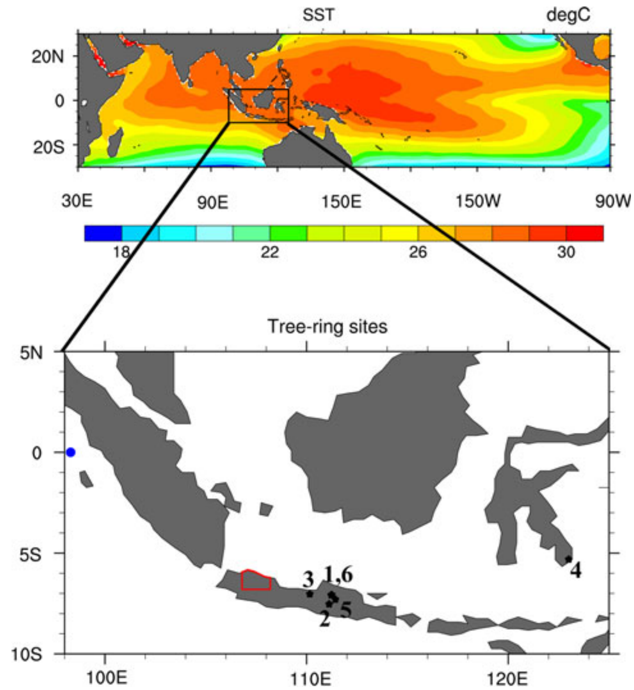

Fig. 1 Plot of Indian-Pacific Ocean Hadley Centre Global Sea Ice and Sea Surface temperature (HADISST), monthly anomalies; 1 degree area grids, 1870 to present; Rayner et al. 2003, 2006). for September–November target season for 1890–2007. *Inset* shows locations of teak tree-ring sites (*black stars*) for Java used to reconstruct Citarum streamflow; *blue dot* is location of Mentawai coral series (Abram et al. 2008), *red outline* shows location of Citarum river basin

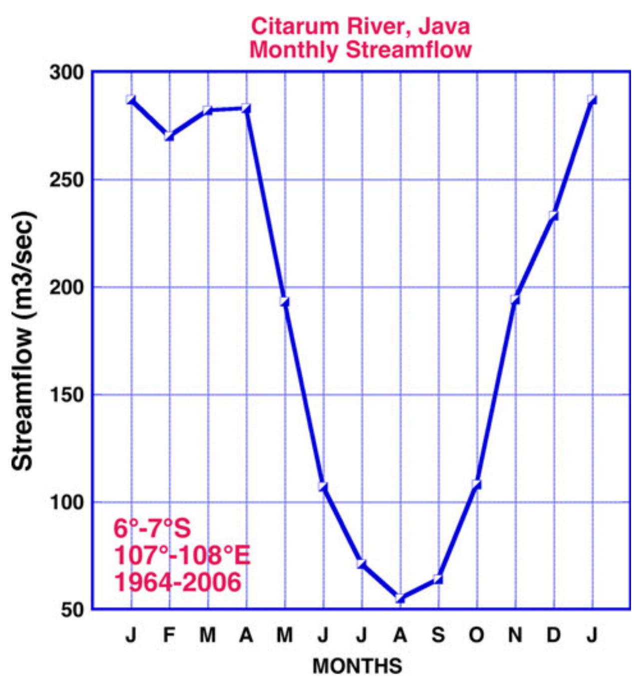

Fig. 2 Monthly average streamflow (m^3/sec) for 1963–2006 for Citarum River, Java. Data obtained from R. Boer, Bogor National University and Ministry of Public Works, Java, Indonesia

Technology 2005, http://portal.iri.columbia.edu/portal/server.pt, NOAA 2009).

Alternatively, high-resolution, well-dated proxy records from tree rings, corals and other data archives are of considerable value for developing longer time series for analysis. Tree-ring based hydrometeorological reconstructions have been developed for numerous sites around the globe. Notably, this research includes much work in the United States (e.g. Stockton and Jacoby 1976; Cleaveland 2000; Meko et al. 2001; Woodhouse 2002; Woodhouse et al. 2006), as well as Turkey and other locations (e.g. Akkemik et al. 2008,) However, paleostreamflow records are quite limited for Asia (e.g. for China—Gao et al. 2006, and Mongolia—Pederson et al. 2001), particularly near the equator.

In this paper, we present a tree-ring reconstruction of Citarum River streamflow that extends available instrumental observations by more than two centuries, and discuss its linkages with both tropical Indian and Pacific atmosphere–ocean climate variability. The tree-ring based Citarum River basin streamflow reconstruction was generated using a tree-ring chronology network from *Tectona grandis* (teak) using multiple sites across western Java and Sulawesi, Indonesia. Based on the closely coupled relationships between tree growth, rainfall, and Indo-Pacific climate for this region, this reconstruction was used to quantitatively assess past hydrometeorological variability over the pre-instrumental period. We compare this record to other observational and proxy records for the region, specifically to a coral-based index of Indian Ocean SSTs (Abram et al. 2008). Along with tropical Pacific variability linked to ENSO, Indian Ocean climatic conditions have been implicated as a dominant factor forcing drought and wetness extremes across much of Australasia (Abram et al. 2008; Ummenhofer et al. 2009).

2 Materials and methods

2.1 Instrumental data

We use the instrumental gauge record of monthly streamflow for the Citarum Basin, west Java (Figs. 1, 2) to calibrate the tree-ring reconstruction. The Citarum River has experienced considerable human modification due to land usage and other factors (Santoso and Warrick 2003; Lasco et al. 2004; Boer et al. 2004, 2005, 2007). Despite this, it correlates very strongly with large-scale climate variables, e.g. the Southern Oscillation Index (May–July, $r = 0.49$, 0.0007, $n = 44$) and Dipole Mode Index or DMI (Oct-Nov HADISST, $r = -0.75$, 0.0000, $n = 44$). Albeit short, it is one of the longest and highest quality streamflow records for Indonesia, spanning from 1963-present (data from the Ministry of Public Work, Republic of Indonesia; kindly provided by Dr. R. Boer, Bogor National University, Bogor, Java, Indonesia). This reconstruction is only relevant to the Citarum station; other streamflow records for Java are typically 10 years or less in length (R. Boer, Bogor Agricultural University, pers. comm..). Gridded HADISST (global ocean surface temperature, monthly 1 degree area grids, 1870 to present, Hadley Center, UK; Rayner et al. 2003), rainfall data from the Vasclim (Variability Analysis of Surface gridded monthly rainfall dataset, Climate Observations, analysis, 1951–2000, 0.5° spatial resolution (Beck et al. 2005), and the Kaplan Nino-3.4 SST index (1856-present, anomalies in 5S–5N, 120–170W, Kaplan et al. 1998; Knutson et al. 1999) were also used for comparison to the reconstruction, using simple and spatial field correlation analyses. Analyses were performed using KNMI Climate Explorer (http://climexp.knmi.nl/).

2.2 Indonesian proxy data

The teak tree-ring records that have been developed for Indonesia by the Lamont-Doherty Earth Observatory's Tree-Ring Laboratory (TRL-LDEO) have been described in detail elsewhere, and have been shown to be sensitive to past drought variability (D'Arrigo et al. 2006a, b, 2008) (Table 1). The teak sites are typically natural plantations that are mainly found in central and east Java. Although not definitively proven, it is generally believed that teak was introduced in Java from mainland south Asia many centuries ago. These natural plantations are typically sites that have been retained as natural parks and are not managed by irrigation or other modifications. Some of these records, along with coral data for the region, were used previously to reconstruct warm pool SSTs (D'Arrigo et al. 2006a) and the Palmer Drought Severity Index (PDSI), a metric that incorporates both precipitation and temperature information (Dai et al. 2004; D'Arrigo et al. 2006b, 2008). Relationships were identified between Java drought and tropical Pacific (ENSO) and Indian Ocean (dipole) climate parameters, including SST variability (D'Arrigo and Wilson 2008; D'Arrigo et al. 2006b, 2008). This work has been part of a larger-scale project to reconstruct the climate of monsoon Asia for the past millennium (Buckley et al. 2006; (http://www.ldeo.columbia.edu/res/fac/trl/research/AsiaMonsoon/AsiaOverview.html). These records together provide good coverage across the island of Java, the region of most relevance to this paper.

We also utilize the coral-based reconstruction of the Indian Ocean Dipole Mode Index (DMI SST) (Abram et al. 2008; Fig. 1), which includes coral oxygen isotope data for the Mentawai Islands, off Sumatra, western Indonesia, for independent validation of the Citarum streamflow reconstruction. This record is based upon a suite of coral isotopic

Table 1 Tree-ring site information for six candidate chronology predictors used in nested regression models to reconstruct Citarum River, Java streamflow

Site name	Record length	Longitude	Latitude	Correlation year t ($t+1$)
1. Bekutuk	1834–2004	111.22°E	7.07°S	0.61 (−0.22)
2. Donoloyo Cagar Alam	1746–2004	111.12°E	7.52°S	0.18 (0.020)
3. Pagerwunung Darupono	1820–2004	110.16°E	7.02°S	0.42 (−0.52)
4. Muna	1673–2005	123.00°E	5.30°S	0.52 (−0.29)
5. Sakla (combined Saradan, Klangon Natural Forest)	1812–2004	111.43°E	7.29°S	0.14 (−0.29)
6. RBGB (combined Randublatung. Gubug Payung, Bekutuk, Begin)	1879–2004	111.25°E	7.06°S	0.75 (−0.13)

Record lengths are truncated to only include periods represented by more than 10 individual tree-ring series (radii). The number of series in each chronology are as follows: Bekutuk (20), Donoloyo (13), Pagerwunung (19), Muna (39), Sakla (45) and RBGB (71). Two series (Sakla and RBGB) represent composites in which data from individual sites was merged to improve sample replication. Correlations (r) with instrumental streamflow data for 1963–2000 common period are indicated for years t, the current year of growth, and $t+1$, in parentheses. Positive correlations in current year reflect tendency for greater radial growth of teak when precipitation and streamflow are above average

Table 2 Calibration and verification statistics for four nested reconstruction models. Ar^2: variance explained in calibration period, accounting for degrees of freedom

Proxy nests	Calibration period	Verification period	ar^2 (%)	P	RE	CE	Sign test
1. 6 Proxy Series: 1834–2000	1963–2000		53				
	1963–1979	1980–2000	66	0.68 (0.00)	0.44	0.43	15+5− (0.02)
	1980–2000	1963–1979	38	0.87 (0.00)	0.73	0.73	12+4− (0.04)
2. 5 Proxy Series: 1830–2000	1963–2000		46				
	1963–1979	1980–2000	61	0.64 (0.00)	0.36	0.36	14+6− (0.06)
	1980–2000	1963–1979	28	0.81 (0.00)	0.60	0.60	12+4− (0.04)
3. 4 Proxy Series: 1820–2000	1963–2000		37				
	1963–1979	1980–2000	51	0.61 (0.00)	0.31	0.31	15+5− (0.02)
	1980–2000	1963–1979	24	0.78 (0.00)	0.53	0.52	12+4− (0.04)
4. 3 Proxy Series: 1759–2000	1963–2000		11				
	1963–1979	1980–2000	35	0.51 (0.01)	0.21	0.21	14+6− (0.06)
	1980–2000	1963–1979	18	0.59 (0.01)	0.30	0.30	12+4− (0.04)

P Pearson's correlation coefficient, positive (negative) Sign Test results for calibration period indicate number of years in which tree-ring estimates correctly, + (incorrectly, +) track sign of observations (Cook and Kairiukstis 1990)

Verification: *RE* reduction of error, *CE* coefficient of efficiency statistics Note that sample size reaches a minimum of 30 series for the early period of the least replicated nest (3 proxies, at least 10 samples each, 1759–2000), increasing to over 200 for the most replicated recent nest (1834–2000, 6 proxies) (see Table 1)

records from across the Indian Ocean with a common period since 1846. These data were used to develop a basin-wide gradient index of SST variability linked to the IOD system, ENSO and the Asian monsoon.

2.3 Reconstruction development and analysis

Standard methods of dendroclimatic reconstruction development were used herein (Cook 1985; Cook and Kairiukstis 1990). As outlined in prior studies (D'Arrigo et al. 2006a,b), the raw tree-ring series for Java were detrended following a power transformation technique (Cook and Peters, 1997). A two-step procedure was utilized, which involved stabilization of variance using a power transformation (based on local mean and standard deviation). The potential for end fitting-type bias is minimized by calculating residuals from expected growth curves, rather than ratios. Detrending was performed using negative exponential or linear negative/zero slope functions prior to generation of final ring-width chronologies for the sites in Java. Sample depth decreases back in time because older trees, particularly for the commercially valuable teak, are relatively rare in Java today. In order to improve early sample depth, raw data from some sites were composited (D'Arrigo et al. 2006a, b). Thus, raw ring width measurements for a few sites were combined prior to generation of final chronologies. Rigorous calibration-verification statistics (Cook and Kairiukstis 1990) were used to test the statistical significance and reliability of the reconstruction (Table 2). These include the reduction of error (RE), coefficient of efficiency (CE), sign test (ST), and Pearson's correlation coefficient (Fritts 1976; Cook and Kairiukstis 1990). A split period calibration-verification scheme was applied. Principal components regression analysis (Cook and Kairiukstis 1990) was the method used to develop the reconstruction of Citarum streamflow. A nested record was generated in order to optimize the length of the reconstructed series (Cook et al. 2002; D'Arrigo et al. 2006a, b). This is needed because, as noted above, replication weakens going back in time, as the number of tree-ring samples typically declines in the earlier part of the record, typical of proxy data. This process was taken iteratively as each proxy series left the data matrix, until the final longest proxy series remained. For this study, six candidate chronology predictors (see Table 1) were utilized and four nested series were developed. To derive the final reconstruction, the mean and variance of each nested series were adjusted (normalized) to that of the most replicated nest in order to minimize artifact-related changes in variance through time, with the relevant sections of each nested series then all spliced together to derive the final reconstruction.

The reconstruction is most robust at higher frequencies, since the instrumental streamflow time series for the September–November season has no autocorrelation, and since the proxies were prewhitened to remove persistence (there are varying degrees of coherency at low frequencies for some series (Cook and Kairiukstis 1990). Lags t and $t + 1$ were used in the regression (Cook and Kairiukstis 1990).

Trends in the recurrence rate of low flow and high flow streamflow events were tested against the null hypothesis of constant recurrence rate. A Gaussian kernel analysis was employed for this purpose (Mudelsee et al. 2003), for which the event threshold was set at -1 sigma for low flow and $+1$ sigma for high flow events, with the data normalized for the 1963–2000 period of overlap between the observed and reconstructed streamflow data. The kernel window was 35 years and 10,000 bootstrap simulations were used to estimate the 90% confidence interval.

3 Results and discussion

Our reconstruction is based upon a significant and positive relationship between tree-ring width variations of teak trees (*Tectona grandis*) for several sites on the island of Java east of the Citarum basin (Table 1; Fig. 1;) and Citarum streamflow during the months of September–November. We have not found old-growth teak sites in the more populated Citarum basin area. This relationship signifies that tree growth increases when moisture availability from rainfall, and hence streamflow, is above average. Correspondence (as measured by monthly correlation, regression analyses) between teak tree growth, streamflow and climate are consistent with prior instrumental analyses that indicate that the most coherent, large-scale climate signal over Java is related to Pacific and Indian Ocean atmosphere–ocean conditions during this dry, pre-monsoon season (Haylock and McBride 2001; Aldrian and Susanto 2003). The final nested reconstruction based on the Java tree-ring chronologies (Table 1; Fig. 1) spans from AD 1759–2006 (instrumental variance spliced onto reconstruction since 2000). Figure 3 compares the streamflow observations with those estimated in regression analysis using the tree-ring data for the most replicated (1834–2000) nest. This regression model accounts for 53% of the variance (ar^2) in streamflow observations over the common period from 1963 to 2000 (Table 2). Some of these sites were used previously to reconstruct a Java-wide (5–10°S, 105–115°E) drought index, the PDSI (D'Arrigo et al. 2006b), which is positively correlated with Citarum streamflow: $r = 0.79$ over 1963–2002.

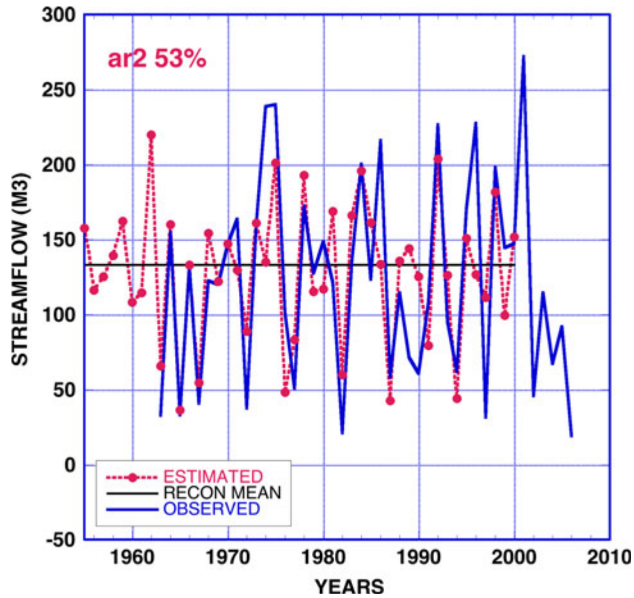

Fig. 3 Observed and estimated September–November streamflow record for Citarum River, West Java Indonesia for 1963–2000 (instrumental observations shown through 2006). Tree-ring estimates are based on most replicated nest which represents the common period for all chronology predictors (1834–2000). The tree growth-streamflow relationship, as for precipitation, tends to be stronger for dry years

The entire Citarum streamflow reconstruction is presented in Fig. 4, and calibration and verification statistics (Cook and Kairiukstis 1990) used to evaluate the validity and stability of the nested regression models are described in Table 2. The reconstruction demonstrates reasonably strong statistical results, although as noted the common

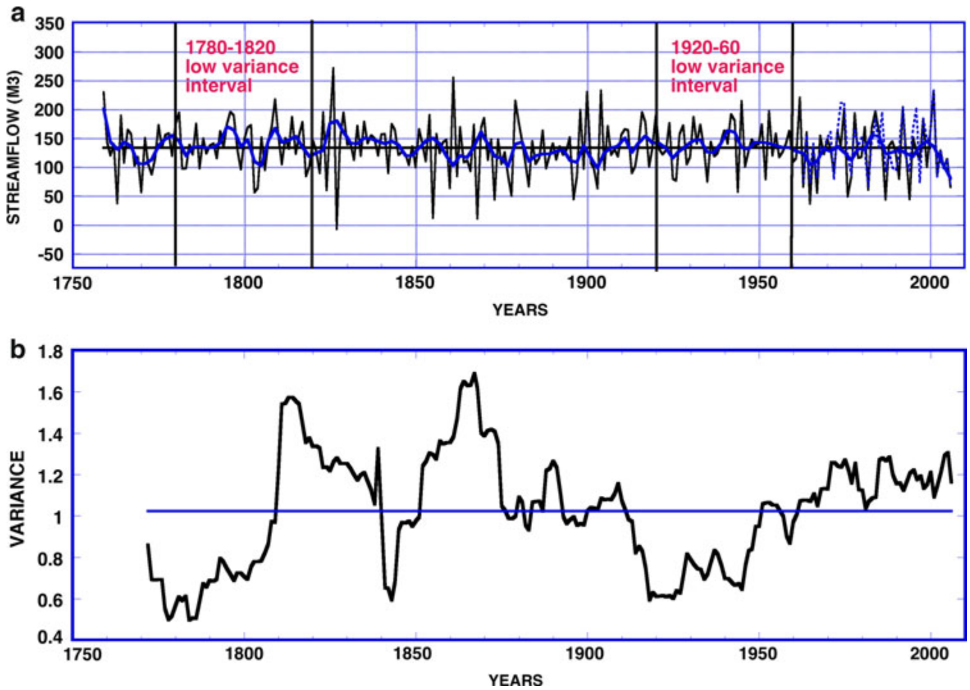

Fig. 4 Upper plot, September–November Citarum, Java streamflow reconstruction based on teak tree rings, spanning from 1759 to 2000 (*black line*; *solid blue line* shows 5-year smoothed values). *Dotted blue line* shows streamflow observations since 1963. *Vertical black lines* denote well-known (Allan 2000) low-variance interval from 1920 to 1960 (variance 0.68; variance even lower, 0.64 over period from 1905 to 1960), and previous interval of similar length (1780–1820) that also displays low variance (0.71) relative to variance of entire record (1.01). The four nested intervals begin in 1759, 1820, 1830 and 1834. Lower plot, sliding 31-year variance of normalized streamflow reconstruction showing low variance intervals in ~1780–1820 and 1920–1960

period available for analysis is quite short (Fig. 3; Table 2). The statistical results also weaken back in time, as expected, as the number of predictors and sample size decline towards the earlier part of the record. We therefore truncated the reconstruction at 1759, when each of the individual chronologies utilized in the reconstruction is based on at least 10 individual wood samples (an arbitrary indication of sample replication; Table 1). Although the level of explained variance weakens considerably in the early part of the record (from 53%, most replicated nest; to 11%, least replicated nest), there is still useful climatic information in even the least replicated nests, which demonstrate moderately positive reduction of error (RE) and coefficient of efficiency (CE) values. The CE is considered a particularly rigorous indicator of model skill (Cook and Kairiukstis 1990) and can be used to conclude that there is meaningful information in the reconstruction over its length. In addition, the significant Sign Test results, nearly all statistically significant above the 0.05 level, are a good indication that the trees are correctly tracking the sign of change between the observed and reconstructed values in the instrumental period. The weakening of model stability back in time is partly related to the period of low variance described below, which appears to impart a weaker climatic signal in the tree data. The teak climate signal is also most robust for drought rather than flood events, as found in other tree-ring studies (Fritts 1976). This non-linearity in tree growth response is likely at least partly the explanation for larger residuals in some wet years. Correlation of the Citarum streamflow reconstruction with the Southern Oscillation Index (SOI) for June–September is $r = 0.46$ (0.0000, $n = 141$, Climatic Research Unit—CRU, East Anglia, UK). For the Dipole Mode SST Index (DMI, 1958–2006, HADISST), $r = -0.59$, August–October, 0.0000, $n = 49$). Both correlations are consistent with the tendency for greater drought in Java and decreased tree growth during ENSO warm events and positive IOD events, respectively.

A low-variance period in the early-mid 20th century is nearly unique over the full length of the reconstruction (Fig. 4**;** variance based on normalized data is 1.01 for entire 1759–2006 period, vs 0.64 for 1905–1960 and 0.68 for 1920–1960). The latter interval of low variability has been described as a pronounced weakening in the interannual variance of the monsoon-ENSO-IOD systems, primarily detectable within the 4–7 year peak bandwidth (Kestin et al. 1998; Torrence and Webster 1999; Allan 2000; Abram et al. 2008). The cause or causes of this low variance period are not known, but it is believed to be a system-wide phenomenon that is also linked to the

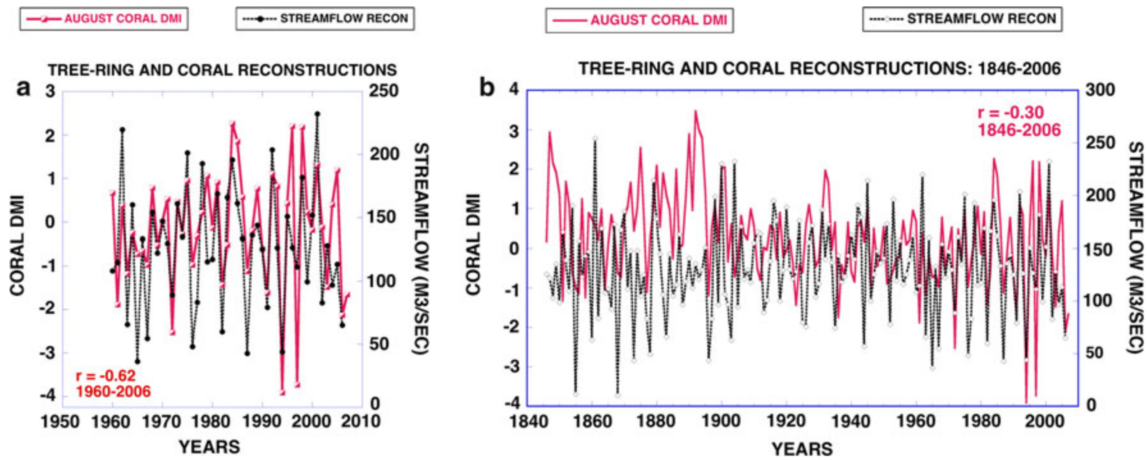

Fig. 5 Comparison of Citarum streamflow tree-ring reconstruction with coral Dipole Mode Index (DMI) sea surface temperature (SST) reconstruction (Abram et al. 2008), showing good agreement over recent decades for 1960–2006 common period (left plot). For the coral data we used values for the month of August, for which correlations were optimal between the two proxies; other months and seasons from August-November also showed significant but slightly lower correlations. Sign of coral record was reversed for ease of visual comparison. Results for this recent period are significant ($r = -0.62$, 0.0000, $n = 47$), despite differences in setting (terrestrial vs. marine) and location (west Java vs across tropical Indian Ocean), reflecting common forcing from tropical Indo-Pacific climate variability during this interval. Correlation for the entire period of overlap (right plot, 1846–2006) is $r = -0.30$, 0.0001, $n = 161$. The weakened correlations pre-1960 are likely due to several factors: the increased frequency of positive IOD's in the recent period (tree rings are typically more sensitive to drought than wet events), the low variance in the 1920–1960 period (which would decrease the large-scale coherency between conditions in the Mentawai and Java areas), and the general weakening of proxy and instrumental data quality going back in time. Correlation of the coral record with actual Citarum streamflow is: −0.64 (1963–2006)

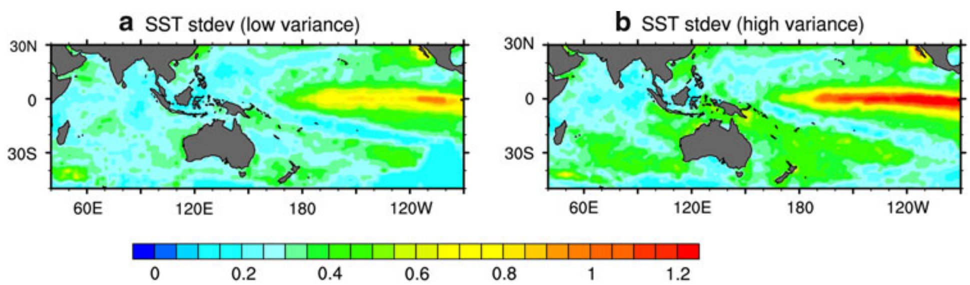

Fig. 6 September–November standard deviation of SST over the periods 1921–1960 (low variance, **a**) and 1976–2006 (high variance, **b**), relative to the entire period 1921–2006. As shown in Fig. 8 below, this figure demonstrates low variance in tropical Indian and Pacific Ocean conditions (ENSO and IOD) during the 1921–1960 period, relative to the later higher variance period. According to the classification of ENSO/IOD years in a study by Ummenhofer et al. (2009) (their Auxiliary Table 1), the period 1921–1960 also stands out in regard to the high number of neutral years, with 18 years without an ENSO and/or IOD event; this compares to 12 neutral years each for the periods 1881–1920 and 1961–2000

behavior of the Indian monsoon, and may involve a shift in internal atmosphere–ocean circulation variability, external forcing, or some combination of the two (see references above). Interestingly, reconstructed streamflow during an earlier period of comparable length (1780–1820) also features lower than average variance (0.71), and may indicate another time of relatively quiescent ENSO and/or IOD activity; although we caution that this event occurs during the earlier, less replicated part of the reconstruction.

Consistent with the above findings, correlation of the Citarum streamflow reconstruction with Niño-3.4 SSTs is low during the 1920–1960 period ($r = -0.22$ (ns), $n = 40$; results for September–October, slightly more optimal than September–November). Similarly, correspondence between the streamflow reconstruction and an independent, coral-based reconstruction of the Indian Ocean Dipole Mode Index (DMI SST—Abram et al. 2008; Fig. 5) is low during this period ($r = -0.20$ (ns), $n = 41$); reflecting the apparent decline in coherency of the large-scale atmosphere–ocean signal in the tropical Indo-Pacific at this time. Correlation for the entire period of overlap (1846–2006) is $r = -0.30$, 0.0001, $n = 161$—correlations are strongest post-1960 ($r = -0.62$; 1960–2006, 0.0000).

Other coral records from the tropical Pacific (Urban et al. 2000), and northeastern Australia (Hendy et al. 2003) also show weakening of linkages with ENSO, reflecting the

Table 3 Percentage of years in ~50 year reconstruction increments in which normalized departures of reconstructed streamflow exceed ±1 standard deviation

Time interval (years)	High flow (years) (%)	Low flow (years) (%)
1759–1808 (50)	10	10
1809–1858 (50)	16	8
1859–1908 (50)	14	20
1909–1958 (50)	14	10
1959–2006 (47)	15	23

Negative departures (low flow, dry) years often coincide with warm ENSO and positive IOD events, and positive departures (high flow, wet) years with cold ENSO cold and negative IOD events. Instrumental data is spliced onto reconstruction after 2000, after adjusting for mean and variance. Note that percentage of low streamflow events is the highest on record in recent decades, one indication of intensified drought activity linked to ENSO warm events and positive IOD conditions

considerable spatial extent of subdued ENSO (as well as IOD) conditions at this time (Fig. 6).

The subsequent interval (1963–2006) reveals a higher level of streamflow variance (1.23, based on reconstruction with spliced instrumental values;; decreasing slightly to 1.1 for 1963–2000, based on reconstructed values only) as well as the highest frequency of low streamflow events (events below–1 sigma) over the past two centuries (Table 3). A Gaussian kernel technique (Mudelsee et al. 2003) quantifies this result further, showing a significant ($p = 0.07$) increase in the number of low streamflow events in recent decades (Fig. 7), while the recurrence rate of high flow events shows no comparable significant trend. It is likely that the regime shift in the Pacific Ocean during this interval, which has seen an increase in warm ENSO events (Urban et al. 2000), is an important factor in the increased frequency of low Citarum streamflow events. Similarly, an intensification in the frequency and magnitude of positive IOD events since the 1960's (when correlation with the streamflow record is also found to be the strongest; Fig. 5) was detected in the coral DMI reconstruction (Abram et al. 2008), and attributed to increased seasonal upwelling in the eastern Indian Ocean. Correlation with the two proxies is strongest in the more recent high variability interval. Changes in Indian Ocean dipole activity, specifically an absence of negative IOD events, have also been linked to an intensification of droughts in Australia in recent decades, including the "Big Dry"of the past 10 years (Ummenhofer et al. 2009; Cai et al. 2009).

In order to further characterize the association between Citarum streamflow and large-scale tropical climate variability, we generated spatial correlation fields of the September–November streamflow reconstruction, as well as the coral DMI reconstruction (Abram et al. 2008), with gridded boreal autumn SST (Rayner et al. 2003) and rainfall (Beck et al. 2005) data for the tropical Indo-Pacific

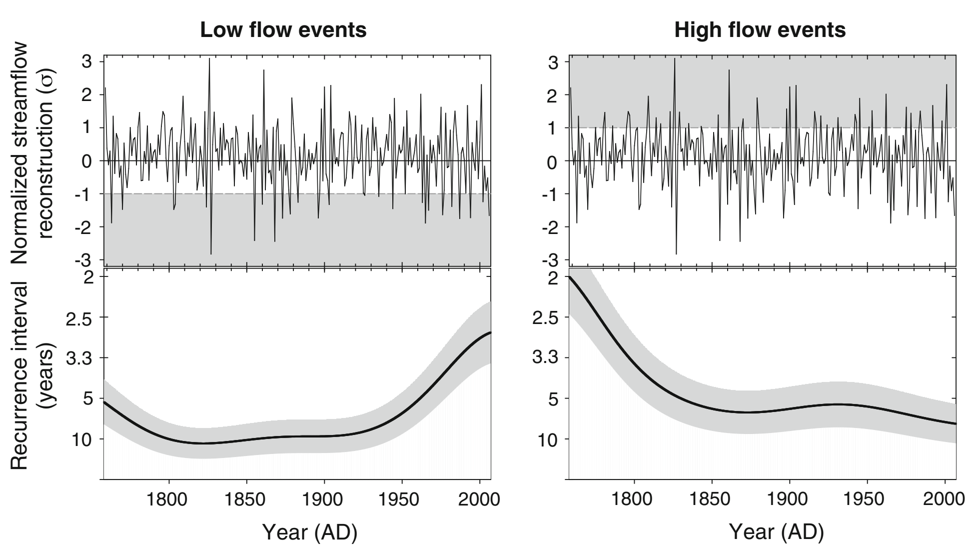

Fig. 7 Recurrence of low and high streamflow events in the Citarum basin, Java. *Upper panels* show the streamflow reconstruction (*black curve*) normalized over the 1963–2000 interval that overlaps with the instrumental record. Thresholds of −1 and +1 standard deviation (*grey dashed line*) were used to identify 27 years of low flow and 45 years of high flow, respectively, since 1758. *Lower panels* show the recurrence interval of low flow events (*left*) and high flow events (*right*) calculated using a Gaussian kernel technique (*black curve*) with 90% confidence interval (shaded band) using 10,000 bootstrap simulations and a kernel window length of 35 years. A significant increasing trend in low flow events is identified ($p = 0.07$ in the Cox-Lewis test; similar results and significance are also observed using a threshold of -1.5σ). This is consistent with similar findings of an increasing trend in the occurrence of IOD events in a coral reconstruction of the DMI (Mudelsee et al. 2003; Abram et al. 2008). High streamflow events show a non-significant decreasing trend ($p = 0.34$; or 0.13 with an increasing trend at the $+1.5\sigma$ threshold)

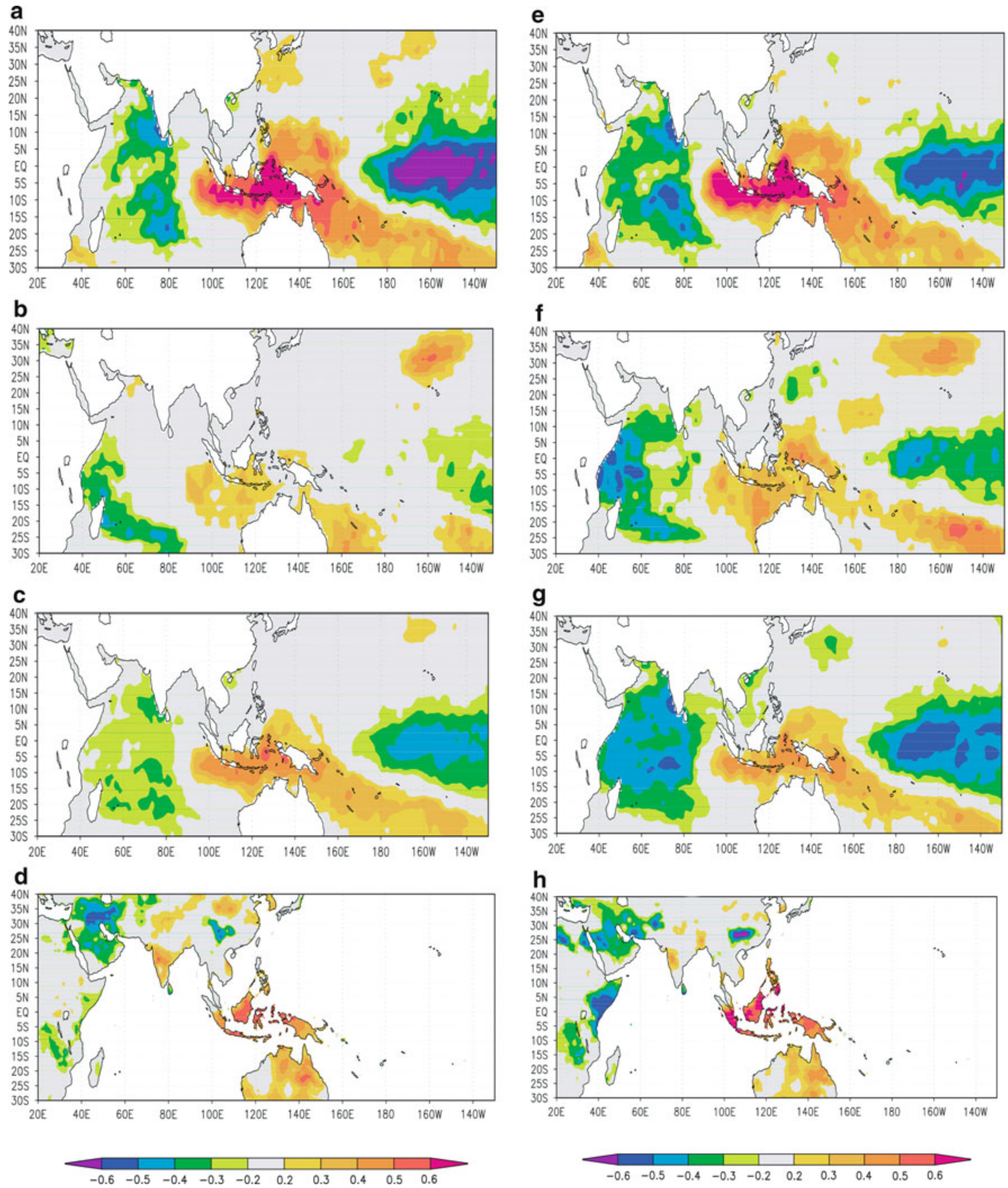

Fig. 8 Spatial correlation plots for Citarum streamflow (*left*) and coral DMI of Abram et al. (2008) (*right*) based on tree-ring and coral proxies, respectively, for September–November season (streamflow) and month of August (DMI; correlations were similar but slightly lower for other months or seasons) with gridded September–October HADISST (Rayner et al. 2003) and Vasclim rainfall (Beck et al. 2005); correlations were slightly higher for this season). Top panels (**a, e**): SST, recent interval from 1960 to 2006, second panels (**b, f**): SST, low variance period from 1920 to 1960, third panels (**c, g**): SST, extended interval from 1890 to 2006. Fourth panels (**d, h**): rainfall, over available period from 1951 to 2000. Results show closely similar climate signatures in the two proxies: correlations between the tree-ring and coral reconstructions are −0.62 for 1960–2006 (0.0000, $n = 47$); −0.20 for 1920–1960 (ns; $n = 41$); −0.39 for 1890–2006 (0.0000, $n = 117$). Sign of coral DMI reversed for comparison. Figure generated using KNMI Climate Explorer

Oceans (Fig. 8). Comparisons were made with SST's for the recent period (A, E; 1960–2006, for which intensified positive dipole activity can be observed), the low variance period from 1920 to 1960 (B, F; when spatial correlations are considerably weakened), and a longer common interval from 1890 to 2006 (C, G). Comparisons with rainfall were made for the interval since 1951 (D, H). The results reveal a common, large-scale signal in the coral and tree-ring proxies that is closely linked to tropical Pacific and Indian Ocean climate variability and to the ENSO, IOD and Asian monsoon systems during this boreal autumn season. As expected, SST correlations with the proxies are strongest during the most recent period (Fig. 8a, e) of highest replication and quality of proxy and instrumental data. Correlations are weakest for the low variance 1920–1960 interval (Fig. 8b, f), although some evidence of ENSO and IO dipole-type structure can still be observed. Large-scale climate signals are moderate over the longest interval of comparison relative to recent decades (Fig. 8c, g). The tree-ring and coral records also reveal quite similar spatial patterns with rainfall over the land areas surrounding the tropical Indian Ocean, reflecting the tendency for drought to occur over the Indonesian Archipelago. Australia and India, when there are wetter conditions over east Africa and the Arabian Peninsula during ENSO warm events and IOD events (Fig. 8d, h).

4 Conclusions

A long-term perspective on past streamflow variability has been provided by the tree-ring reconstruction for the Citarum River, west Java, Indonesia, one of the first such high-resolution proxy reconstructions for Indonesia and for monsoon Asia as a whole (Figs. 1, 2). Although the instrumental observations used for calibration and verification testing are limited in length, and proxy availability and model quality decline back in time, model statistics are reasonably robust over the more recent period of the reconstruction and provides some climatic information even back to the weaker, earlier part of the record. The reconstruction substantially extends the short streamflow record for the region, by several centuries. It displays sensitivity to both tropical Pacific and Indian Ocean climate conditions, as illustrated by the spatial correlation fields with large-scale SST and rainfall data for the region (Fig. 8). Over the common period, comparison with Niño 3.4 SSTs indicates a very weak correlation from 1920 to 1960, a time of unusually low (nearly quiescent) ENSO activity which is also evident in the trans-Indian Ocean coral DMI (Abram et al. 2008) and in tropical Pacific coral records (Urban et al. 2000). Our results indicate that the apparent weakening of the ENSO-IOD system that occurred at this time was unusual, and possibly unique, in the context of the past two centuries. It has been hypothesized that future greenhouse warming may lead to further intensification of tropical climate variability (Abram et al. 2008), and our results demonstrate that this could have serious implications for water resources in the Indonesian archipelago, including the Citarum basin.

This streamflow reconstruction adds to the network of proxy records and reconstructions being generated from across monsoon Asia (e.g. Buckley et al. 2006). The temporal and spatial coverage of this network is improving and will prove useful for eventual multiproxy studies that investigate ENSO evolution and behavior in the tropical Indo-Pacific region. In particular, this record might provide a useful verification tool for historical climate data rescued from historical archives (e.g. Atmospheric Circulation Reconstructions over the Earth, or ACRE, http://www.met-acre.org/Home). A multiproxy approach using tree rings, corals, and other proxies can be integrated with historical data to considerably aid understanding of the spatiotemporal evolution of ENSO, its stationarity over time and its teleconnections.

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