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Discrete seasonal hydroclimate reconstructions over northern Vietnam for the past three and a half centuries

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Abstract We present a 350-year hydroclimatic year (HY) index for northern Vietnam derived from three discrete seasonal reconstructions from tree rings: an index of autumn rainfall from the earlywood widths of Chinese Douglas fir (*Pseudotsuga sinensis*), the first such record from this species, and two nearby published Palmer Drought Severity Index (PDSI) reconstructions from cypress (*Fokienia hodginsii*) tree rings for spring and summer, respectively. Autumn rainfall over the study region constitutes only around 9% of the annual total, but its variability is strongly linked to the strength of the atmospheric gradient over Asia during the transition from the boreal summer to winter monsoons. Deficit or surplus of autumn rainfall enhances or mitigates, respectively, the impact of the annual winter dry season on trees growing on porous karst hillsides. The most protracted HY drought (dry across all seasons) occurred at the turn of the twentieth century at a time of relative quiet, but a mid-to-late eighteenth century multi-year HY drought coincided with a period of great societal turmoil across mainland Southeast Asia

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and the Tay Son Rebellion in northern Vietnam. A mid-nineteenth century uprising accompanied by a smallpox epidemic, crop failure and famine, occurred during the worst autumn drought of the past two and a half centuries but only moderate drought in spring and summer. The "Great Vietnamese Famine" of the mid-twentieth century was dry only in autumn, with a wet spring and an average summer.

1 Introduction

The area that comprises present-day Vietnam has been occupied and settled for thousands of years, with the Red River (Sông Hồng) valley in the country's north serving as home to the first Vietnamese states around 2879 BC (Taylor 1983). Since that time, the region has seen multiple wars and periods of extreme unrest owing to a variety of causes (Chapuis 1995), including climate (Lieberman and Buckley 2012). Progress on tree-ring reconstructions of climate from mainland Southeast Asia has intensified over the past several years, most notably through the use of Vietnamese cypress (*Fokienia hodginsii*) that span much of the past millennium from northern (Sano et al. 2008, 2012), central (Buckley et al. 2016), and southern Vietnam (Buckley et al. 2010, 2014). Tree-ring reconstructions have also been produced from Myanmar *Tectona grandis* (D'Arrigo et al. 2013; D'Arrigo and Ummenhofer 2014), Lao P.D.R. *Fokienia hodginsii* (Xu et al. 2011), Thailand *Pinus merkusii* (Buckley et al. 1995; D'Arrigo et al. 1997; Xu et al. 2015), and Thai *Tectona grandis* (Buajan et al. 2016; Buckley et al. 2007; Pumijumnong et al. 1995).

This increase in the number of paleoclimate reconstructions has allowed for the analysis of Southeast Asian climate variability with far greater spatio-temporal resolution than from individual sites alone. Cook et al. (2010) developed the Monsoon Asia Drought Atlas (MADA) from a composite of 327 tree-ring sites from across Monsoon Asia, enabling an investigation of historic droughts and pluvials across space and time. A critical component of this research was the addition of key sites from Vietnam that extended at least five centuries into the past and exhibited very strong linkages to El Niño–Southern Oscillation (ENSO) variability (Sano et al. 2008; Buckley et al. 2010). Anchukaitis et al. (2010) used the MADA and in particular the Buckley et al. (2010) Vietnam cypress record to demonstrate that explosive volcanism leads to wetting over Indochina instead of drying as suggested by most general circulation models. Ummenhofer et al. (2013) used the MADA to explore relationships between Indo-Pacific climate variability and drought across Asia, a relationship that is strongly contributed to by the Vietnamese tree-ring records. While the MADA offers an efficient tool for looking at past spatiotemporal aspects of the hydroclimate over Asia, coverage over the tropics remains somewhat sparse and the reconstructions themselves are limited to spring/summer seasonality. Further development of records from underrepresented locales, reflective of seasons other than the spring and summer, will therefore greatly enhance our ability to produce a more nuanced analysis of climate variability for key periods of human history over Asia.

With this paper, we present a reconstruction of autumn (October–November, henceforth ON) rainfall, derived from the earlywood (EW) portion of cross-dated growth rings of *Pseudotsuga sinensis*, or Chinese Douglas fir (henceforth Douglas fir). Ours is the first such record produced from this species, the first use of this genus from the Asian tropics, and the first reconstruction of the autumn season hydroclimate from mainland Southeast Asia. Ours is also the first direct reconstruction of station rainfall from Vietnam, rather than indexed variables such as the Palmer Drought Severity Index or PDSI that has been previously reconstructed from northern and southern Vietnam (Sano et al. 2008, 2012; Buckley et al. 2010) and the Standardized Precipitation Evapotranspiration Index or SPEI from central Vietnam (Buckley et al. 2016). As such, this study marks an important step toward a more complete understanding of the paleoclimate of mainland Southeast Asia across multiple seasons, in particular for the autumn transition from summer to winter monsoon regimes.

2 Materials and methods

2.1 The study area

Douglas fir is found in Vietnam only in the northernmost provinces, on limestone soils on high forest ridges at altitudes between 550 to 1600 m (Luu and Thomas 2004). Our samples come from trees growing on steep limestone mountains at the Kim Hy Natural Reserve in Bac Kan province of northern Vietnam (22°24′N, 106°.03′E, Fig. 1). Climate over this region is characterized by the warm and wet summer monsoon between June and September when nearly 63% of the annual rains fall and a cold and dry season from December to April that accounts for about 5% of the annual total (Fig. S1). The "shoulder" seasons leading into (March–May, henceforth MAM) and out of (October–November, ON) the summer monsoon account for about 23 and 9% of the annual rainfall, respectively. The hydroclimate variability of these shoulder seasons is of great importance for agriculture, particularly with regard to planting of rice during MAM, the season of reconstruction of Sano et al. (2008) from Mu Cang Chai cypress trees to the west of Kim Hy (Fig. 1) and Buckley et al. (2010) from southern

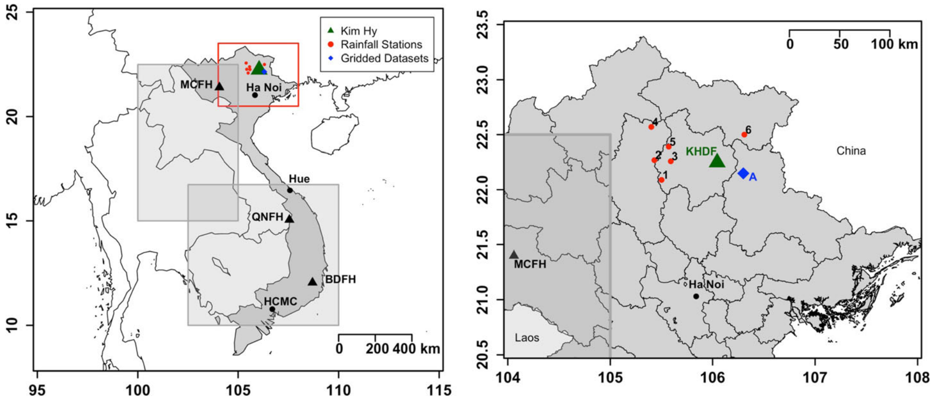

Fig. 1 The location of the study site in broad view (left) and close-up (right) of the area within the red box on the left. The Kim Hy Douglas fir sampling site is indicated by the green triangle in both maps; three published Vietnamese cypress records MCFH (Sano et al. 2008), QNFH (Buckley et al. 2016), and BDFH (Buckley et al. 2010) as black triangles. The six rainfall stations used for climate reconstruction are shown as red dots along with the APHRODITE rainfall record shown as the blue diamond (A, on the right panel). The large gray boxes (left) outline the regionally averaged PDSI grids used for reconstructions by Sano et al. (2008, 2012) for spring and summer PDSI, to the north, and by Buckley et al. (2010) for spring PDSI to the south. The numbered rainfall stations (red dots) shown on the right are 1 = Bac Kan, 2 = Cho Ra, 3 = Ngan Son, 4 = Bao Lac, 5 = Nguyen Binh, and 6 = Trung Khanh. These six stations were combined with A to comprise the A6S regional rainfall record used for reconstruction

Vietnam cypress. Both of these studies demonstrated strong connection between MAM hydroclimate and the variability of ENSO, a relationship whose strength increases from north to south (Buckley et al. 2016). While the mean average annual temperature for Bac Kan province is 25 °C, the minimum temperature drops to near freezing during the coldest months and may exceed 35 °C during much of the warm season. Cold surges related to wind anomalies in the lower troposphere are frequent during the winter shoulder season (ON) and can often bring anomalously high rainfall to central Vietnam (Yokoi and Matsumoto 2008) and increased wind and moisture into the study region.

2.2 Tree-ring sampling and data development

Three sampling expeditions were launched in November 2007, November 2011, and most recently in June 2016. In total, we collected 170 core samples from 75 Douglas fir trees from between 600 and 800 m above mean sea level on elevated karst terrain (Table S1). All annual growth rings were cross-dated using traditional visual and microscopy-based techniques, for example, skeleton plotting (Stokes and Smiley 1968), prior to measurement. Each dated core was then scanned using an EPSON Perfection V850 Pro model scanner coupled with Silverfast imaging software in order to produce a high-resolution image (2400 dpi). These images were analyzed with the software CooRecorder V8.1.1 and CDendro V8.1.1 from Cybis Dendrochronology (Larsson 2016). CooRecorder was used for making discreet measurements of EW, latewood (LW), and total ring width (TRW) as shown in Fig. 2 while its companion program CDendro facilitated real time correlation analyses between sequential measurements from individual cores and master growth indices (i.e., multiple cross-dated cores averaged

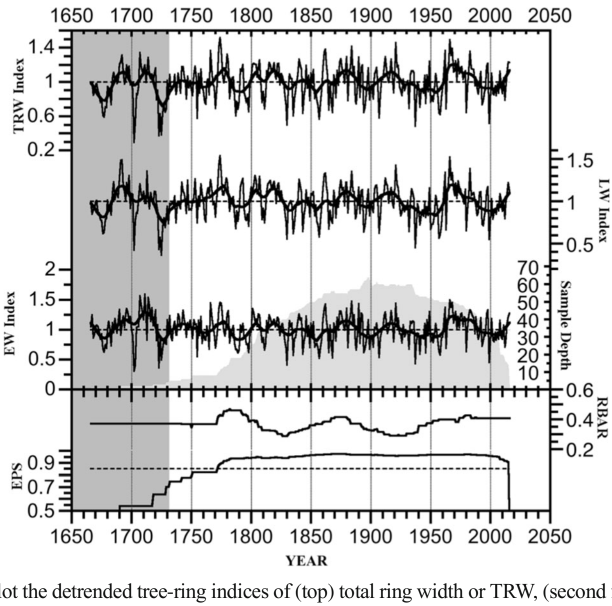

Fig. 2 Here, we plot the detrended tree-ring indices of (top) total ring width or TRW, (second from top) latewood or LW, and (third) earlywood widths (EW) from Kim Hy Natural Reserve in northern Viet Nam. The bottom plot shows the 51-year running correlation Rbar (top) along with the expressed population signal, or EPS (bottom). The dashed line in the EPS plot represents the generally accepted 0.85 threshold (Wigley et al. 1984), and the gray-shaded region represents years with an EPS < 0.75, and thus the segment of our record we do not use for further analyses

together). Measurements in CooRecorder are made using a linear *x*, *y* coordinate system with a sensitivity of 0.001 mm. The boundary of each annual ring, as well as the EW/LW seasonal wood division, is marked successively with a coordinate point, and the distance between each of those points is measured. Each of the three-time series (TRW, EW, and LW) were detrended and normalized using the relatively new method of "signal free" standardization (Melvin et al. 2007; Briffa and Melvin 2011) as used and described by Buckley et al. (2016) for Vietnamese cypress in central Vietnam. For this purpose, we used the program RCSig, a freeware program developed at the Lamont-Doherty Earth Observatory that is based on the commonly used program ARSTAN (Cook 1985). See Supplemental Information (SI) for full details on the selection of EW/LW boundaries and the signal-free standardization procedures.

2.3 The A6S rainfall composite

We selected daily precipitation measurements from six weather stations from within a 75-km radius of Kim Hy (locations shown in Fig. 1). These station records were compiled for a World Bank study (Thomas et al. 2010) and span from 1975 to 2006. We summed the daily values for each month to produce a monthly dataset for each of the six stations and then combined them with the nearest grid point (22°N, 106°30′E, approximately 30 km from our study site) from the Aphrodite gridded rainfall dataset that spans from 1951 to 2007 (Yatagai et al. 2012). The resultant seven-station mean and variance-adjusted average (henceforth A6S) represents the overall regional rainfall for the 52-year period from 1955 to 2007. The largest percentage of the annual rainfall for A6S occurs during the June–September (JJAS) summer monsoon season (63%), followed by March–May (MAM = 23%) and ON (9%) of the annual average.

2.4 Climate analyses and reconstruction

We used the Lamont-Doherty Earth Observatory Tree Ring Laboratory program PCReg (principal components regression) to analyze the point-by-point regression response of EW, LW, and TRW to monthly values of climate (e.g., A6S rainfall) over a 24-month window, in order to determine the most significant season of climate for tree growth (EW is shown in Fig. 3 and LW and TRW are shown in Fig. S6). We also compared our EW, LW, and TRW indices with gridded climate fields including those for sea surface temperature (SST), PDSI, the standardized precipitation-evapotranspiration Index (SPEI), and various interpolated temperature and precipitation datasets. We used the web-based KNMI Climate Explorer (Trouet and Van Oldenborgh 2013) for analyzing basic spatial patterns of response and then used the Lamont-Doherty program PCReg and the freely available dplR (Bunn 2008) for more detailed statistical correlation analyses and climate reconstruction.

3 Results and discussion

We successfully cross-dated 76 cores from 33 trees to produce discreet records of earlywood (EW), latewood (LW), and total ring width (TRW) measurements that span three and a half centuries (Fig. 2). We disclose full details about the tree-ring record in the SI. The Kim Hy Douglas fir (KHDF) index provides evidence of persistent, below-average growth for several key periods that include the late eighteenth century, the mid-nineteenth century, the turn of the

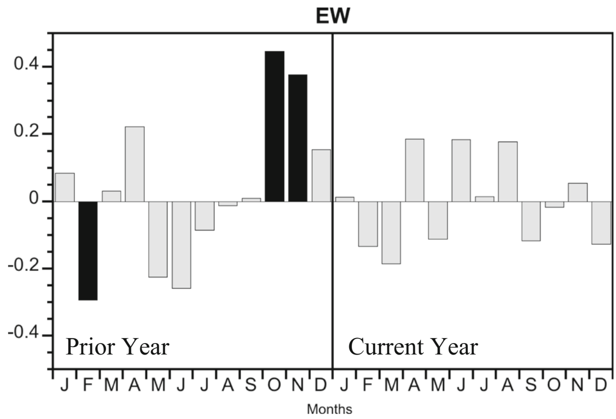

Fig. 3 The 24-month correlation window between EW and the A6S rainfall composite using point-by-point regression that treats each monthly correlation individually (for the full period of 1955–2007). The current year is shown on the right and the year prior to growth is shown on the left. The black-shaded bars highlight the months for which there is a significant relationship, most notably the ON season that was used for reconstruction as described in the text. For the same comparison with LW and TRW, please see Fig. S6

twentieth century, and the mid-twentieth century. While all three parameters exhibit a similar response to climate (Fig. 3 and Fig. S6), EW provided the most stable reconstruction model for ON rainfall of the year prior to growth, likely due to EW's higher MSI (0.567) relative to LW and TRW (0.403 and 0.537, respectively) as shown in Table S2. In spite of its lower percentage of rainfall relative to spring and summer, ON is the season most strongly correlated with the following year's growth at our site for all three tree-ring parameters and is the least correlated season with total annual rainfall (Fig. S5). Given the highly porous karst landscape at Kim Hy, ON rainfall is likely crucial for staving off the deleterious effects of a winter dry season that falls between December and February. A deficit of ON rainfall effectively serves to increase the soil moisture deficit for trees as they enter the winter dry period, which in turn serves as a negative feedback to growth the following year.

Based on the above discussion, we used EW as a predictor of prior ON A6S rainfall to create a reconstruction model that explains 29.64% of the variance of the calibration period data (1965–2007). While this value for explained variance might seem somewhat low, it is comparable or higher than other hydroclimate reconstructions from the region (see Table 1) and most importantly passes all of the standard statistical tests commonly used for dendroclimatology (Cook and Kairiukstis 2013). These tests include the reduction of error (RE = 0.579) and the coefficient of efficiency (CE = 0.539) for the verification period. While there is no statistical significance test for CE per se, any values greater than zero indicate model skill (Cook and Kairiukstis 2013), and for both halves of our split calibration-verification scheme, our reconstruction exhibits a positive CE. Calibration on either half of the record produced robust results, though with a higher degree of explained variance from calibrating on the most recent years due to increasing quality of the data through time. In addition, explained variance is highest after first differencing, indicating strong year-to-year agreement between actual and estimated values (Table S4). For complete calibration-verification statistics, please see SI.

Our final ON rainfall reconstruction was standardized and compared with two regional reconstructions developed from a Vietnamese cypress collection from nearby Mu Cang Chai (MCFH in Fig. 1). The first is a MAM PDSI reconstruction from ring width (Sano et al. 2008),

Table 1 Basic statistics from the various hydroclimate reconstructions mentioned in our text. Listed from left to right is the site and tree-ring variable measured (e.g., EW), the earliest year on record, last year on record, the number of cores/trees in each record, and the mean series intercorrelation (MSI) of each record. Also shown is the hydroclimate variable reconstructed along with the season of reconstruction and the percentage of explained variance. The * in the season of reconstruction for the MCFH–δ^{18}O record shows the full season of the published record which extends from May to October. The explained variance also coincides with this full reconstruction. However, in our study, we reproduced the reconstruction for June–Sep, so as not to overlap with our other seasonal reconstructions, and we list this value directly below

Record	1st year	Last year	Cores/trees	MSI	Reconstructs	Season	Variance explained (%)
KHDF-EW	1666	2016	76 / 33	0.565	Rainfall	ON	29.64
MCFH-TRW	1470	2004	42 / 22	0.474	PDSI	MAM	19.00
MCFH-δ^{18}O	1705	2004	6 / 6	0.729	PDSI	MJJASO*	44.00
					PDSI	JJAS	41.40
QNFH-TRW	1347	2013	71 / 37	0.526	SPEI	April	23.30
BDFH-TRW	1030	2008	74 / 38	0.578	PDSI	MAM	35.00

and the second is a summer monsoon (June–September, JJAS) reconstruction derived from the stable isotopes of oxygen from the same trees (Sano et al. 2012). The δ^{18}O record was published by Sano et al. (2012) as a May–October PDSI reconstruction; however, we ran a new reconstruction model on the JJAS season in order to remove the one-month of overlap with the MAM and ON reconstructions, respectively. Model statistics for our reconstruction are comparable with the original Sano et al. (2012) model with only a slight loss of explained variance (from 44 to 42%, see Table 1). In order to compare the different proxies of monsoon reconstruction (i.e., rainfall and PDSI), we standardized each record by subtracting the mean and dividing by the standard deviation to convert to z-scores, thereby creating three independent seasons of annual hydroclimate that span nearly the entire year. We then summed the standardized reconstructions together to produce the composite hydroclimate year (HY) index that we use to analyze annual rainfall variability for the past three centuries.

We present our reconstruction of ON rainfall in Fig. 4 along with the Mu Cang Chai MAM PDSI and JJAS PDSI reconstructions (Sano et al. 2008, 2012) as described above. We also present the HY index that characterizes the entire annual monsoon season across northern Vietnam over the past three and a half centuries, and we highlight periods where two or three seasons are simultaneously in deficit or surplus. The most notable decadal-scale occurrences of HY drought fall between the 20-year periods of 1780–1800, 1850–1870, and 1890–1910. These periods also coincide with historical accounts of societal turmoil (i.e., famine, disease, and drought), as mentioned below and discussed more thoroughly in the SI.

3.1 The autumn rainfall regime over Vietnam

ON rainfall over Vietnam is modulated by the East Pacific-North Pacific (EP-NP) teleconnection as explained by Li et al. (2015), a phenomenon that is expressed most clearly over central Vietnam. Strong EP-NP phases coincide with anticedal anomalies in the SSTs of the South China Sea (SCS), which in turn lead to strong positive or negative precipitation anomalies along the coast (Li et al. 2015). A positive EP-NP is associated with negative SST anomalies in the SCS that lead to decreased rainfall and vice versa. Buckley et al. (2016) highlight the importance of ON rainfall for tree growth in central Vietnam, suggesting as we do here that the ON season will influence tree physiology at the start of the next year's growth

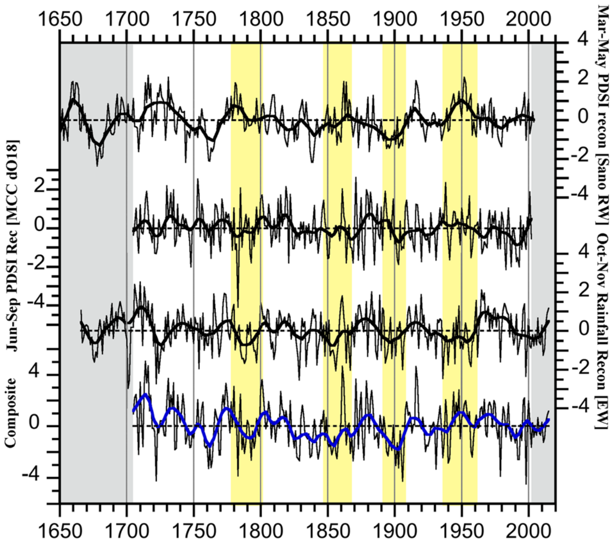

Fig. 4 Three hydroclimate reconstructions of (a) Mu Cang Chai March–May PDSI from *Fokienia hodginsii* ring width indices (Sano et al. 2008), (b) Mu Cang Chai June–September PDSI derived from $\delta^{18}O$ indices from the same trees as in (a) by (Sano et al. 2012), and (c) our October–November rainfall anomalies developed from the current study. The lower plot (d) is the "hydroclimate-year" (HY) index, which is the simple sum of the *z*-scores of all three reconstructions. The heavy lines in each plot (blue for HY) shows the 20-year low-pass filtered version of each record to accentuate decadal variability

increment. The importance of ON rainfall for tree growth lies in its potential role in setting the soil moisture conditions prior to the onset of the winter dry season, which is more pronounced in the north and south of Vietnam than it is in the center of the country (Buckley et al. 2016). From a climate standpoint, ON rainfall reflects the strength of the seasonal temperature/pressure gradient over Asia and the transfer of energy between hemispheres via the cross-equatorial flow (e.g., Sachs et al. 2009; Yan et al. 2015).

Yokoi and Matsumoto (2008) describe the ON season in terms of the transition from the boreal summer monsoon into the winter monsoon season, when the southwesterly wind regime of summer gives way to the northeasterly flow of winter (Fig. S8). The strength of the temperature and pressure gradients over Asia at this time dictates the vigor with which this northeasterly flow crosses the Indochina Peninsula (IP). Episodic cold surges—excursions of anomalously cold air masses from the Asian mainland that are steered along the Tibetan Plateau—bring increased surface pressure and anomalously low temperatures to the SCS and coastal Vietnam. When these cold surges meet with tropical disturbances over the SCS, the cold and moist air masses are steered over the IP where they can bring anomalously high rainfall (Yokoi and Matsumoto 2008).

In northern Vietnam, annual autumn rainfall is normally low in comparison to that in central Vietnam. For example, in our A6S composite of monthly rainfall, the ON season averages about 120 mm per year, an amount that is more than doubled along the central coast (Chen et al. 2012). However, while the total autumn rainfall is relatively low overall compared with central Vietnam, the effects from the EP-NP as well as the cold surge mechanisms described above may also influence rainfall well to the north. We compare rainfall over the study region with three measures of the strength of the temperature/pressure gradient related to the onset of the winter monsoon—meridional wind stress (MWS), zonal wind stress (ZWS), and net water flux (P-E), as shown in the top panel of Fig. 5. For all three factors, we see a significant ($p < 0.05$), direct relationship between ON rainfall amount and circulation vigor. As shown in the bottom panel of Fig. 5, the relationship between EW and these same three factors is essentially identical to that for ON rainfall.

3.2 Societal turmoil and drought

We highlight four distinct periods over the past three and a half centuries when documented societal upheaval over northern Vietnam coincided with multi-year hydroclimate anomalies for at least one of the three seasons of reconstruction (Fig. 4). We focus here on the first of these in the mid-to-late eighteenth century, when a protracted decadal-scale drought struck northern Vietnam from 1740 to 1770 (Sano et al. 2008). Buckley et al. (2010) and D'Arrigo et al. (2013) revealed that this drought extended to southern Vietnam and central Myanmar, respectively, though with slightly different timing. Cook et al. (2010) coined the name "Strange Parallels Drought (SPD)", after Victor Lieberman's (2003) seminal work on the simultaneous collapse of the polities of Southeast Asia and northern Eurasia. Lieberman

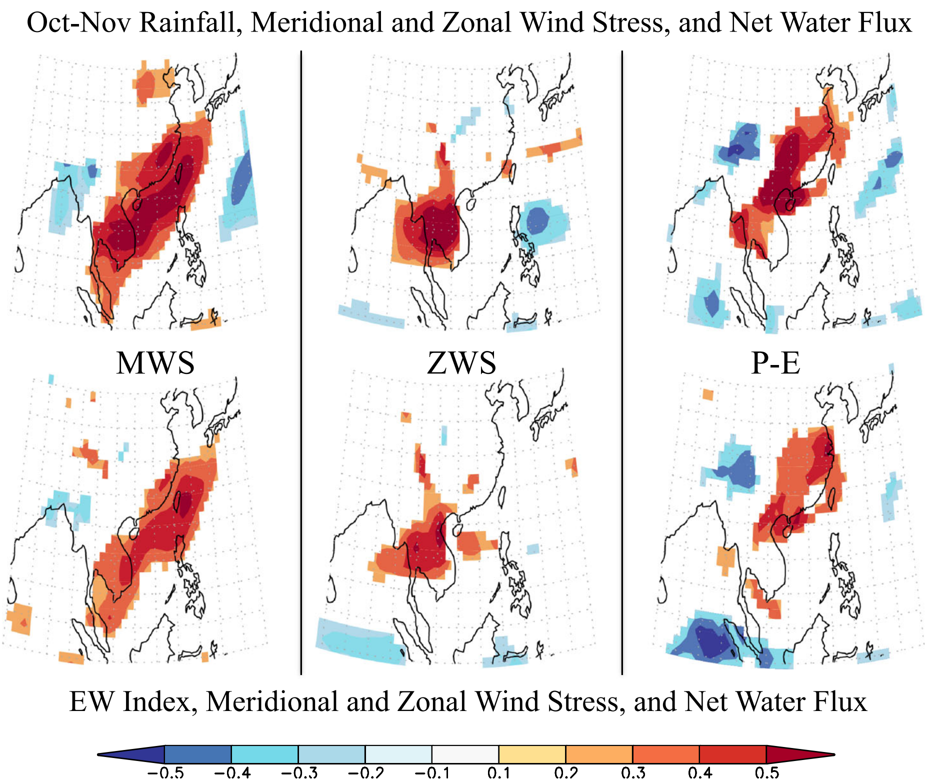

Fig. 5 Spatial comparisons between ON rainfall over the study region (top) and the EW index (bottom) with (left to right) meridional wind stress (MWS), zonal wind stress (ZWS), and net water flux (P-E), all from the ERA-twentieth century reanalysis dataset. The period of comparison is 1955–2007 for all variables. Only significant values ($p < 0.05$) are shown, and dark red indicates strong direct correlation with these three factors that are related to the atmospheric temperature/pressure gradient at the onset of the East Asian winter monsoon (EAWM). All data were detrended prior to correlation

surmised the cause of collapse to be climate, but it was only with the development of the tree-ring reconstructions of Buckley et al. (2007, 2010) that the evidence supported this premise (Lieberman and Buckley 2012).

The MADA maps in Fig. S9 indicate widespread drought during the period from 1756 to 68 over all of Southeast Asia; however, Fig. 4 indicates that the more acute period of drought across multiple seasons over northern Vietnam falls between 1780 and 1800 as reflected by the JJAS and ON reconstructions. The HY composite shows that, across all seasons, the 60-year period from 1740 to 1800 was marked by near continuous, below average rainfall. It was during this period that French missionaries reported severe food shortages over northern Vietnam in 1770, 1778–79, and 1785–86 (Buckley et al. 2014). These shortages occurred during some of the worst periods of drought, according to our reconstructions, and contributed to the defeat of the Le Dynasty (1428–1789), the Tay Son Dynasty (1773–1802), and the subsequent defeat of the Tay Son by the Nguyen Dynasty (1802–1945) (Dutton 2006). While Buckley et al. (2010) and Cook et al. (2010) note the relationship between drought over Southeast Asia and the warm phase of ENSO, Hernandez et al. (2015) attributed the decadal nature of the SPD to El Niño Modoki variability, where cool anomalies persist on both sides of the tropical Pacific Basin rather than on the western flank only. For a thorough treatment of the societal impacts that occurred during all four periods noted above, please refer to the SI.

4 Conclusion

We have produced precisely dated, annual EW, LW, and TRW indices from northern Vietnamese Douglas fir (*Pseudotsuga sinensis*) that span the past three and a half centuries. We used EW as the predictor for autumn (ON) rainfall of the prior year to produce a reconstruction for northern Vietnam with an explained variance of nearly 30% and that passes all standard statistical tests of reconstruction model fidelity. Ours is the first such record for this region and species, the first use of this genus in the Asian tropics, the first reconstruction of the autumn season, and the first direct reconstruction of an instrumented variable from Vietnam. We combined our autumn rainfall reconstruction with spring and summer PDSI reconstructions from cypress trees growing in nearby Mu Cang Chai to provide a hydroclimate year (HY) index that strongly correlates with historically documented periods of societal upheaval, famine, disease, and drought. Protracted drought events in the mid-to-late eighteenth century (the well-documented Strange Parallels Drought) and the mid-nineteenth century occurred amidst the upheaval of all the major polities across Southeast Asia in the former case, and severe disruption across Vietnam in the latter case. While our multi-seasonal reconstruction is of great value for assessing the impact of sustained drought, a typical shortcoming of tree-ring reconstructions is to fail to capture high-magnitude rain events that result from shorter-term major storm trajectories and stalled systems. These events typically occur during the autumn transitional season into the winter monsoonal regime, hence highlighting the importance of the ON reconstruction presented in this paper. As noted in prior studies, from the region, it is often these excess rain events that cause significant damage to critical systems infrastructure (e.g., dams and irrigation canals) that results in tipping points for societies. Developing additional parameters of growth indices, perhaps using sub-annual measurements of stable isotopes, might assist with assessing extreme wet events. Integrating additional proxy data sources from corals, lacustrine sediments, and speleothems would be a prudent next step.

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