Moisture and Temperature Covariability over the Southeastern Tibetan Plateau during the Past Nine Centuries^①

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ABSTRACT

Accurate projections of moisture variability across the Tibetan Plateau (TP) are crucial for managing regional water resources, ecosystems, and agriculture in densely populated downstream regions. Our understanding of how moisture conditions respond to increasing temperatures over the TP is still limited, due to the short length of instrumental data and the limited spatial coverage of high-resolution paleoclimate proxy records in this region. This study presents a new, early-summer (May–June) self-calibrating Palmer drought severity index (scPDSI) reconstruction for the southeastern TP (SETP) covering 1135–2010 CE using 14 tree-ring records based on 1669 individual width sample series. The new reconstruction reveals that the SETP experienced the longest period of pluvial conditions in 1154–75 CE, and the longest droughts during the periods 1262–80 and 1958–76 CE. The scPDSI reconstruction shows stable and significant in-phase relationships with temperature at both high and low frequencies throughout the past 900 years. This supports the hypothesis that climatic warming may increase moisture by enhancing moisture recycling and convective precipitation over the SETP; it is also consistent with climate model projections of wetter conditions by the late twenty-first century in response to global warming.

1. Introduction

The Tibetan Plateau (TP), frequently referred to as the “water tower of Asia” (Xu et al. 2008; Immerzeel et al. 2010), is the source region of many large rivers in Asia, including the Yellow River, Yangtze River, Nu Jiang River, Mekong River, and Indus River. Moisture variability on the TP therefore has a considerable

influence on water resources, agriculture, and ecosystems not only on the TP itself but also in countries downstream, thereby affecting the well-being of billions of people (Gao et al. 2019). Accurate projections of future moisture changes under global warming are important for the TP, but such predictions are largely dependent on a well-constrained temperature–moisture relationship in climate model simulations (Ljungqvist et al. 2016). However, state-of-the-art climate models show large uncertainties in the coupling between changes in temperature and moisture, especially at regional scales (Stephens et al. 2010; Christensen et al. 2013; Orłowsky and Seneviratne 2013; Nasrollahi et al. 2015). Uncertainties in how moisture variability will respond to global warming are particularly large for the

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TP and adjacent regions of East Asia (Osborn et al. 2015).

Instrumental observations show that the TP has experienced a rapid warming during the past six decades, with a higher rate of temperature increase than the global average (Pepin et al. 2015; You et al. 2017). Although changes in precipitation over the TP, unlike the well-recognized warming, show large spatial and seasonal variability, an overall wetting trend is observed in instrumental data (Yao et al. 2012; W. Zhang et al. 2017). The increased precipitation over the TP has been suggested to be related to intensified local moisture recycling in response to increasing surface temperature during the past decades (Guo and Wang 2014; Curio et al. 2015). However, the response of precipitation to temperature as indicated by instrumental observations need to be further validated over longer time scales beyond those of the brief period covered by instrumental data. Recent studies suggest time scale-dependent relationships between temperature and moisture in Europe (Seftigen et al. 2017; Ljungqvist et al. 2019b) and East Asia (Rehfeld and Laepple 2016), but these are too short to be fully resolved by instrumental observations. Moreover, temperature and presumably also precipitation (or moisture) have been increasingly influenced by anthropogenic forcing (e.g., greenhouse gas concentration and aerosols) during the instrumental period (Myhre et al. 2013). Taken together, these issues stress the importance of using paleoclimate data to place the current and future climate regimes in a long-term perspective (Cook et al. 2004, 2010, 2015; Mann et al. 2009; Büntgen et al. 2011, 2016; Esper et al. 2018; Ljungqvist et al. 2012, 2016, 2019a,b; Luterbacher et al. 2016; Wilson et al. 2016; PAGES Hydro2k Consortium 2017).

Considerable progress has recently been made in developing high-quality tree-ring records covering the centuries and millennia over the eastern Tibetan Plateau (ETP) (e.g., Zhang et al. 2003; Bräuning and Mantwill 2004; Sheppard et al. 2004; Liu et al. 2006; Liang et al. 2008; Zhu et al. 2008; Fang et al. 2009; Fan et al. 2010; Shao et al. 2010; Griesinger et al. 2011; Yang et al. 2014, 2019; Gou et al. 2015; Deng et al. 2016; Yin et al. 2016; Li et al. 2017; Wernicke et al. 2017). The ETP, with the highest alpine tree line in the world (mostly exceeding 4000 m above mean sea level), is well suited for developing temperature-sensitive tree-ring chronologies from the upper tree-line area (Liang et al. 2008; Deng et al. 2014; Duan and Zhang 2014; Wang et al. 2014; Shi et al. 2016; Li and Li 2017). Wang et al. (2015) found strong covariance between these temperature-sensitive site chronologies from the ETP, enabling the development of a regional summer (June–August) temperature

reconstruction covering the past millennium (1000–2005 CE; hereinafter all years are in the common era). The majority of the tree-ring-based moisture reconstructions have been developed from moisture-limited sites, around the lower tree-line areas (Fan et al. 2008; Fang et al. 2009; Li et al. 2017; Shi et al. 2018), although some have also been derived from the upper tree-line areas (Liu et al. 2011; He et al. 2013; Yang et al. 2014). Zhang et al. (2015) found substantial differences between changes in the moisture-sensitive tree-ring chronologies of the southern and northern ETP (with the regime division at $\sim 33^\circ\text{N}$), attributing this contrast to a south–north moisture dipole. These tree-ring records now serve as a basis for new opportunities to conduct detailed and accurate regional moisture reconstructions with which the history of the moisture changes can be described.

In this study, we use 14 previously published moisture-sensitive tree-ring width records to develop a new regional-scale early summer (May–June) self-calibrating Palmer drought severity index (scPDSI) reconstruction for the southeastern TP (SETP) covering the period 1135–2010. We assess the temporal relationships between moisture and temperature at interannual to centennial time scales. Using this new reconstruction in tandem with a model-simulated scPDSI dataset, we place the current (twentieth century) moisture variability and future (twenty-first century) projections within the context of the past millennium.

2. Data and methods

a. Instrumental data

The gridded Climatic Research Unit (CRU) TS 4.01 $0.5^\circ \times 0.5^\circ$ monthly temperature and precipitation dataset (Harris et al. 2014) were used to investigate the relationship between climate and tree growth. We only used CRU data after 1950, because very few meteorological stations in this region are available prior to this time (Liu and Chen 2000). The regional (i.e., SETP scale; 27° – 33°N , 90° – 102°E) average of monthly CRU data was calculated and used to examine the correlations between tree-ring records and regional climate variables.

The Palmer drought severity index (PDSI), as a standardized index, is widely used as an indicator of soil moisture variability (Palmer 1965; Dai 2011, 2013). The zero values of PDSI represent the baseline for average conditions and positive (negative) values indicate wet (dry) departures from the baseline climatology. The self-calibrating PDSI (scPDSI; Wells et al. 2004), a revised version of the PDSI, applies a more physically realistic Penman–Monteith parameterization for potential

TABLE 1. Metadata for the 14 moisture-limited tree-ring chronologies over the SETP. Abbreviations are as follows: mean sample length (MSL); “not a number” (i.e., information missing in the original literature) (NaN); expressed population signal (EPS); signal free (SF); linear regression function (LRF), cubic spline function (CSF), and negative exponential function (NEF) are detrending techniques applied to calculate site chronologies by the original authors; r shows the correlation between site tree-ring chronologies and May–June scPDSI over the period 1950–2001; median β refers to the contribution of site chronologies to the reconstruction for the best replicated nest during 1702–2001.

Site No.	Site name	Lat (°N)	Lon (°E)	Alt (m)	Species	No. of cores	Detrending method	MSL (yr)	Period (EPS > 0.85)	r with scPDSI	Median β	Reference
1	Baima Snow Mountain	27.58	99.35	3240	<i>Picea likiangensis</i>	136	NEF, LRF	297	1655–2005	0.27	0.09	Fan et al. (2008)
2	Baizha	31.87	96.52	3908	<i>Juniperus tibetica</i> Kom.	64	CSF	NaN	1442–2000	0.02	0.14	Zhang et al. (2015)
3	Basu	30.06	97.12	4382	<i>Juniperus tibetica</i> Kom.	58	CSF	NaN	1702–2006	0.25	0.07	Zhang et al. (2015)
4	Bianbamx	31.08	94.58	4144	<i>Juniperus tibetica</i> Kom.	48	CSF	NaN	1449–2006	0.34	0.19	Zhang et al. (2015)
5	Gbjda	29.82	92.65	4250	<i>Juniperus tibetica</i> Kom.	46	CSF	NaN	1611–2005	0.23	0.10	Zhang et al. (2015)
6	Gongjue	30.75	98.69	3817	<i>Juniperus tibetica</i> Kom.	48	CSF	NaN	1475–2006	0.47	0.09	Zhang et al. (2015)
7	Langxian	29.00	93.33	3139	<i>Juniperus tibetica</i> Kom.	311	CSF	332	1300–2010	0.13	0.01	Liu et al. (2012)
8	Linzhou	30.30	91.50	4200	<i>Juniperus tibetica</i> Kom.	161	SF	377	1085–2008	0.07	0.10	He et al. (2013)
9	Luolong	30.58	96.18	4440	<i>Juniperus tibetica</i> Kom.	64	CSF	NaN	1548–2006	0.40	0.15	Zhang et al. (2015)
10	Mangkang	29.45	98.35	4050	<i>Juniperus tibetica</i> Kom.	56	CSF	NaN	1451–2006	0.48	0.08	Zhang et al. (2015)
11	Sangri	29.38	91.97	4275	<i>Juniperus tibetica</i> Kom.	140	CSF	483	1480–2008	0.28	0.02	Liu et al. (2011)
12	Daocheng	29.15	99.95	3530	<i>Abies forrestii</i>	95	SF	291	1523–2010	0.47	0.10	Li et al. (2017)
13	Suoxian-jiali	30.57	93.55	4005	<i>Juniperus tibetica</i> Kom.	329	CSF	328	1135–2010	0.23	0.16	He et al. (2018a)
14	Weixi	27.59	99.45	3040	<i>Abies forrestii</i>	113	CSF	297	1440–2007	0.31	0.08	Fang et al. (2009)

evapotranspiration (van der Schrier et al. 2013) and has been demonstrated as being suitable for describing moisture conditions over the TP (Zhang et al. 2015; Li et al. 2017; He et al. 2018a). In this study, the regional monthly scPDSI data (van der Schrier et al. 2013) were used to identify relationships with the tree-ring chronologies. This global gridded scPDSI product, however, is based on the gridded temperature and precipitation

from the CRU TS 3.10.01 climate dataset (van der Schrier et al. 2013).

b. Tree-ring data

A total of 14 moisture-sensitive tree-ring width (TRW) chronologies from the SETP, published in previous studies and comprising 1669 individual TRW samples, were used in this study (Table 1). The species

FIG. 1. Box plot (expressed as 10th, 25th, 50th, 75th, and 90th percentiles) for correlations of the 14 site tree-ring chronologies included in our new reconstruction with the monthly temperature, precipitation, and scPDSI over the SETP during the period 1950–2001. Gray shading indicates the 95% confidence interval.

used in our study include fir (*Abies forrestii*), juniper (*Juniperus tibetica* Kom.), and spruce (*Picea likiangensis*). The growth of these species over the SETP is particularly sensitive to soil moisture availability (mainly from rainfall and snowmelt) in the early growing season (Fang et al. 2015a; Li et al. 2017). There might be some differences in physiological response across the study site network, but the common element among the sites and species is a response to moisture stress (Fang et al. 2015a; Zhang et al. 2015; Yang et al. 2017). Three tree-ring chronologies were previously used by original authors to reconstruct the mean annual precipitation changes (He et al. 2013; Liu et al. 2011, 2012), whereas the other 11 chronologies were used to reconstruct moisture (i.e., scPDSI) variability in the pregrowing or growing seasons (Fan et al. 2008; Fang et al. 2009; Zhang et al. 2015; Li et al. 2017). Among these, 12 site chronologies were developed by applying a traditional standardization method (e.g., ratios from negative exponential curves, linear regression curves, and cubic splines; Cook and Peters 1981, 1997), whereas the other two site chronologies were developed using the “signal-free” method (Melvin and Briffa 2008). The generally long segment length of the tree-ring series (with a median value of 328 years) enables these site chronologies to resolve climatic frequencies at centennial scales even when using traditional detrending methods, but capturing multicentennial frequencies is more challenging (Cook et al. 1995). The positive correlations (median $r = 0.22$, $p < 0.05$, for the common period 1702–2001; Fig. S1 in the online supplemental material) among the 14 tree-ring records suggest a common climate factor driving the year-to-year variability of tree growth across these sites.

The site chronologies show generally positive correlations with precipitation from the previous October to the current September, with the significant correlations during the early-summer months of May and June

(median $r = 0.28$, $p < 0.05$) over the period 1950–2001 (Fig. 1). All site chronologies correlate negatively with the early-summer (May–June) temperature (median $r = -0.32$, $p < 0.05$). The positive effect of precipitation and negative effect of temperature found here indicate the typical moisture stress on tree growth during the early summer. We therefore examined the correlations with scPDSI during the period 1950–2001. Significant positive correlations with the scPDSI are found for all months investigated, with the highest values for current May–June (median $r = 0.47$, $p < 0.001$). This suggests that the early growing season moisture condition is the most critical factor limiting tree growth at the moisture-limited sites of the SETP.

c. Reconstruction methods

We used a nested principal component regression (PCR) approach (Cook et al. 1999, 2004; Luterbacher et al. 2004; Maxwell et al. 2011; Pederson et al. 2013; Ortega et al. 2015; Wang et al. 2017) to conduct the early-summer (May–June) scPDSI reconstruction for the SETP. This approach creates a suite of nests, considering that the number of available tree-ring chronologies decreases before the earliest common year (here, 1702) and after the latest common year (here, 2001) of the 14 tree-ring site chronologies. For each nest, a sliding window approach for calibration (2/3 length of the instrumental data) and verification (1/3 length of the instrumental data) was used to produce the reconstruction (Schneider et al. 2015; Smerdon et al. 2015; Wang et al. 2017; Yang et al. 2019). The initial calibration interval extended from 1950 to 1984 and was incremented by one year until reaching the final interval 1967–2001, creating an ensemble of 18 plausible reconstruction members. For each nested subset, the reduction of error (RE), coefficient of efficiency (CE), root-mean-square error (RMSE), and coefficient of determination

FIG. 2. (a) Comparison between the targeted and reconstructed MJ scPDSI using calibration (validation) interval reconstruction, for each calibration (validation) year, shown as the median and 2.5th-, 50th-, and 97.5th-percentile values of the 18 ensemble members produced by the sliding calibration/verification windows (see section 2c). (b) As in (a), but for the first-differenced data. (c),(e) Spatial correlation maps between the reconstructed and the targeted MJ scPDSI over, respectively, the calibration interval and the verification interval, shown as the median of the 18 correlations at each grid point. (d),(f) As in (c) and (e), but for the first-differenced data. Light green points show the locations of the tree-ring sampling sites across the SETP. Correlations not significant at the 95% level have been masked out on the map.

(R^2) statistics were used to assess the skill of each nested model (Cook et al. 1999, 2004). The final scPDSI reconstruction, RE, CE, R^2 , and RMSE statistics were then characterized as the median values of the 18 ensemble members. The full “nested” reconstruction was then produced by appending each subset median reconstruction after scaling to the most replicated 1702–2001 nest. The reconstruction is further validated by examining spatial correlation patterns between the reconstruction and the CRU dataset for the validation interval only, and

the results are shown as the median of 18 correlations at each grid point in spatial maps (Fig. 2 and Fig. S2). For a detailed description of the reconstruction method, see Wang et al. (2017).

d. Temperature reconstructions

The annually resolved summer (June–August) temperature reconstruction for the ETP by Wang et al. (2015) was used to examine the relationships between temperature and moisture. This temperature reconstruction

was conducted by applying a nested composite-plus-scale approach (Jones et al. 2009; Christiansen and Ljungqvist 2017) to 12 temperature-sensitive TRW chronologies, including 946 individual TRW samples from upper tree-line areas across the ETP. In addition, an annual (January–December) temperature reconstruction using tree-ring width samples from upper tree-line mountain areas in Qamdo, SETP (Wang et al. 2014), was used to further validate the association between temperature and moisture in this region.

The differences in the climatic seasonality between reconstructions should not hamper their comparisons, because the site TRW records used in the temperature reconstruction also include temperature signals for May and June (Wang et al. 2014, 2015), and the site TRW records used in the moisture reconstruction also contain moisture signals for summer and other seasons (Fig. 1). In addition, there are no common predictors between the temperature and moisture reconstructions, which rules out any circular logic in the comparison. However, the temperature and scPDSI reconstructions used here are not fully independent in terms of their reconstruction targets as the scPDSI and CRU temperature data they used to calibrate are not independent of each other, as we stated earlier.

e. Wavelet coherence analysis and ensemble empirical mode decomposition

Wavelet coherence analysis (Torrence and Compo 1998) was used to examine the time-scale-dependent relationships between the temperature and moisture reconstructions over their common period 1135–2005. A Morlet wavelet (with $w_0 = 6$) was used to provide a good balance between time and frequency localization, and the significance level was calculated against a red noise spectrum (Grinsted et al. 2004).

The ensemble empirical mode decomposition (EEMD) method (Huang and Wu 2008; Wu and Huang 2009) was used to extract multiple intrinsic mode functions (IMFs) from interannual to centennial time scales in temperature and moisture reconstructions. This decomposition created nine IMFs for each reconstruction, and the adjacent IMFs were combined to create four frequency domains, at interannual (1–10 years), decadal (10–30 years), multi-decadal (30–100 years), and centennial (>100 years) time scales.

f. CMIP5 simulated scPDSI data for the twentieth and twenty-first centuries

The model-simulated scPDSI dataset for the period 1900–2005 and future projections (2006–99) under the “moderate” emissions scenario RCP4.5 (Zhao and Dai 2015; available at <http://aspen.atmos.albany.edu/adai/>

[pdsi/cmip5/scPDSIpm/](http://aspen.atmos.albany.edu/adai/pdsi/cmip5/scPDSIpm/)) was used to analyze the model-simulated moisture variability over the SETP. This scPDSI dataset was calculated from the monthly precipitation, temperature, net radiation, wind, and vapor pressure from the output of the 14 CMIP5 models, using the Penman–Monteith formulation for potential evapotranspiration (Dai 2011, 2013). We calculated the regional mean May–June scPDSI index for the SETP using this model scPDSI dataset over the period 1900–2099. For separation and comparison with the reconstructed scPDSI, the model-simulated scPDSI was centered and scaled to have the same mean and standard deviation as the reconstruction data over the period 1900–99 (Smerdon et al. 2015).

Quantile–quantile plots and the residual quantile–quantile plots (Marzban et al. 2011; PAGES 2k PMIP3 group 2015) were used to evaluate the climatological consistency in the reconstructions and the simulations (Fig. S3). These plots show the biases between the simulated and the target (reconstructed) quantiles, suggesting the poor skill of the model simulations to reproduce the year-to-year variability of the scPDSI. Thus, we only compare the probability distributions of the 50-yr mean scPDSI in reconstructions and simulations as in Cook et al. (2015).

3. Results and discussion

a. The new MJ scPDSI reconstruction

We produced an 876-yr reconstruction of early summer [May–June (MJ)] moisture variability covering the period 1135–2010 based on a network of 14 TRW chronologies (Figs. 2 and 3 and Table 1). The 14 chronologies produced 19 nested reconstructions, created by sequentially running the PCR approach on decreasing subsets of tree-ring chronologies with progressively earlier start years (backward from 2001 to 1135; 12 nests), and later end years (forward from 2002 to 2010; 7 nests). The reduction of error (RE) and coefficient of efficiency (CE) for all nests are positive (Fig. 3b), indicating the predictive skill of the PCR model in each nest (Cook et al. 1999). In particular, the RE and CE values remained positive before 1300 when the number of available tree-ring site chronologies drops below two. For the full instrumental period (1950–2001), the nested reconstructions could explain 30% (1135–1299) to 65% (1548–1610) of the MJ scPDSI variance among the 19 nests (Fig. 3b). The explained variance ranged from 32% (1300–1439 nest) to 64% (1611–54) in the calibration period only, and ranged from 31% (1135–1299) to 63% (2010) in the verification period only. Despite the decreasing number of predictor chronologies back in

FIG. 3. (a) The MJ scPDSI reconstruction covering 1135–2010, presented at annual resolution [black line; $\pm$ RMSE; gray shading] and after applying a 30-yr low-pass filter (red). (b) RE, CE, RMSE, and R^2 statistics for each nest. (c) The number of contributing site tree-ring chronologies and principal components (PCs) used in each nest.

time (e.g., only two chronologies available for the most backward nest 1135–1439) and forward in time (e.g., only three chronologies available for the most forward nest in 2010), the reconstruction still demonstrates predictive skill (i.e., positive RE and CE values).

The positive RE and CE values and generally high R^2 for calibration and verification across nests with different numbers of available site chronologies, implies that the reconstruction is stable and that results are independent of site-specific chronologies. This inference is supported by positive beta weights (β values in Table 1) of all site chronologies in the most replicated nest 1702–2001. The reconstruction shows higher prediction skill over the period 1451–1610 when 7 to 11 tree-ring records are used in the reconstruction (Fig. 3b). The comparison between reconstructions with or without using the nesting method indicates no substantial differences throughout most of the reconstruction period for inter-annual variability (Fig. S4a), but slight differences during several intervals of the reconstruction for multidecadal variability (Fig. S4b). This suggests that our reconstruction may be more reliable, and subject to small uncertainty, at higher frequencies than at lower frequencies. Nevertheless, the robustness of the reconstruction is finally corroborated by the very small uncertainty ranges across 100 alternative reconstructions calculated

after randomly removing two or four site chronologies (Fig. 4).

For calibration interval reconstruction, the spatial correlation map shows a close relationship between the reconstructed and instrumental MJ scPDSI data over most areas of the SETP, with correlations exceeding 0.50 ($p < 0.05$) across most of the area of interest (Figs. 2c,d). For validation interval reconstruction, the grid points with significant correlation are spatially reduced, and only located at central and western areas of the SETP (Fig. 2e); this is especially the case for the first-differenced data (Fig. 2f). The reduced number of grid points with significant correlation for validation interval might be due to the largely reduced degrees of freedom in this case. In addition, for the validation interval only, the reconstruction also show significant ($p < 0.05$) positive correlations with current-season precipitation, and with annual (January–December) scPDSI, over the western areas of the SETP (Fig. S2). Nevertheless, the significant correlations between the reconstruction and instrumental data found over the validation interval only provide independent evidence that our scPDSI reconstruction is a robust representation of regional moisture changes.

Based on our new scPDSI reconstruction, we investigate the temporal distribution of drought and pluvial

FIG. 4. Comparison of the final reconstruction with uncertainty (10–90th percentiles) ranges of the 100 alternative reconstructions based on a truncated proxy network with random removal of 2 or 4 site chronologies in each reconstruction. The correlations as the 10th, 50th, and 90th percentiles of the 100 reconstructions are also shown.

episodes with durations of three or more years. Here, duration is defined as the number of consecutive years with values larger/smaller than the median of long-term (1135–2010) scPDSI values. Magnitude refers to the sum of all the reconstructed scPDSI values for a given duration, and intensity is the ratio between magnitude and duration (Pederson et al. 2012, 2013). As shown in Fig. 5, the SETP experienced the longest pluvial event during the period 1154–75, with 21 consecutive years of positive scPDSI anomalies, and the longest drought events

during the periods 1262–80 and 1958–76, with 19 consecutive years of negative scPDSI anomalies, respectively. Despite their longest durations, the two “mega-droughts” had relatively small intensities (mean values of -0.45 and -0.61 , respectively), for example having smaller amplitudes than the 5-yr drought of 1331–35 (mean intensity = -1.33). The thirteenth century, with eight multiyear droughts (including one of the longest droughts, in 1262–80), had the highest frequency of droughts; the twentieth century, with five multiyear

FIG. 5. Temporal distribution of (a) magnitude and (b) intensity of pluvial and drought events with durations of 3 or more years. Magnitude indicates the cumulative scPDSI anomalies in each drought or pluvial event while the intensity is the average scPDSI anomaly in each event.

FIG. 6. (a) Comparison of the reconstructed MJ scPDSI in this study with reconstructions of summer temperature by Wang et al. (2015) and annual temperature by Wang et al. (2014). (b) The 100-yr running correlations between these reconstructions, with significant correlations at the 95% confidence level falling outside of the gray shading.

drought events (including the other longest drought in 1958–76) was the second driest century. Moreover, our reconstruction also captured several well-known large-scale droughts documented in the tree-ring-based Monsoon Asia Drought Atlas (Cook et al. 2010); for example, the drought periods 1639–41 (mean intensity of -0.84), 1759–62 (mean intensity of -1.32), and 1872–77 (mean intensity of -0.34), reflecting the late Ming Dynasty Drought (Zheng et al. 2014), the Strange Parallels Drought (Lieberman 2003; Buckley et al. 2010), and the late Victorian Great Drought (Davis 2002; Singh et al. 2018), respectively. In addition, our reconstruction indicates that recent moisture variability observed in instrumental data (Yang et al. 2011; Gao et al. 2014; Guo and Wang 2014; W. Zhang et al. 2017) is not exceptional in the context of the past nine centuries (Figs. 3 and 5), consistent with previous findings based on site TRW records for this region (Fan et al. 2008; Fang et al. 2009; Zhang et al. 2015; Li et al. 2017). However, this statement should be interpreted with caution as tree-ring-based reconstructions always have considerable uncertainties in capturing long-term (e.g., multicentennial scale) climate variability when traditional detrending methods are used (Cook et al. 1995).

b. The relationship between moisture and temperature

We compared our new moisture reconstruction for the SETP with the summer temperature reconstruction

for the ETP (Wang et al. 2015) and annual temperature reconstruction for the SETP (Wang et al. 2014). The moisture reconstruction shows good agreement with both temperature records over the last nine centuries (Fig. 6). The correlations between temperature and scPDSI generally exceed 0.30 and are significant at the 95% level over the past nine centuries, despite interruptions by periods with insignificant correlations in the mid-thirteenth and mid-fourteenth centuries. We complement our simple comparisons with cross-wavelet coherence analysis and EEMD analysis to evaluate the temperature–moisture relationship at different time scales. The cross-wavelet coherence analysis reveals that the scPDSI and temperature reconstructions share significant ($p < 0.05$) in-phase variance from interannual to multidecadal time scales throughout most of the last 900 years, and at centennial time scales over a few parts of the 900 years (Fig. 7). The results from the cross-wavelet analysis are further corroborated by the results from the EEMD analysis (Fig. 8). For the summer temperature reconstruction, correlations with moisture are significant ($p < 0.05$) at all frequencies from interannual to centennial time scales and are especially strong at multidecadal time scales ($r = 0.42$, $p < 0.05$). Similarly, the correlations between moisture and annual temperature reconstruction are all significant at the 0.05 significance level except for centennial time scales, and are especially strong at interannual time scales ($r = 0.51$, $p < 0.05$). These results generally suggest in-phase and positive correlations between moisture and temperature

FIG. 7. Wavelet coherence (WTC) (a) between the MJ scPDSI reconstruction in this study and the summer temperature reconstruction by Wang et al. (2015) and (b) between the MJ scPDSI reconstruction in this study and the annual temperature reconstruction by Wang et al. (2014). The 95% confidence level (against red noise) is shown as the thick black contour. Arrows pointing to the right (left) represent in-phase (out-of-phase) relationships.

at both high and low frequencies during the period 1135–2010. However, we are more confident about the in-phase relationship between temperature and moisture at higher (e.g., interannual and decadal) time scales because the reconstruction might be subject to smaller uncertainty at these frequencies (e.g., Fig. S4).

The positive association between temperature and moisture observed here is consistent with reanalyses of the High Asia Refined Reanalysis dataset (Curio et al. 2015; Curio and Scherer 2016). In these analyses, it was found that local supply provides more moisture to the TP than input from external moisture sources (e.g., Indian summer monsoon circulation). This is related to the different precipitation patterns between the TP and India. The decrease in precipitation across India over recent three decades has been frequently reported (Choudhury et al. 2019; Annamalai et al. 2013) and contrasts with the wetting trend on the SETP (W. Zhang et al. 2017). The in-phase relationship between temperature and moisture could be explained by the following mechanisms. First, higher temperatures are expected to increase the water holding capacity of air according to the Clausius–Clapeyron relation, and hence increase precipitation (Allen and Ingram 2002). Second, higher temperatures increase the evaporation from large lakes, soil moisture, the active layer of permafrost, snowmelt, and glacier run-off, and then enhance local moisture recycling, thereby favoring the formation of convective precipitation over the SETP

(Curio et al. 2015; An et al. 2017; Li et al. 2017). The latter mechanism, as a classical hypothesis, has been frequently used to illustrate an enhanced hydrological cycle under a warmer climate over the TP (Yao et al. 2019).

The positive correlations between temperature and scPDSI observed here also support the previous findings in tree-ring-based reconstructions in this region (Li et al. 2017; Shi et al. 2018). The in-phase relationship observed here is also consistent with model simulations in which warmer and wetter conditions during the Medieval

FIG. 8. Correlations of the MJ scPDSI reconstruction in this study with the two temperature reconstructions (Wang et al. 2014, 2015) from interannual to centennial time scales. Time scale-dependent frequencies are isolated by the ensemble empirical mode decomposition method. The degrees of freedom were adjusted following Wang et al. (2017), and significant correlations at the 95% confidence level are marked with an asterisk.

Climate Anomaly (MCA) and contrasted with cooler and drier conditions during the Little Ice Age (LIA) over the typical areas of East Asian and Indian summer monsoon circulations (Man et al. 2012; Tejavath et al. 2019). The in-phase variance between temperature and moisture during the MCA and LIA in model simulations are caused by land–sea thermal contrast changes caused by the effective radiative (i.e., solar and volcanic) forcing (Man et al. 2012). The “warmer land–colder ocean” pattern during the MCA leads to a stronger summer monsoon circulation, whereas the “colder land–warmer ocean” pattern during the LIA favors a weaker monsoon circulation. This kind of mechanism proposed in climate model studies might also contribute to the in-phase relationship between temperature and moisture found over the SETP. This is related to the fact that, although small, a non-negligible part of atmospheric moisture needed for precipitation over the TP is provided by Asian summer monsoon circulations (Curio et al. 2015; Curio and Scherer 2016). This kind of explanation about the contribution of Asian summer monsoon might be especially the case at long-term time scales. Nevertheless, the in-phase relationship between temperature and moisture suggests that moisture variability over the SETP has been more sensitive to changes in moisture supply (precipitation) rather than evaporative demand (potential evapotranspiration) during the period 1135–2010.

Despite the clear relationships identified above, tree-ring records have limitations and uncertainties when capturing the coupling effect between changes in temperature and moisture (Seftigen et al. 2017; Ljungqvist et al. 2019b). For example, tree growth on the TP might be influenced by both moisture and temperature (Fang et al. 2015a), which complicates the interpretation of temperature–moisture relationships. To address this issue, we conducted an alternative reconstruction using a reduced proxy network by excluding four tree-ring records (Langxian, Baizha, Gongjue, and Basu in Table 1) having significant ($p < 0.05$) correlations with monthly temperatures over the instrumental period. We found that the correlations between temperature and moisture are still significant over most periods of the last 900 years (Fig. S5). Nevertheless, we cannot fully address this issue as the tree-ring-based temperature records (Wang et al. 2014, 2015) used in our analyses are also significantly influenced by soil moisture variability of the pregrowing and growing seasons. In addition, the reconstruction targets that are used to calibrate the moisture and temperature reconstructions are related to each other, which further complicate to make an independent comparison between moisture and temperature reconstructions. Future work could develop and expand the network of other high-resolution proxy records (e.g.,

ice core records and historical documentary data) to permit a robust cross-proxy validation of the results presented here (e.g., Schneider et al. 2019).

c. The twenty-first-century moisture variability and its implications

We analyze model-simulated scPDSI data for the period 1900–2099 (Dai 2011, 2013; Zhao and Dai 2015) to assess projections of future moisture changes over the SETP. We found that correlation between temperature and moisture conditions in the model simulations is rather weaker than the correlation we found in the reconstructions (Fig. S6a). This phenomenon is also seen in the analyses of first-order difference data instead of the original data (Fig. S6b), suggesting it should not be caused by the greater autocorrelation in tree-ring data than model data (Franke et al. 2013). Moreover, higher correlations in reconstructions than model simulations might be partly related to the aforementioned non-independent comparison between the moisture and temperature reconstructions, including multiple climate signals (both temperature and moisture) recorded in tree-ring width data, and nonindependent climate data used in calibration targets for temperature and moisture. In addition, the lower correlations between temperature and moisture in model simulations may be largely due to the biases of state-of-the-art climate models reproducing the year-to-year moisture variations over the SETP (Fig. S3). This is in line with other studies that suggest considerable uncertainties about future moisture projections in climate models (Stephens et al. 2010; Christensen et al. 2013; Orlowsky and Seneviratne 2013; Nasrollahi et al. 2015). Our reconstruction–model simulation comparison might have implications for future projection of moisture over the TP. Our results suggest an underestimation of the positive relationship between temperature and moisture over the SETP in general circulation models. This is due to the fact that moisture changes over the TP are largely controlled by local moisture recycling, a process that is incapable of being well described in general circulation models. To reduce uncertainty of moisture projection, regional climate models that are capable describing the influences of mesoscale and microscale topography, and processes of land–atmosphere interactions will be helpful (Gao et al. 2015; Wang et al. 2016).

Focusing on the 50-yr mean moisture conditions, the probability distributions suggest generally wetter conditions during the twenty-first century under future global warming (Fig. 9). This comparison indicates that early-summer months of the late twenty-first century will be slightly wetter over the SETP than those of the late twentieth century and those of the 1135–1950 mean

FIG. 9. (a) Reconstructed and climate model-simulated scPDSI for the SETP. Gray shading around the climate model ensemble mean shows the 25th- and 75th-percentile ranges from the 14 model ensemble members. (b) Kernel density functions for distributions of scPDSI across the SETP, calculated from the reconstructed scPDSI over the period 1135–1950 and from the simulated scPDSI over the periods 1950–99 and 2050–99 (under the RCP4.5 scenario).

conditions (Fig. 9). This is also the case for the annual (January–December) moisture variability (Fig. S7), consistent with the significant correlations between the MJ scPDSI and annual scPDSI over the SETP during recent decades (Fig. S2). The wetter conditions and continued in-phase temperature–moisture relationships (i.e., warm = wet) indicate that the increased precipitation (moisture supply) will be sufficient to offset the increased evaporative demand caused by warming in the coming decades (Cook et al. 2014; Dai 2013; Zhao and Dai 2015).

The wetter conditions over the SETP in the future will have important implications for water supplies and water management because of the important role of the TP in Asian water resources (Xu et al. 2008; Immerzeel et al. 2010). Global warming has caused, and will continue to cause, significant changes of water resources over the TP by contributing to glacial retreat, snowmelt, and permafrost degradation (Yao et al. 2019). The wetter conditions, together with increased meltwater runoff in the coming decades, will have substantial influences on water resources by expanding lake volumes and increasing river flow (G. Zhang et al. 2017; Huss and Hock 2018). This may contribute to a larger supply of water from the TP to downstream areas, suggesting enhanced water availability over most of Asia (Gao et al. 2019). The increased water availability will be especially beneficial for ecosystems and agriculture over the TP and wider regions of Asia, as our prediction of increased moisture is largely focused on early summer (May–June), coincident with the onset of the growing season: at this time, climate changes may have an important influence on the vegetation phenology (Shen et al. 2014; Yang et al. 2017; He et al. 2018b,c). In

addition, warmer and wetter conditions lead to increase in vegetation cover (Jiang et al. 2015), which will further increase moisture over the SETP through positive feedbacks among climate, vegetation cover, and biogenic volatile organic compounds (Fang et al. 2015b). On the other hand, the increased water availability will increase the risk of water-related hazards such as landslides, debris flows, and lake outbursts in the coming decades (Yao et al. 2019). Policymakers need to develop more relevant policies and regulations for reducing the potential water-related risks in the coming decades.

4. Conclusions

The May–June scPDSI reconstruction presented in this study contributes to our understanding of the long-term moisture variability across the SETP, where accurate predictions of moisture changes are crucial for managing water resources, ecosystems, and agriculture in downstream regions. Our scPDSI reconstruction is well calibrated and well validated, demonstrating excellent predictive skill in all nest segments covering the period 1135–2010. This new reconstruction indicates that recent moisture variability observed during the instrumental period falls within the range of natural variability over the past nine centuries. The thirteenth century experienced the highest frequency of drought, including eight multiyear droughts. The scPDSI reconstruction is positively correlated with temperature reconstructions from interannual to multidecadal time scales over the past nine centuries. The in-phase temperature–moisture covariability found here provides a long-term perspective in which global warming enhances water recycling and thus increases precipitation over the

TP. Assessments of projected future scPDSI changes suggests generally wetter conditions over the SETP in response to global warming during the next decades. Projected wetter conditions will be beneficial for water resources, ecosystems, and agriculture over the TP and its countries downstream, but also imply a higher risk of potential water-related geohazards in these regions.

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