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Coordinated hydrological regimes in the Indo-Pacific region during the past two millennia

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[1] Instrumental data suggest that major shifts in tropical Pacific atmospheric dynamics and hydrology have occurred within the past century, potentially in response to anthropogenic warming. To better understand these trends, we use the hydrogen isotopic ratios of terrestrial higher plant leaf waxes (δD_{wax}) in marine sediments from southwest Sulawesi, Indonesia, to compile a detailed reconstruction of central Indo-Pacific Warm Pool (IPWP) hydrologic variability spanning most of the last two millennia. Our paleodata are highly correlated with a monsoon reconstruction from Southeast Asia, indicating that intervals of strong East Asian summer monsoon (EASM) activity are associated with a weaker Indonesian monsoon (IM). Furthermore, the centennial-scale oscillations in our data follow known changes in Northern Hemisphere climate (e.g., the Little Ice Age and Medieval Warm Period) implying a dynamic link between Northern Hemisphere temperatures and IPWP hydrology. The inverse relationship between the EASM and IM suggests that migrations of the Intertropical Convergence Zone and associated changes in monsoon strength caused synoptic hydrologic shifts in the IPWP throughout most of the past two millennia.

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1. Introduction

[2] The tropical Pacific, as a coupled ocean-atmosphere system, is a "nexus" for global climate change [*Pierrehumbert*, 2000], primarily because this region is the center of action for the El Niño–Southern Oscillation (ENSO), whose effects are global in scope. In addition, the stretch of warm ocean waters (>28°C) spanning the eastern Indian Ocean through the western Pacific, known as the Indo-Pacific Warm Pool, is the largest zone of deep atmospheric convection on earth, and thus a primary source of global heat and water vapor. Perturbations in IPWP deep convection, which can modify both Hadley and Walker circulation cell strength, have profound consequences for both tropical and extratropical climates [*Neale and Slingo*, 2003]. Furthermore, variations in lower tropospheric water vapor, a potent greenhouse gas, act as an important climatic feedback mechanism [*Hall and Manabe*, 1999; *Held and Soden*, 2006]. Thus, constraining past changes in warm pool hydrology is necessary to understand the nature of tropical climate change as well as the potential role of the tropics with regards to anthropogenic warming.

[3] Recent examination of instrumental sea level pressure anomaly data suggests that Walker circulation across the Pacific basin may be weakening in response to anthropogenic warming [*Vecchi et al.*, 2006; *Zhang and Song*, 2006], or at the least, may be weakening on a seasonal basis [*Karnauskas et al.*, 2009] signaling a major shift in tropical hydrology with potentially global ramifications. To better understand what this observation may portend, it is necessary to constrain past variations in IPWP hydrology, yet presently, paleoclimate reconstructions of hydrology in the IPWP of sufficient resolution are scarce and those that do exist provide a conflicting view of recent, historical trends. For example, authigenic Mg/Ca data from a crater lake in Java indicate dry conditions [*Crausbay et al.*, 2006] during the Little Ice Age (LIA), 1400–1850 A.D. [*Lamb*, 1982], yet speleothem $\delta^{18}O$ data from northern Borneo suggest little change in rainfall amount during this time period [*Partin et al.*, 2007]. Conversely, high-resolution $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) estimates from the southern Makassar Strait suggest that the lowest $\delta^{18}O_{sw}$ values (and presumably freshest sea surface conditions) of the last 2000 years occurred during the LIA [*Newton et al.*, 2006; *Oppo et al.*, 2009]. Furthermore, new data from Palau suggest dry conditions during the earlier portion of the LIA (1500–1750 A.D.), and wet conditions in the latter portion (1750–1850) [*Sachs et al.*, 2009]. It is unclear whether these apparently conflicting trends in the paleoclimate data reflect real geographic gradients of precipitation (e.g., presently, Borneo

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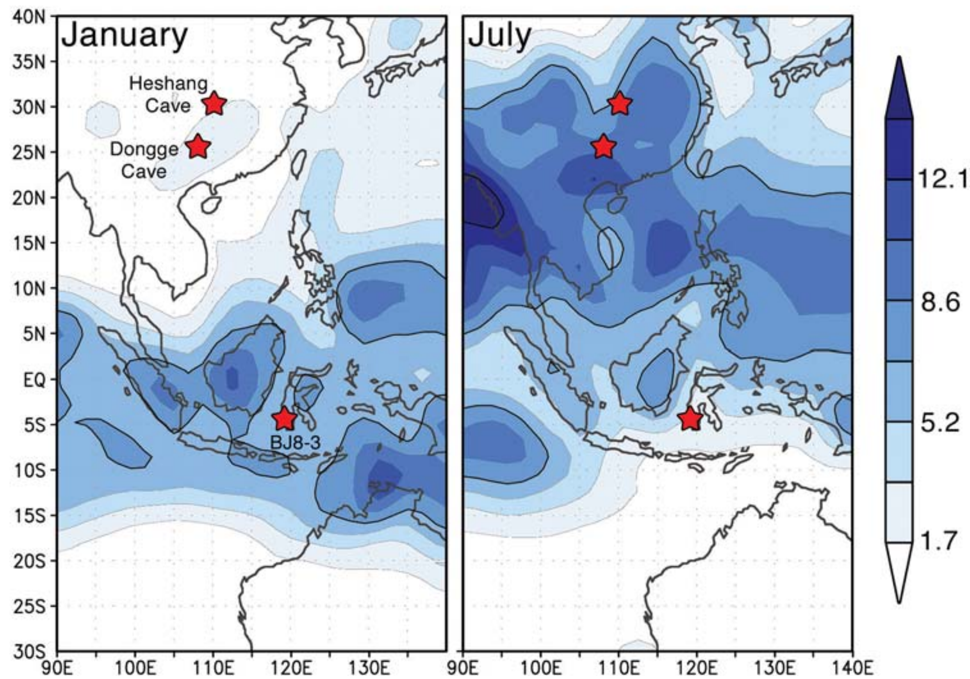

Figure 1. Seasonal precipitation regimes in the Western Pacific Warm Pool region (contours are in units of precipitation rate, kg/m^2/d, from NCEP monthly long-term mean data [*Kalnay et al.*, 1996]) and the location of the BJ8-3 cores 31MC (3.88°S, 119.454°E, 459 m below sea level (bsl)) and 34GGC (3.88°S, 119.446°E, 503 m bsl) analyzed for δD_{wax} in this study. Also shown are the locations of Heshang and Dongge caves in southeast China, data from which comprise the $\Delta\delta^{18}O$ record mentioned in the text and plotted in Figure 3.

experiences very little seasonality in its annual precipitation whereas rainfall in Java is concentrated in the austral summer [*Aldrian and Susanto*, 2003]), or shortcomings and limitations of the proxy records.

2. Compound-Specific δD Approach

[4] To better define the hydrologic history of this region, we present a detailed reconstruction of hydrology in central Indonesia spanning the last two millennia that also overlaps with the instrumental record, thus allowing for direct comparison of proxy data with indices of IPWP hydrology and an assessment of past changes in the context of modern trends. Our record consists of compound-specific hydrogen isotopes of terrestrial long-chain leaf waxes (C_{28}–C_{32} *n*-acids) from marine sediment cores from the West Sulawesi margin (BJ8-03-31MC and BJ8-03-34GGC; Figure 1). It has been demonstrated that the deuterium/hydrogen isotopic ratio of these specific higher plant leaf wax compounds in sediments reliably tracks the δD of local precipitation across a variety of terrestrial biomes and climatic conditions [*Sachse et al.*, 2004; *Hou et al.*, 2008; *Rao et al.*, 2009]. Though changes in dominant plant physiological type (e.g., grasses versus trees) have the potential to bias the δD signal recorded by leaf waxes [*Hou et al.*, 2007; *Liu and Yang*, 2008], this is unlikely to be an issue for this particular study given that the dominant vegetation type in central Indonesia (a humid biome which receives 2–3 m of rainfall in a year), has in all likelihood remained tropical rain forest during the relatively short time span of our study. In the tropics, the δD of precipitation and water vapor is a complex hydrological tracer reflecting a variety of non-Rayleigh processes including the “amount effect” (i.e., secondary evaporation), moist convection, and large-scale subsidence [*Worden et al.*, 2007; *Frankenberg et al.*, 2009]. Thus the δD value of leaf waxes can be considered an indicator of past changes in hydrologic intensity, which may in some cases arguably relate to precipitation amount [*Schefuß et al.*, 2005; *Tierney et al.*, 2008], yet in other cases may reflect primarily larger-scale processes that affect tropical isotopes of precipitation independent of rainfall amount [*Oppo et al.*, 2007; *LeGrande and Schmidt*, 2009]. In ocean sediments, leaf waxes can be transported via fluvial and aeolian processes, the latter potentially bringing waxes from remote sources. We assume, however, that our leaf wax data reflect predominantly local sources, as the high accumulation rates (>100 cm/kyr at the margin sites of 31MC and 34GGC [*Oppo et al.*, 2009]) imply substantial input of terrestrial material.

3. Analytical Methods

[5] Chronology for cores 31MC and 34GGC is based on a combination of radiocarbon dates, ^{210}Pb analyses, and correlation with an ash layer to the 1815 A.D. eruption of

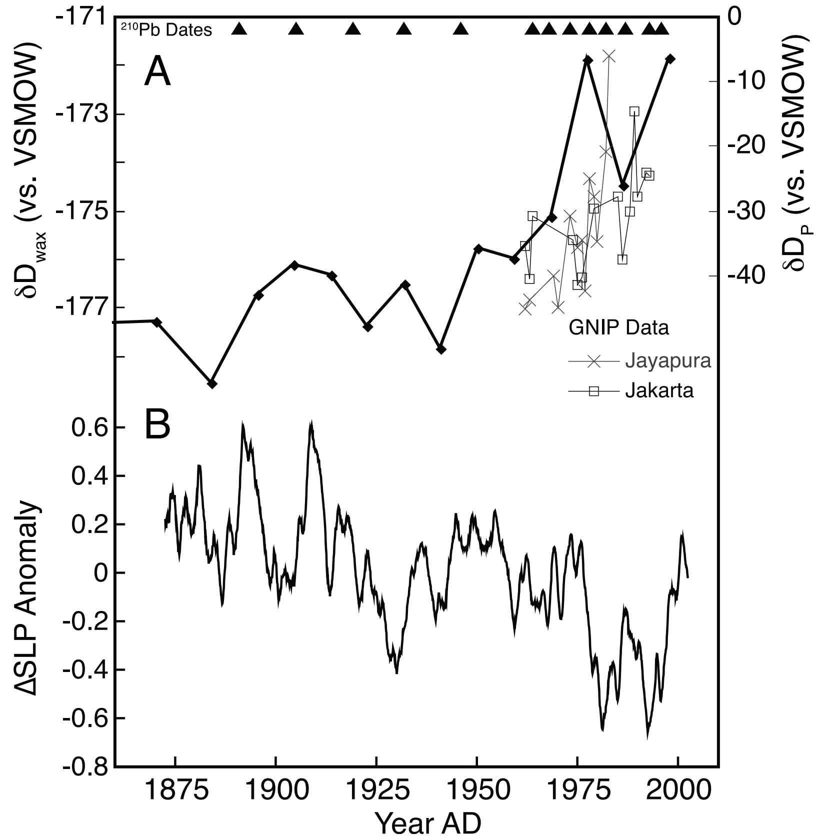

Figure 2. (a) Here δD_{wax} from the top of core 31MC and weighted mean δD data from the Global Network of Isotopes in Precipitation (GNIP) from Indonesian stations Jakarta and Jayapura (IAEA/WMO Global Network of Isotopes in Precipitation, GNIP Database, http://isohis.iaea.org, 2006) show an enrichment trend since the 1960s. (b) The 5 year moving average of Pacific Ocean ΔSLP anomaly calculated from the HadSLP2 data set, a proxy for Walker circulation strength [*Vecchi et al.*, 2006]. Triangles at the top of the plot indicate ^{210}Pb dates.

Mount Tambora [*Oppo et al.*, 2009] (also see auxiliary material and Figures 2 and 3).[1]

[6] Multicore 31MC was sampled every 2 cm and gravity core 34GGC was sampled every 8 cm. Sediments were freeze-dried, homogenized, then extracted using a DIONEX Accelerated Solvent Extraction (ASE) system with CH_2Cl_2: MeOH (9:1). The resulting total lipid extracts were separated into neutral and acid fractions by column chromatography over LC-NH_2 gel using CH_2Cl_2:isopropanol (2:1) and 4% acetic acid in ethyl ether as eluents. The acid fraction was methylated using acetyl chloride-acidified GC grade methanol of a known isotopic composition, and further purified by column chromatography over silica gel and elution with hexane and CH_2Cl_2, respectively. The CH_2Cl_2 fraction, containing the saturated fatty acid methyl esters (FAMEs), was dried under N_2 gas and redissolved in toluene prior to analysis. The hydrogen isotopic composition of the C_{28}, C_{30} and C_{32} *n*-acids (as FAMEs) was determined by gas chromatography–isotope ratio monitoring–mass spectrometry (GC-IR-MS) with a Thermo Finnigan Delta XL mass spectrometer at Brown University. H_2 gas of a known isotopic composition was used as a working reference standard, and all analyses were performed in triplicate. Mass balance corrections were made for the added methyl group. Final values are expressed as ‰ versus VSMOW. 1σ error based on long-term, repeat analysis of an external FAME standard is 2‰–3‰; 1σ error of the C_{28}, C_{30} and C_{32} *n*-acid triplicates was 0.9‰, 0.7‰, and 0.9‰, respectively. Results presented here are triplicate means. δD downcore trends in the C_{28}, C_{30}, and C_{32} acids are similar (see Figure S1); thus hereafter the C_{30} *n*-acid data are plotted as a representative record and referred to as δD_{wax}.

4. Results and Discussion

[7] To constrain our interpretations of the paleo-δD_{wax} signal, we first compare our δD_{wax} results from multicore 31MC with the instrumental hydrological record from the IPWP region (Figure 2). We note that since ~1960 A.D., there is significant enrichment in δD_{wax} (Figure 2a). Similarly, instrumental isotopic data from two Global Network of Isotopes in Precipitation (GNIP) rainfall stations (IAEA/WMO Global Network of Isotopes in Precipitation, GNIP

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/pa/2009pa001871. Other auxiliary material files are in the HTML.

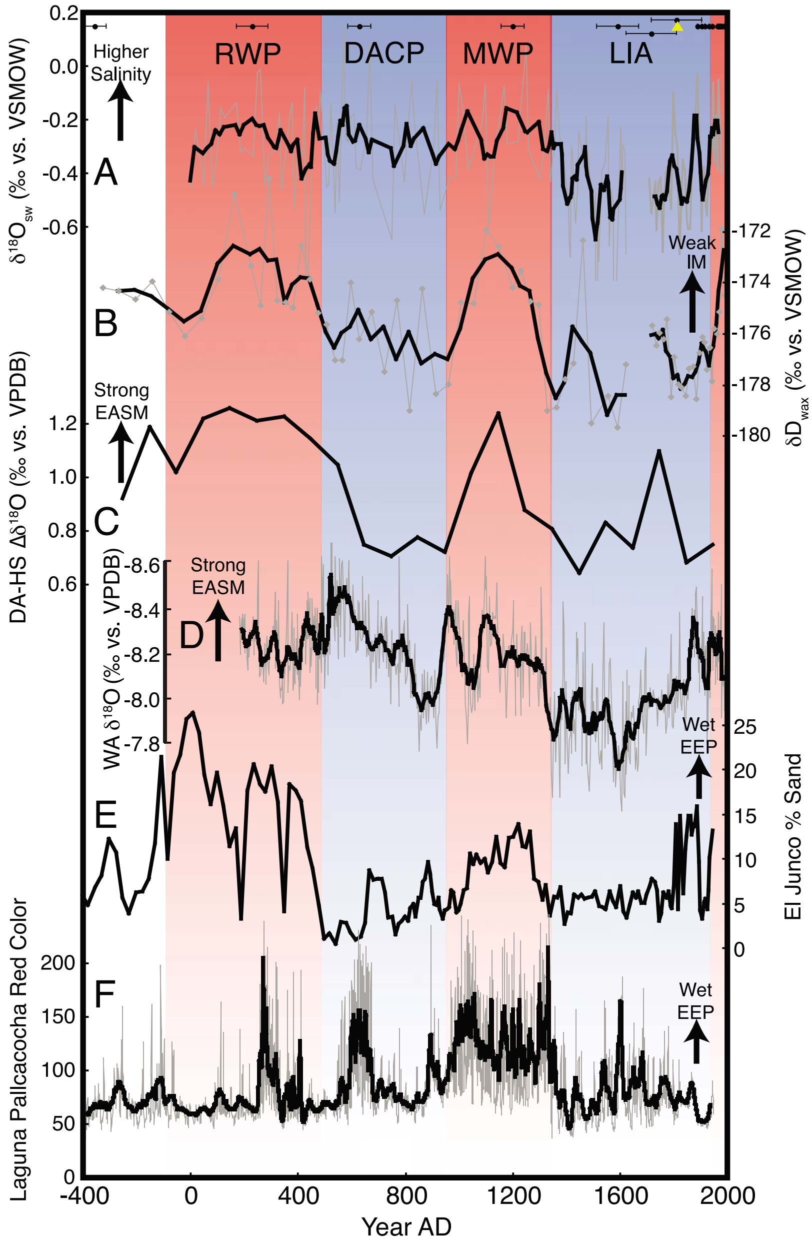

Figure 3. (a) Plot of $\delta^{18}O_{sw}$ data from cores 31MC and 34GGC (raw data in gray and 5 point moving average in black [*Oppo et al.*, 2009]); (b) δD_{wax} (raw data in gray and 3 point moving average in black) from cores 31MC and 34GGC (this study); (c) $\Delta\delta^{18}O$ record from southeast China, which represents the difference in $\delta^{18}O$ between two speleothem records (Dongge Cave–Heshang Cave (DA-HS)) (higher $\Delta\delta^{18}O$ implies greater isotopic distillation between the cave sites and thus a stronger EASM [*Hu et al.*, 2008]); (d) $\delta^{18}O$ data from a Wanxiang Cave (WA) speleothem (raw data in gray and 10 point moving average in black [*Zhang et al.*, 2008]); (e) percent sand in El Junco lake in the Galápagos Islands [*Conroy et al.*, 2008]; and (f) red color intensity (proxy for terrestrial runoff) in Laguna Pallcacocha in Ecuador (raw data in gray and 20 point moving average in black [*Moy et al.*, 2002]). RWP, Roman Warm Period; DACP, Dark Ages Cold Period; MWP, Medieval Warm Period; and LIA, Little Ice Age. Points plotted at the top indicate ^{14}C dates (with 1σ error bars), ^{210}Pb dates (top of 31MC), and the Mount Tambora Ash tie point (yellow triangle).

Database, http://isohis.iaea.org, 2006) in Indonesia also show a dramatic enrichment in the past 30 years, akin to the δD_{wax} signal though much greater in magnitude (~20‰ versus ~6‰, Figure 2b).

[8] It could be assumed that the core top enrichment in δD_{wax} is serendipitous, and in reality a reflection of sedimentary diagenesis or anthropogenic modification of the landscape. A diagenetic effect is unlikely, as hydrogen bound to the carbon skeleton of leaf wax lipids is considered nonexchangeable; in fact, δD_{wax} was found to be impervious to exchange with sedimentary waters in sediments of Miocene age [*Yang and Huang*, 2003]. With respects to landscape modification, it is possible that enrichment could reflect increased input from agricultural C_4-type grasses, which tend to produce leaf waxes more enriched in δD_{wax} than C_3 plants [*Smith and Freeman*, 2006]. Yet were this the case, there would also be a clear trend in the carbon isotopic composition of the recently deposited leaf waxes, as C_4 plants and C_3 plants typically have *n*-acid $\delta^{13}C$ values of −22‰ and −37‰, respectively [*Chikaraishi et al.*, 2004]. However, the $\delta^{13}C$ analyses of the upper samples from core 31MC show no evidence of such a trend (see Data Set S1). Additionally, compound-specific lipid δD values from a sedimentary sequence from the western Pacific island of Palau also show a significant modern enrichment from circa 1970 A.D. [*Sachs et al.*, 2009].

[9] We conclude then that the enrichment in δD_{wax} does in fact record regional δD of precipitation, though the significant difference in magnitude of the signal probably reflects of the residence time of the leaf waxes en route to the core site as well as postdepositional bioturbation. Residence times of leaf waxes in soil organic matter are unknown in tropical environments, though we presume that they are short due to high weathering rates and rapid organic matter cycling. Indeed, the clear enrichment trend in our δD_{wax} data suggests that these compounds are indeed at least partially recording regional modern variability, and thus argues in favor of a relatively short (on the order of decades) transport time for these compounds.

[10] Poor quality instrumental data preclude a rigorous assessment of long-term shifts in regional precipitation amount in the central Indonesian region. However, the enrichment trend in the rainwater isotopes does correspond with large-scale changes in IPWP hydrology that characterize the last half-century, including a general weakening of Pacific Walker circulation (accentuated by a precipitous drop from the late 1970s to 2000 A.D. (Figure 2b) [*Vecchi et al.*, 2006]). We speculate that the mechanisms contributing to a reduction in Walker circulation, specifically, a reduction of tropical convective mass flux [*Held and Soden*, 2006; *Vecchi and Soden*, 2007], may have also directly or indirectly resulted in isotopic enrichment in central Indonesian moisture. One possible mechanism could be that reduced mass convection may have caused a reduction in the rate of lateral advection of remotely derived (and thus more depleted) moist air parcels, essentially resulting in a source shift from "upstream" central warm pool derived moisture to local, more recycled moisture. Another possibility is that changes in evaporation and recycling rates in the moisture source region itself modified the isotopic composition of overlying water vapor. Isotope-enabled modeling experiments would be needed to determine whether either of these hypotheses is valid and the exact mechanisms involved. In any case, δD_{wax} appears to be a robust indicator of large-scale convective, hydrological processes in the IPWP. Under this framework, more depleted δD_{wax} values in our paleorecord indicate an invigorated regional hydrological cycle, essentially a stronger Indonesian monsoon (IM), and conversely enriched δD_{wax} values suggest reduced hydrologic intensity and a weak IM.

[11] During the past two millennia, δD_{wax} values oscillated between −170 and −180 per mil (Figure 3b), and show systematic trends suggestive of notable climatic changes. Until 1600 A.D., there is a long-term depletion in δD_{wax} indicating an increasingly stronger IM. This trend is punctuated by a persistent enrichment in δD_{wax} from 1000 to 1300 A.D. and from 0 to 400 A.D., suggesting that weak regional convection prevailed during most of the Medieval Warm Period [*Hughes and Diaz*, 1994] and the so-called Roman Warm Period (RWP), respectively, interrupted by an increase in hydrologic activity during the Dark Ages Cold Period (DACP) [*Lamb*, 1982]. The most depleted δD_{wax} values, and thus the strongest IM conditions, occurred during the Little Ice Age.

[12] Our data are somewhat consistent with $\delta^{18}O_{sw}$ data from the southern Makassar Strait [*Newton et al.*, 2006] and these same cores (Figure 3a) [*Oppo et al.*, 2009] in that they show significant depletion during the LIA. The δD_{wax} record, however, has much more pronounced centennial-scale structure than the $\delta^{18}O_{sw}$ reconstructions. Specifically, the MWP and RWP are clear features in the δD_{wax} record, but not apparent in $\delta^{18}O_{sw}$ (Figure 3a). This is likely a reflection of the differences between what the two hydrological proxies record, and their respective sensitivities. $\delta^{18}O_{sw}$ may provide a more integrated view of regional hydrology than δD_{wax}, but it is affected by factors other than regional hydrology, like changes in surface currents [*Oppo et al.*, 2007] and local riverine inputs. Furthermore, its sensitivity as a proxy is limited by the compound error involved in making the $\delta^{18}O_{sw}$ calculation from measurements of $\delta^{18}O$ and Mg/Ca of planktonic foraminifera, whose seasonal bias may also change through time. Because δD_{wax} is uncomplicated by oceanic factors, it is arguably a more sensitive recorder of regional hydrology. We conclude then that multicentennial variability indicated by δD_{wax} is a salient feature of central Indonesian hydrologic history, and either these variations, LIA excepted, were not accompanied by changes in sea surface salinity, or such changes were small and cannot be resolved by the $\delta^{18}O_{sw}$ proxy. More data from Indonesia are needed to ascertain whether this disparity in proxy information is climatologically meaningful.

[13] The impressive relationship between our δD_{wax} record and a speleothem-based $\Delta\delta^{18}O$ record from Heshang and Dongge caves in southeast China [*Hu et al.*, 2008], as well similarities with a $\delta^{18}O$ record from Wanxiang Cave, China [*Zhang et al.*, 2008] demonstrates that the patterns recorded by δD_{wax} likely represent large-scale reorganizations of IPWP hydrology (Figures 3b, 3c, and 3d). The $\Delta\delta^{18}O$ record from southeast China is interpreted to represent rainfall amount associated with the EASM season, with

high values representing a stronger EASM. The correlation between a 3 point smooth of δD_{wax} and $\Delta\delta^{18}O$ (r = 0.75, n = 23) is highly significant ($p < 0.005$), based on Monte Carlo tests using 10,000 phase-randomized simulations [*Ebisuzaki*, 1997], demonstrating that periods of a strong IM (depleted δD_{wax} values) are associated with periods of a weak EASM (low $\Delta\delta^{18}O$). This relationship between the hydrology of Indonesia and China is best explained by centennial-scale migrations of the Intertropical Convergence Zone (ITCZ), linked to associated changes in the IM and EASM. A more northerly ITCZ and an enhanced EASM would shift the tropical rain belt away from Indonesia on a mean annual basis, weaken convection during the winter monsoon season [e.g., *Yancheva et al.*, 2007], and transport more depleted moisture from the IPWP to southeast China, leaving an enriched mass behind [e.g., *LeGrande and Schmidt*, 2009], thus producing an antiphased isotopic signature between the two monsoon regions.

[14] As already noted, the centennial-scale changes in the EASM and IM are remarkably coherent with historical trends in northern European climate for the past two millennia, suggesting a dynamic link between hydrology in the IPWP and Northern Hemisphere temperatures. Intervals of strong EASM/weak IM, indicative of a more northerly position of the ITCZ, correspond with warm European temperatures during the Roman Warm Period and Medieval Warm Period [*Lamb*, 1982]. Conversely, a weak EASM/strong IM occurs during the relatively cool DACP and LIA. This pattern is entirely consistent with modeling experiments linking Northern Hemisphere temperature variability to meridional shifts in the ITCZ [*Broccoli et al.*, 2006], as well as data from the Cariaco basin (10°N, 65°W, north of South America) and the central tropical Pacific that delineate similar shifts in tropical ITCZ position for the past 2000 years [*Haug et al.*, 2001; *Sachs et al.*, 2009]. However, our data are unique in that they demonstrate in detail that many of the major climatic shifts noted historically in Europe had a significant hydrologic expression in the IPWP.

[15] Though meridional shifts in the ITCZ explain our data well, we also consider that in modern climatology rainfall in central Indonesia is highly sensitive to ENSO variability, with El Niño events typically resulting in reduced dry season precipitation and subsequent drought [*Aldrian and Susanto*, 2003]. Thus it is possible that changes in the background state of the tropical Pacific, so-called "El Niño–like" or "La Niña–like" conditions, may have contributed to the centennial-scale hydrological trends observed in our paleorecord. To assess this, we compare our record to two lake sedimentary records from the eastern equatorial Pacific (EEP) (Laguna Pallcacocha in Ecuador [*Moy et al.*, 2002] and El Junco lake in the Galápagos Islands [*Conroy et al.*, 2008]) that represent rainfall intensity during past 2000 years (Figures 3d and 3e).

[16] Collectively, these data show that during the LIA and the DACP, a weak EASM and strong IM corresponded with reduced rainfall in the EEP, and during the MWP and to a lesser extent the RWP, a strong EASM and weak IM were coupled with enhanced rainfall in the EEP (Figure 3). These data thus roughly suggest the prevalence of an El Niño–like mean state during the MWP, and a La Niña–like mean state during the LIA. However, these patterns conflict with expectations from modeling experiments, which typically show that a northerly ITCZ/strong EASM (such as during the MWP) contributes to an increased zonal SST gradient in the equatorial Pacific and thus a more La Niña–like mean state [*Mann et al.*, 2005; *Chiang et al.*, 2008], as well as with $\delta^{18}O$ coral data from Palmyra that support this scenario [*Cobb et al.*, 2003]. This disparity suggests that either (1) the teleconnections between ENSO and the EASM/ITCZ are mischaracterized in the models, (2) some of the proxy data are misinterpreted, or (3) the distinctive centennial-scale structure in hydrological anomalies across the Pacific during the past two millennia are unrelated to ENSO dynamics. As continuous paleoclimate data are presently scarce in the central and eastern Pacific and do not always agree, hypothesis 2 is still a distinct possibility. However, the data shown in Figure 3 do at the least show a coherent pattern during the LIA and MWP, leading us to conclude that hypothesis 3 may be the most likely explanation. We speculate that the centennial-scale shifts outlined by our data represent mean state shifts in Walker circulation that are superficially akin to ENSO-like mean state change, yet occur on a completely different timescale and thus imply fundamentally different physical mechanisms. In relevance to this point, recent reanalysis of historical sea surface temperature (SST) and sea level pressure (SLP) data suggests that SLP and SST gradients in the tropical Pacific during the past century have decreased in boreal spring and increased in boreal fall, respectively [*Karnauskas et al.*, 2009]. This implies that very different mechanisms control centennial-scale shifts in tropical Pacific climate than those active in interannual ENSO events, in which SLP and SST anomalies are usually coupled.

5. Conclusions

[17] In summary, our data demonstrate that centennial-scale, coordinated hydrological regimes, characterized by a strong connection between the Asian monsoon system and central Indonesian hydrology, defined IPWP climatology during the last 2000 years. Correspondence with high-latitude climatic events (LIA, MWP, DACP, RWP) suggests that on centennial timescales IPWP hydrology is primarily responding to ITCZ displacement induced by changes in Northern Hemisphere climatic mean state. Concomitant hydrological changes in the eastern Pacific paleorecords, particularly during the LIA and MWP, suggest Pacific basin-wide teleconnections, though more paleodata are needed to assess how robust these relationships are. These Pacific-wide connections are superficially akin to an ENSO response but likely implicate lower-frequency shifts in Walker circulation strength and/or position of the Walker cells.

[18] **Acknowledgments.** We thank T. Eglinton, K. Anchukaitis, and C. Maupin for helpful comments and M. Alexandre and Y. Huang for analytical assistance. This research was supported by the U.S. NSF, the Ocean and Climate Change Institute at WHOI, and a National Defense Science and Engineering Graduate Fellowship to J. Tierney. The authors declare that they have no competing financial interests.

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