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Intensification of southwestern Indonesian rainfall over the past millennium

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[1] Modern precipitation in Indonesia is strongly correlated to variations in the Asian/Australasian monsoons, the Walker circulation, and migrations of the Intertropical Convergence Zone (ITCZ), but controls on multidecadal to millennial rainfall variations are less clear. We present a new, high-resolution, precipitation proxy reconstruction from Lake Lading (8°S, 113°E), Java, from 850 Common Era (C.E.) to present, based on the δD of terrestrial plant waxes. We find that rainfall has steadily increased in Java over the past millennium. This increase persists into the twentieth century despite evidence from other tropical proxy records for a northward ITCZ migration during the last two centuries, which should introduce drier conditions to Java. Aspects of this long-term increase in rainfall resemble records from the Northern Hemisphere, tropical Indo-Pacific, suggesting that strengthening Walker circulation played an important role in this long-term increase in rainfall and decrease in the δD of precipitation, while ITCZ variations may have been important to climate variations on multidecadal to centennial timescales.

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1. Introduction

[2] Variations in the tropical monsoons, the Walker circulation, and the Intertropical Convergence Zone (ITCZ) have all been cited to explain climatic changes in the tropics during the past millennium. Among the studies that are available, there is broad consensus that the ITCZ migrated over the past millennium in response to changes in the inter-hemispheric heat gradient [*Newton et al*., 2006; *Oppo et al*., 2009; *Sachs et al*., 2009; *Zhang et al*., 2008]. These findings are in general agreement with theoretical and modeling studies showing a southward shift of the ITCZ mean position in response to cooling in the Northern Hemisphere relative to the Southern Hemisphere [*Broccoli et al*., 2006]. Despite these changes in ITCZ mean position, proxy data indicate considerable disagreement as to the role of the ITCZ in causing continental hydrological variations during the past millennium, and we have very few high-resolution records from the tropical Indian and Pacific Ocean regions that span the past millennium to test the interactions between changes in the ITCZ and the Walker circulation. While some studies in the Indo-Pacific region have invoked north–south migrations of the ITCZ to explain coeval droughts and pluvials occurring on either side of its northern and southern extent during the Little Ice Age (LIA) [*Oppo et al*., 2009; *Sachs et al*., 2009], more recent studies from the region have suggested that a simple north–south gradient is not evident during the LIA [*Yan et al*., 2011]. These studies suggest that changes in Pacific Walker circulation may contribute to the significant zonal complexity observed during this time [*Tierney et al*., 2010].

[3] We present a new high-resolution record of the δD of terrestrial plant wax compounds (δD_{wax}) preserved in the sediments of Lake Lading (8°0.529′S, 113°18.75′E, 324 m asl), southwestern Indonesia (Figure 1). Lake Lading occupies a 0.14 km^2 maar crater in East Java, on the western slope of Mount Lamongan, one of Java's 22 historically active volcanoes associated with Sunda arc volcanism. Java is situated at the southwestern edge of the Indo-Pacific Warm Pool, bordering the Indian Ocean. Although rainfall in northern and equatorial Indonesia can be spatially heterogeneous, largely due to complex interactions between permanent orographic features and seasonal moisture convergence boundaries (Figure 1), southern Indonesia experiences a true monsoonal climate that is highly influenced by regional and remote sea surface temperatures [*Aldrian and Susanto*, 2003]. Lake Lading receives approximately ~2500 mm of rainfall per year, primarily during the Australasian summer monsoon season (October–March); in contrast, austral winter is particularly dry (Figure 1c).

[4] East Java is located near the southern extent of the wide band of precipitation associated with the ITCZ, making its precipitation highly sensitive to perturbations in the strength of the austral summer monsoon. Modern interannual variability is highly correlated with the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Zonal Mode (IOZM), which affect the length and intensity of the rainy season [*Aldrian and Susanto*, 2003]. Isotopes of precipitation in the region reflect these modes of variability [*Vuille et al*., 2005a; 2005b].

2. Sediment Core Preparation and Compound-specific δD Analysis

[5] Sediment cores LAD08-2P and LAD08-3P were collected from 8.6 m water depth in July 2008. Surface sediments are composed of massive silty clays, while deeper sediments

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All Supporting Information may be found in the online version of this article.

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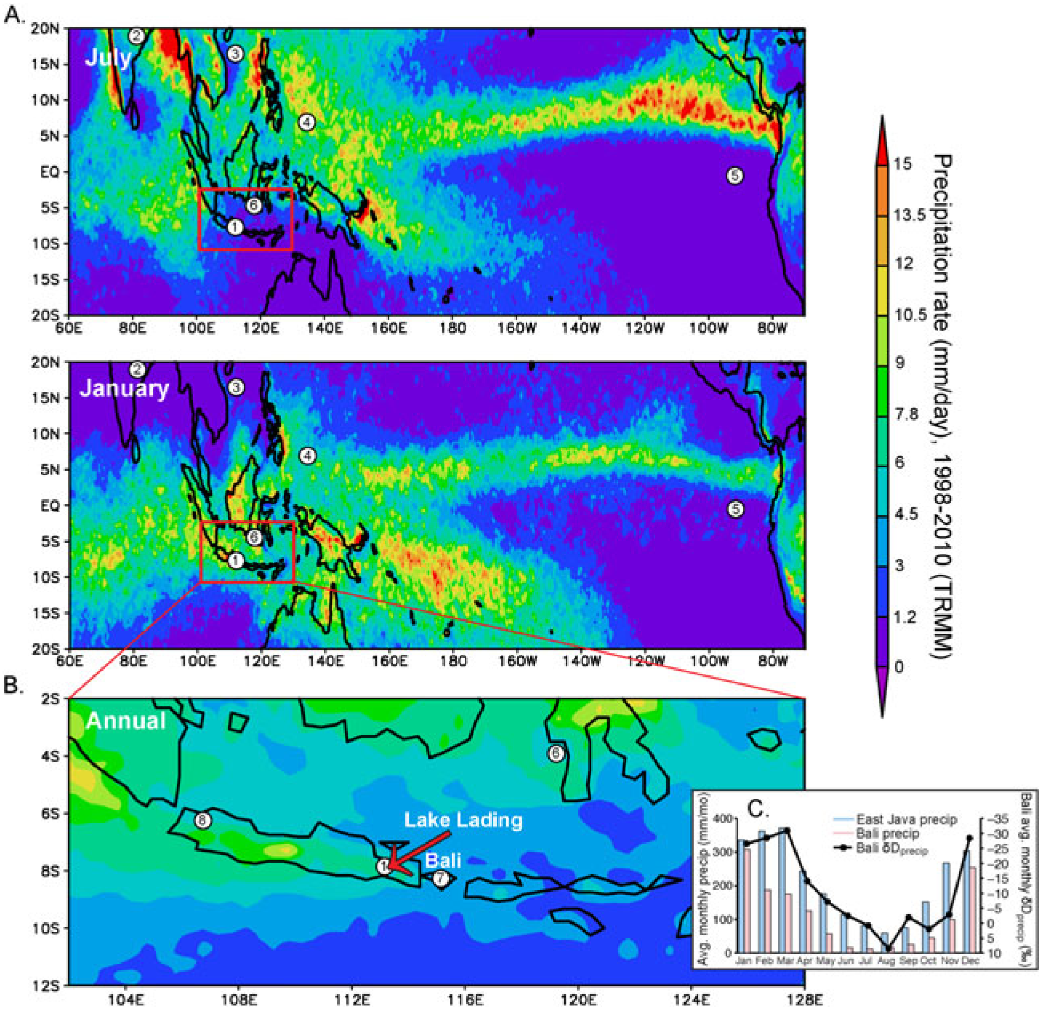

Figure 1. (A) Precipitation climatology of Java (red box) and the Indo-Pacific region during July, austral winter (top) and January, austral summer (bottom) measured by the Tropical Rainfall Measuring Mission (TRMM) satellite, 1998–2010. (B) Annual TRMM precipitation climatology of Java and environs; location of Lake Lading, East Java (red arrow). Circles denote locations of sites presented in Figures 2 and 3: (1) Lake Lading, (2) Dandak Cave, (3) Cattle Pond, (4) Spooky Lake, (5) El Junco, (6) Makassar Strait, (7) Denpasar, Bali, and (8) Jakarta, West Java [*Sachs et al.*, 2009; *Sinha et al.*, 2007; *Tierney et al.*, 2010; *Yan et al.*, 2011; *Kurita et al.*, 2009]. TRMM imagery courtesy of Jian-Jian Wang, (NASA/GSFC, University of Maryland). (C) Blue bars, precipitation climatology from East Java (Ranuklakah). Pink bars, precipitation climatology from Denpasar, Bali. Black line, average monthly δD of precipitation measured at Bali station. Precipitation amount and δD were measured during 2003–2006 [*Kurita et al.*, 2009].

are composed of thinly bedded to laminated muds with no clear hiatuses. A core composite was developed from both LAD08-2P and LAD08-3P to avoid gaps in sediment. The age model for the LAD08 cores (Figure 2) is derived from a mixed-effect regression [*Heegaard et al.*, 2005] using 5 AMS ^{14}C dates and a ^{210}Pb chronology in the uppermost sediments [*Rodysill et al*, in prep].

[6] Samples for δD_{wax} analysis were taken at an average resolution of 8.5 years (ranging approximately 3 to 25 years). One hundred seventy sediment samples were freeze-dried, homogenized, and extracted using a Dionex Accelerated Solvent Extractor 350 to yield the soluble lipid fraction. Fatty acids were then purified according to previously described methods [*Konecky et al.*, 2011]. δD was measured on the C_{28} *n*-alkanoic acid, the dominant homologue in all samples, using gas chromatography-pyrolysis-isotope ratio-mass spectrometry. Samples were randomized and run in duplicate, except for a subset of 18 samples that were run in triplicate. The pooled standard deviation of triplicate samples was 1.08‰, and the 1-σ error on a synthetic fatty acid methyl ester standard run between every six replicates was 2.5‰. δD_{wax} values are reported relative to Vienna Standard Mean Ocean Water.

3. Reconstructing δD_{precip} in Southwestern Indonesia

3.1. Controls on the Modern δD of Precipitation at Lake Lading

[7] In southwestern Indonesia, as in many tropical locales, δD of precipitation (δD_{precip}) corresponds to convective intensity and rainfall amount, where intense convection and/or high amounts of rainfall lead to D-depleted precipitation [*Vuille et al.*, 2005a; *Kurita et al.*, 2009]. Interannual variability in the isotopes of Indonesian precipitation reflect variability in the intensity of the summer monsoon [*Vuille*

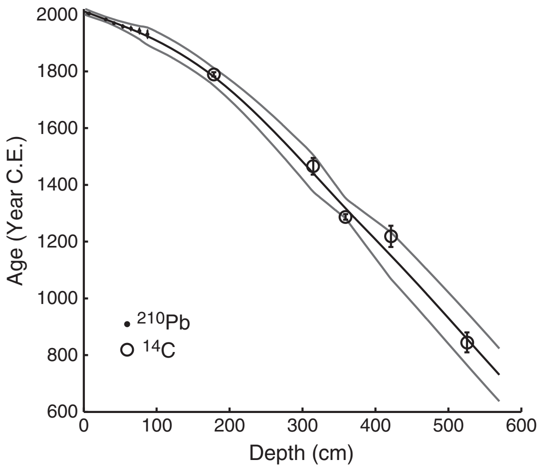

Figure 2. Age model for Lake Lading composite core, constructed using a mixed-effect regression [*Heegaard et al.*, 2005].

et al., 2005a], which is influenced by regional climatic modes such as ENSO and the IOZM [*Vuille et al.*, 2005b] and remote sea surface temperatures in the Indian Ocean, the Banda Sea, and the South China Sea [*Aldrian and Susanto*, 2003]. Although no δD_{precip} data exist for East Java, studies from Denpasar, Bali (~200 km east of Mt. Lamongan) and Jakarta, West Java (~730 km northwest of Mt. Lamongan; Figure 1b) both show that monthly anomalies in δD_{precip} and precipitation amount—which inherently reflect interannual variability—are significantly correlated ($p < 0.005$ and $p < 0.05$, respectively) [*Vuille et al.*, 2005a; *Kurita et al.*, 2009]. Precipitation amount is therefore highly influential on the variability of δD_{precip}, with δD_{precip} at individual stations strongly reflecting region-wide precipitation amount and convection [*Kurita et al.*, 2009].

[8] At Bali, the closest isotopic monitoring site to Lake Lading, over 80% of precipitation measured from July 2003 to June 2006 fell between October and March (61% during November–February), coinciding with the southernmost extension of the ITCZ associated with summer intensification of the Australasian monsoon (Figure 1c). The weighted October–March average δD_{precip} during that time period was −18.72‰, similar to the weighted annual (July–June) average of −20.42‰, reflecting the strong control of wet season δD_{precip} on the annual average δD_{precip} [*Kurita et al.*, 2009]. While large-scale changes in atmospheric circulation could certainly cause the relationship between precipitation amount and δD_{precip} to vary, these modern observations indicate that δD_{precip} reflects Australasian monsoon strength.

3.2. Controls on δD_{wax} at Lake Lading

[9] Plant wax δD has been shown to primarily reflect the δD of precipitation [*Sachse et al.*, 2012]. The modern δD of precipitation at Lake Lading is estimated to be approximately −39.5‰ during the October–March wet season and −32.3‰ during the April–September dry season [*Bowen*, 2012]. River samples taken during a field campaign in July 2008 averaged −33.70‰, similar to the estimated dry season value. The uppermost δD_{wax} values (~30 years) average −153.0‰, suggesting an apparent fractionation between precipitation and the C_{28} *n*-acid ($\varepsilon_{wax\text{-}precip}$) of approximately 110–120‰, which is consistent with reported $\varepsilon_{wax\text{-}precip}$ ranges of ~100–120‰ from North American sites with high relative humidity (>60%) [*Hou et al.*, 2008].

[10] The hydrological catchment of Lake Lading is composed of moist tropical forest, with little human settlement. The degree of biosynthetic fractionation occurring between δD_{precip} and δD_{wax} can differ significantly among plant types, e.g., between C_3 grasses and C_3 trees [*Sachse et al.*, 2012]. However, pollen analyses from Lake Lading indicate that the catchment has been composed of moist tropical forest throughout the study period, with no major changes in the relative abundance of grasses, and that inputs of C_3 grasses are negligible [*Crausbay*, 2000]. Although the hydrological catchment of Lake Lading remains unsettled, palynological and lithological indicators from Lake Lading and other nearby lakes indicate human influence after 1860 C.E. [*Rodysill et al.*, 2010, 2012]. However, these landscape modifications involved the intensification of woody C_3 plants (e.g., teak, tea) in an already C_3-dominated landscape and are thus unlikely to have significantly affected $\varepsilon_{wax\text{-}precip}$. Minor changes in C_4 grass inputs, if present, would not significantly alter $\varepsilon_{wax\text{-}precip}$ due to the similar degree of biosynthetic fractionation experienced between C_4 graminoids and C_3 trees [*Sachse et al.*, 2012]. Hence, we assume biosynthetic fractionation to be relatively constant. Because plant waxes are produced year-round, we interpret δD_{wax} to record weighted annual δD_{precip}, which is highly influenced by variations in the Australasian monsoon.

4. Evolution of Southwestern Indonesian Precipitation since 850 C.E.

[11] Overall, over the past 1150 years Lake Lading δD_{wax} exhibits a progressive D-depletion of more than 20‰, ranging from −128.3‰ in ~880 C.E. to −155.2‰ in 1986 C.E. Based on modern controls on southwestern Indonesian δD_{precip} (see section 3.1), decreasing δD_{wax} at Lake Lading likely reflects increasing Australasian monsoon precipitation in East Java since 850 C.E.

[12] Due to Lake Lading's location at 8°S near the southern extent of the ITCZ over Indonesia, one possible interpretation of increasing wet conditions at East Java could be a southward migration of the ITCZ's mean position over the past millennium, as has been suggested by other studies [*Sachs et al.*, 2009]. In particular, other studies highlight northward displacement of the ITCZ during the Northern Hemisphere warm interval known as the Medieval Climate Anomaly (MCA; ~1000–1200 C.E.), followed by southward ITCZ migration as the Northern Hemisphere cooled during the Little Ice Age (LIA; ~1550–1800 C.E.). However, some evidence from those studies also points to a more northward shift of the ITCZ beginning about 1750 C.E. [e.g., *Haug et al.*, 2001; *Sachs et al.*, 2009], which is not consistent with our results: if this were the case, Lake Lading would become drier after ~1750 C.E., which should cause δD_{wax} to become more D-enriched.

[13] The strengthening austral summer monsoon indicated by our record would have extended the southern reaches of the tropical rain belt over Indonesia, i.e., a southward shift of the ITCZ's mean position. But stable isotopic records from Cattle Pond, Dongdao Island, located at ~17°N in the South China Sea (Figure 3), suggest that monsoon precipitation has also been increasing during boreal summer over the past millennium [*Yan et al.*, 2011]. A 500-year algal

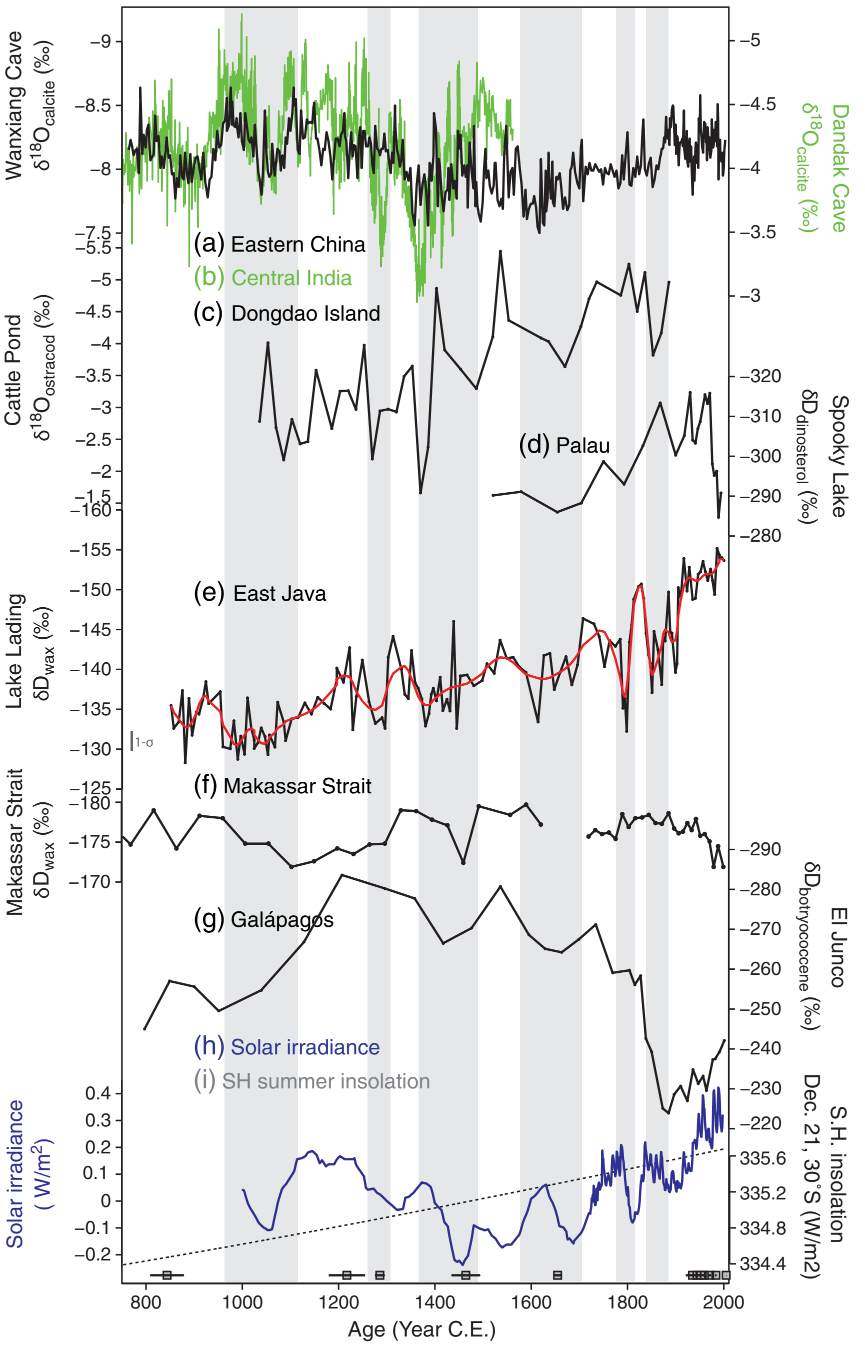

Figure 3. Continental stable water isotope records from the Indo-Pacific Warm Pool region and China, plotted with solar irradiance and insolation. Note reversed *y* axis, such that wetter conditions/stronger convection is oriented up. (a) Speleothem $\delta^{18}O$ record from Wanxiang Cave, China (33°N; black line) [*Zhang et al.*, 2008]. (b) Speleothem $\delta^{18}O$ record from Dandak Cave, India (19°N; green line) [*Sinha et al.*, 2007]. (c) Ostracod $\delta^{18}O$ from Cattle Pond, Dongdao Island, South China Sea (17°N) [*Yan et al.*, 2011]. (d) Dinosterol δD from Spooky Lake, Palau, western tropical Pacific (7°N) [*Sachs et al.*, 2009]. (e) Leaf wax δD from Lake Lading, East Java, western Indonesia (8°S; this study). Black line represents raw data, and red line represents low-pass filtered data. Gray bar represents the 1-σ error determined from standards (see section 2). (f) Leaf wax δD from a marine sediment core in the Makassar Strait, central Indonesia (4°S) [*Tierney et al.*, 2010]. (g) Botryococcene δD from El Junco lake, Galápagos (3°S) [*Sachs et al.*, 2009]. (h) Solar irradiance, calculated from ^{10}Be and a sunspot-based irradiance reconstruction [*Crowley*, 2000]. (i) Southern Hemisphere summer insolation (30°S). Figures 3a, 3b, 3e, and 3f record the $\delta^{18}O$ or δD of precipitation, whereas Figures 3c, 3d, and 3g record the $\delta^{18}O$ or δD of lake water. Gray shaded bars correspond to positive excursions in Lake Lading δD_{wax}. Open squares depict age control points and error bars given in Figure 2.

biomarker δD record from Spooky Lake, Palau, located at 7°N in the western Pacific, corroborates this increasing moisture in the western tropical Pacific north of the equator [*Sachs et al.*, 2009]. With precipitation increasing on both sides of the equator during each hemisphere's respective summer, ITCZ position could only be implicated if it were shifting southward during austral summer and northward during boreal summer—in other words, expanding, rather than migrating, over the past millennium. This mechanism has yet to be explored on centennial to millennial timescales. Nevertheless, these records may indicate that migration of mean ITCZ position is not sufficient to explain all Indo-Pacific rainfall patterns over the past millennium.

[14] A more plausible mechanism for increasing precipitation on both sides of the equator in the western tropical Indo-Pacific may be a strengthening of the Walker circulation over the Pacific Ocean over the past millennium. An enhanced Pacific Walker circulation and/or a westward shift of the Pacific Walker cell has been invoked in the past to explain Little Ice Age contrasts between precipitation over mainland Asia and the western Pacific [*Yan et al*., 2011]. Expanding this interpretation to the entire last millennium would explain the similar progressively wetter trend at our site at 8°S and Northern Hemisphere sites along the western edge of the Pacific (especially at 7°N, 17°N; see Figure 3) [*Sachs et al*., 2009; *Yan et al*., 2011]. We argue that although multidecadal to centennial fluctuations in precipitation may be attributable to classic ITCZ dynamics (see section 5), the similarities between our record from 8°S and Northern Hemisphere sites indicate that strengthening convection near the ascending limb of the Walker cell may be more important to long-term precipitation and δD_{precip} trends in southwestern Indonesia. It should be noted that this long-term trend is most prominent in sites located toward the northern and southern extents of the Indo-Pacific tropical rain belt, as a record from the more equatorial Makassar Strait (4°S) lacks a long-term trend over the past millennium [*Tierney et al*., 2010]. However, our interpretation is in agreement with several other studies from the tropics that have found changes in Walker circulation to be more important to local hydrological conditions than simple migration of the ITCZ mean position [e.g., *Cobb et al*., 2003; *Russell and Johnson*, 2007]. Additional continental proxy records from Indonesia are required to illuminate these potential precipitation gradients.

[15] Decreasing δD_{precip} at East Java over the past millennium could also be explained by increasing convection over the eastern Indian Ocean, rather than an intensification of the austral summer monsoon itself. The modern wet season in southern Indonesia/northern Australia is characterized by the replacement of dry easterly surface winds with convective westerlies, which sustain vertical instability over southern Indonesia and draw the zone of deep convection southward during the austral summer [*Aldrian and Susanto*, 2003]. Increasing the strength of these convective westerlies could correspond to an intensifying Indian Ocean Walker Circulation over the past millennium by leading to a state reminiscent of the IOZM negative mode. This would likely have caused a steady decrease in precipitation over East Africa [*Vuille et al*., 2005b]. Further work from East Africa, western Indonesia, and northern Australia is needed to test this mechanism. Regardless, the D- and ^{18}O-depletion observed at East Java and at Northern Hemisphere sites underscores the importance of zonal circulation on Lake Lading δD_{wax}.

5. Multidecadal to Centennial Variations in Western Indonesian Precipitation

[16] Numerous centennial-scale episodes of drier and wetter conditions interrupt the long-term shift from dry to wet conditions over the past millennium (Figure 3). Drier periods lasting several decades to over a century occurred during 960–1090 C.E., 1260–1300 C.E., 1380–1450 C.E., 1600–1690 C.E., 1790–1800 C.E., and 1840–1900 C.E., with a return to wetter conditions in between. The extremely low δD_{wax} variability during the twentieth century (ranging 6.4‰, $1\text{-}\sigma = 2.0$‰) likely reflects increased smoothing in the time domain resulting from progressive changes in sediment lithology and bioturbation (see Supporting Information and *Rodysill et al*. [2010]).

[17] Some similarities to the centennial-scale fluctuations in δ^{18}O at Dandak Cave in India (19°N) [*Sinha et al*., 2007] and Wanxiang Cave in China (33°N; Figure 3) [*Zhang et al*., 2008], especially between ~1200–1700 C.E., could suggest a Walker-related mechanism driving multidecadal to centennial-scale isotopic variations at both sites. However, the wet/dry intervals at Lake Lading appear coeval with wet/dry intervals observed at El Junco Lake, Galápagos Islands in the eastern tropical Pacific Ocean [*Sachs et al*., 2009] (Figure 3). At El Junco, the δD of the algal biomarker botryococcene (δD_{bot}) reflects the δD of lake water, which integrates both δD_{precip} and evaporation from the lake surface. The combined effects of D-depletion during heavy rainfall events and D-enrichment during lake evaporation produces an amplified signal that is highly sensitive to climatic changes, such as excessive rains experienced during frequent El Niño events [*Sachs et al*., 2009]. Modern El Niño events result in rainfall anomalies of opposite direction in Indonesia and the eastern tropical Pacific; therefore, centennial-scale periods of time with more frequent El Niño events should result in rainfall anomalies of opposing directions on either side of the Pacific Ocean. Although age model uncertainties prohibit a robust assessment of the phasing between these records, the centennial-scale variations Lake Lading δD_{wax} are consistently in the same direction as δD_{bot} variations at El Junco throughout the record, with drier/D-enriched and wetter/D-depleted conditions coinciding at both Java and the Galápagos. While these datasets do not resolve individual El Niño events per se, one interpretation of the co-occurrence of positive rainfall anomalies in Java and the Galápagos could be that decadal and longer periods with increased El Niño events were accompanied by increased La Niña events but that these La Niña-driven wet intervals played a bigger role in Javanese rainfall patterns than El Niño-driven drought. However, the impact of El Niño events on Indonesian climate is clearly evident in modern Indonesian rainfall [*Aldrian and Susanto*, 2003]. We therefore suggest that the co-occurrence of D-depleted/D-enriched anomalies in Java and the Galápagos stable isotopic records is inconsistent with an ENSO-like mechanism for centennial-scale dry and wet periods at Java.

[18] We argue that while ITCZ dynamics are not likely responsible for millennium-long precipitation and δD_{precip} trends in the Indo-Pacific region, changes in the ITCZ's mean position, range, and/or intensity played a major role on multidecadal to centennial timescales over the past millennium. Wet (dry) events occurring at both Java and the Galápagos, 8°S and 1°S, respectively, imply either a southward (northward) movement of the ITCZ's mean position or an expansion (contraction) of its southern extent. Although the resolution is too low for a robust comparison, wet events occurring at Dongdao Island (17°N) as well as Lakes Lading and El Junco, such as during ~1500–1590 C.E. and ~1710–1785 C.E., may imply a region-wide increase in convective intensity over the tropical Pacific. In such

cases, changes in convective intensity along the tropical rain belt are not necessarily associated with a migration of the ITCZ's mean position, as both the northern and southern tropics have similar wet conditions. Both pluvials occur during cold and fresh sea surface conditions during peak Little Ice Age cooling in the nearby Makassar Strait [*Oppo et al.*, 2009] and correspond to ^{18}O-depleted periods in a speleothem record from the island of Flores, east of Java, attesting to the regional character of these events [*Griffiths et al.*, 2010; *Oppo et al.*, 2009]. Prominent centennial-scale variability related to the relative strength of the East Asian Summer Monsoon—which is inherently tied to ITCZ position—has also been noted in δD_{wax} preserved in marine sediments from the Makassar Strait (4°S; Figure 3). Although the amplitude of variations observed at the Makassar Strait is much lower than at Lake Lading (less than 7‰; see Figure 3) due to sediment bioturbation and other factors [*Tierney et al.*, 2010], both of these Indonesian δD_{wax} records show D-enrichment during the MCA, indicating reduced precipitation and convective intensity in Indonesia during this time. The maximum δD_{wax} enrichment during the MCA lasts approximately one century at both sites but occurs ~100 years earlier in East Java than at the Makassar Strait, supporting the idea that the ITCZ may have contracted or shifted northward during the peak MCA. During ITCZ migrations, whether the ITCZ's southern limit was expanded/contracted or if its mean position was shifted south/north remains to be explored with additional high-resolution, millennium-long paleohydrological reconstructions from northern tropics in the Pacific Ocean and in the warm pool.

[19] It is possible that solar irradiance played a role in these centennial ITCZ fluctuations: after 1250 C.E., wet intervals at Lake Lading and El Junco correspond to minima in solar irradiance, whereas dry intervals correspond to maxima (Figure 3) [*Crowley*, 2000]. Although age model errors prohibit a robust comparison, studies from tropical Africa and South America have also documented drying during solar irradiance maxima [*Polissar et al.*, 2006; *Verschuren et al.*, 2000], but the mechanism linking solar variability to the intensity or position of the ITCZ has yet to be confirmed.

6. Conclusions

[20] Stable isotopic records from several terrestrial locations in the western Indo-Pacific region reveal progressively wetter conditions over the past millennium (Figure 3). Our new δD_{wax} record from Java reveals that this progressively wetter trend is observed as far north as 16°N and as far south as 8°S, suggesting a north–south migration of the ITCZ is not the primary mechanism for this long-term shift at these sites. On centennial timescales, however, fluctuations at Lake Lading are of similar timing and direction as those from the eastern equatorial Pacific. Hence, it appears that both zonal and meridional asymmetry were of critical importance to western Indonesian rainfall during the past millennium, with an intensifying Walker circulation wielding more influence on the millennial timescale and changes in the ITCZ being more influential on multidecadal to centennial timescales.

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References

Aldrian, E., and R. Susanto (2003), Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature, *Int. J. Clim.*, *23*(12), 1435–1452.

Bowen, G. J. (2012) Online isotopes in precipitation calculator v.2.2., www.waterisotopes.org.

Broccoli, A. J., K. A. Dahl, and R. J. Stouffer (2006), Response of the ITCZ to Northern Hemisphere cooling, *Geophys Res Lett*, *33*(1), L01702.

Cobb, K., C. Charles, H. Cheng, and R. L. Edwards (2003), El Nino/Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, *424*, 271–276.

Crausbay, S.D. 2000. A high-resolution record of climate and lowland vegetation over the past millennium in East Java. Thesis (M.S.)--University of Minnesota, 2000.

Crowley, T. J. (2000), Causes of climate change over the past 1000 years, *Science*, *289*, 270–277.

Griffiths, M. L., et al. (2010), Evidence for Holocene changes in Australian-Indonesian monsoon rainfall from stalagmite trace element and stable isotope ratios, *Earth Planet Sci. Lett.*, *292*(1–2), 27–38.

Haug, G., K. Hughen, D. Sigman, L. Peterson, and U. Rohl (2001), Southward migration of the Intertropical Convergence Zone through the Holocene, *Science*, *293*(5533), 1304–1308.

Heegaard, E., H. Birks, and R. Telford (2005), Relationships between calibrated ages and depth in stratigraphical sequences: An estimation procedure by mixed-effect regression, *Holocene*, *15*(4), 612–618.

Hou, J., W. J. D'Andrea, and Y. Huang (2008), Can sedimentary leaf waxes record D/H ratios of continental precipitation? Field, model, and experimental assessments, *Geochim. Cosmochim. Acta*, *72*(14), 3503–3517.

Konecky, B., J. Russell, T. Johnson, E. T. Brown, M. A. Berke, J. P. Werne, and Y. Huang (2011), Atmospheric circulation patterns during late Pleistocene climate changes at Lake Malawi, Africa, *Earth Planet Sci. Lett.*, *312*(3), 318–326.

Kurita, N., K. Ichiyanagi, J. Matsumoto, M. D. Yamanaka, and T. Ohata (2009), The relationship between the isotopic content of precipitation and the precipitation amount in tropical regions, *J. Geochem. Exp.*, *102*, 113–122.

Newton, A., R. Thunell, and L. Stott (2006), Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium, *Geophys. Res. Lett.*, *33*(19), L19710.

Oppo, D. W., Y. Rosenthal, and B. K. Linsley (2009), 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool, *Nature*, *460*(7259), 1113–1116.

Polissar, P. J., M. B. Abbott, A. P. Wolfe, M. Bezada, V. Rull, and R. S. Bradley (2006), Solar modulation of little ice age climate in the tropical Andes, *Proc. Nat. Acad. Sci.*, *103*(24), 8937–8942.

Russell, J. M., and T. C. Johnson (2007), Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño-Southern Oscillation variability, *Geol.*, *35*(1), 21.

Rodysill, J.R., Russell, J. M., Bijaksana, S., Safiuddin, L., Eggermont, H (2010). Centennial-scale hydrological variations in East Java, Indonesia during the past 1400 years from paleolimnological records. #PP51B-04, 2010 Fall Meeting, AGU, San Francisco, CA, 13–17 Dec

Rodysill, J. R., J. M. Russell, S. Bijaksana, E. T. Brown, L. O. Safiuddin, and H. Eggermont (2012), A paleolimnological record of rainfall and drought from East Java, Indonesia during the last 1,400 years, *J. Paleolimnol.*, *47*(1), 125–139, doi:10.1007/s10933-011-9564-3.

Sachs, J., D. Sachse, R. Smittenberg, Z. Zhang, D. S. Battisti, and S. Golubic (2009), Southward movement of the Pacific Intertropical Convergence Zone AD 1400–1850, *Nature Geosci.*, *2*, 519–525.

Sachse, D., et al. (2012), Molecular paleohydrology: Interpreting the hydrogen-isotopic composition of lipid biomarkers from photosynthesizing organisms, *Ann. Rev. Earth Planet Sci.*, *40*, 221–249.

Sinha, A., K. G. Cannariato, L. D. Stott, H. Cheng, R. L. Edwards, M. G. Yadava, R. Ramesh, and I. B. Singh (2007), A 900-year (600 to 1500 A. D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India, *Geophys. Res. Lett.*, *34*(16), L16707.

Tierney, J., D. Oppo, Y. Rosenthal, J. M. Russell, and B. K. Linsley (2010), Coordinated hydrological regimes in the Indo-Pacific region during the past two millennia, *Paleoceanography*, *25*, PA1102.

Verschuren, D., K. Laird, and B. Cumming (2000), Rainfall and drought in equatorial east Africa during the past 1,100 years, *Nature*, *403*(6768), 410–414.

Vuille, M., M. Werner, R. S. Bradley, and F. Keimig (2005a), Stable isotopes in precipitation in the Asian monsoon region, *J. Geophys. Res.*, *110*(D23), D23108.

Vuille, M., M. Werner, R. S. Bradley, R. Y. Chan, and F. Keimig (2005b), Stable isotopes in East African precipitation record Indian Ocean zonal mode, *Geophys. Res. Lett.*, *32*(21), L21705.

Yan, H., L. Sun, D. Oppo, Y. Wang, Z. Liu, Z. Xie, and W. Cheng (2011), South China Sea hydrological changes and Pacific Walker Circulation variations over the last millennium, *Nature Comm.*, *2*(293), doi:10.1038/ncomms1297.

Zhang, P., et al. (2008), A test of climate, sun, and culture relationships from an 1810-year Chinese cave record, *Science*, *322*(5903), 940–942.