Dear editor and two referees,

Thank you very much for your careful review and constructive suggestions regarding our manuscript "Early summer hydroclimatic signals were well captured by tree-ring earlywood width in the eastern Qinling Mountains, central China".

In the new revision, some tables and figures in the manuscript (Table 2 and 4, and Fig. 6–10) and supplementary (Table S1–S3, and Fig. S2–S4) have been modified due to the correction of running EPS and the subsequent change in tree-ring chronology length. However, these corrections did not affect our original conclusion.

Please see our point-by-point responses as below.

With best regards,

Yesi Zhao (on behalf of all co-authors)

**Response to the First Referee's Comments**

**1. Referee's comment:** I want to thank the editors the possibility to review again the article from Dr Yesi Zhao and colleagues and provide below comments and suggestions to improve the work presented. The actual version of the manuscript is much improved and therefore I can recommend it for publication after correcting some minor problems indicated below.

    **Author's Response:** We sincerely appreciate your comments on our revised manuscript. Please refer to the responses below. We hope you would be satisfied with our responses and revisions.

Just a few comments:

**2. Referee's comment:** I think that the signal obtained in EWW is rather alike to a signal of LWW. The measuring of EWW and LWW in Tsap involves some transformation of the data into individual time series. Can it be possible that the authors mixed up the conversion of the collected data?

    **Author's Response:** Thank you very much for this consideration. We rechecked the data and found sure that there was no mix of EWW and LWW.

    The similar signal shared by EWW and LWW may be due to their similar growth patterns. Here, we took the tree-ring width series detrended using negative exponential function together with linear regression with negative (or zero) slope (NELR) method as an example. As illustrated in Fig. 1, most of tree-ring samples showed significant correlations between their EWW and LWW. Therefore, the final EWW and LWW chronologies may contain similar signals even though EWW was more sensitive to early summer hydroclimate factors than LWW.
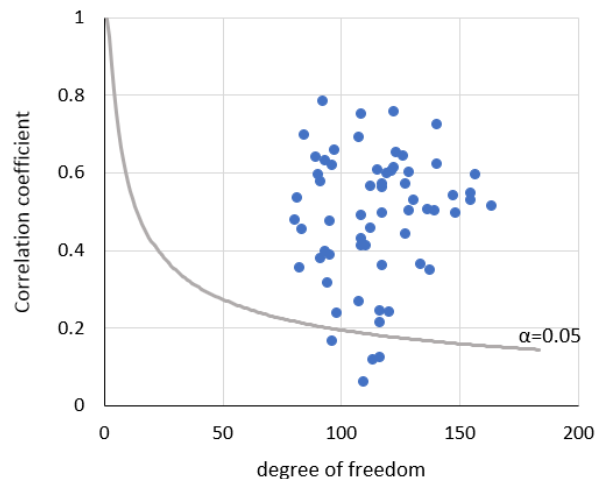


Figure 1. The Pearson's correlation coefficient between the EWW and LWW for each individual tree-ring sample (vertical axis) plotted against the corresponding degree of freedom (horizontal axis). The gray line denotes the correlation coefficients that are statistically significant at the 0.05 level based on two-tailed $t$-test. All EWW and LWW time series have been detrended using the NELR method.

**3. Referee's comment:** In addition, positive correlation with PDSI indicates that dry

conditions are favorable for tree growth. PDSI positive index indicates dry conditions while negative indicates wet conditions. I understand that the index uses both temperature and precipitation data and can be the signal of temperature that dominates the correlation with positive PDSI as it can be seen in figures 3 and 4. Either case, it is important the coverability between predictor and predictand, thus using tree-ring time series as predictor of PDSI, but if the signal is dominated by temperature rather than moisture, this can be the reason of the instability of the relationship of the time series indicated in the figure 8.

**Author's Response:** Thank you for these questions. In fact, the positive PDSI indicates a wet environment while the negative represents a dry condition (Palmer, 1965). Therefore, the positive correlation between PDSI (or scPDSI) and tree-ring width indicated that wet conditions favored tree growth.

Temperature might influence the instability of the relationship between scPDSI and EASMI showed in Fig. 8. However, comparison between scPDSI and temperature did not show enhanced correlation between scPDSI and temperature after the 1940s. Therefore, the cause for the weakened relationship is complicated and cannot be solely attributed to the impacts of temperature and precipitation. The specific cause is difficult to get because other factors such as available energy, humidity and wind speed can influence the scPDSI, too. We presented this discussion in the new revision, please refer to Line 27-32 Page 11 and Line 1-2 Page 12.

**4. Referee's comment:** Line 2 page 2, reconstructions cannot fall. Please reword.

**Author's Response:** We modified the "have fallen" into "have been conducted". Please refer to Line 2 Page 2.

**5. Referee's comment:** Line 7 page 2, I think in this case precipitation "are". Please check if I am correct.

**Author's Response:** According to the Collins English Dictionary (https://www.collinsdictionary.com/dictionary/english), the "precipitation" is an uncountable noun. The use of "is" can be found in Kidd and Levizzani (2001) as they expressed "……since precipitation is spatially and temporally highly variable ……".

**6. Referee's comment:** Line 11 page 2, please change unable for unsuitable.

**Author's Response:** Thank you for this suggestion. It has been modified. Please refer to Line 11 Page 2.

**7. Referee's comment:** Line 14 page 2, caused restrictions of water availability through the growing season

**Author's Response:** Thank you for this suggestion. It has been modified following your suggestion. Please refer to Line 14 Page 2.

**8. Referee's comment:** Line 18 page 2, are the abbreviations BYS and LCM needed? Since it is only one word for each name, I think is more reader friendly the original names, and using the locality names adds charm to the research presented.

**Author's Response:** Thank you for this suggestion. All abbreviations BYS and LCM in the manuscript have been modified into their full names.

**9. Referee's comment:** Line 20 page 2, please consider to mention SPEI index since it was added into the analysis and first mentioned in line 33.

**Author's Response:** Thank you for your suggestion. We have added the description about SPEI index in the introduction. Please refer to Line 26-29 Page 2.

**10. Referee's comment:** Line 22 page 2, please consider to give a very short background of the EASMI, what does it mean in terms of hydroclimate or temperature in the study area.

**Author's Response:** Thank you for your suggestion. We have added the contents about the background of EASMI and its impacts on the core region of EASM in the introduction. Besides, we removed the reasons that we selected this EASMI in the method section to avoid repetition. Please refer to Line 30 Page 2 to Line 3 Page 3.

**11. Referee's comment:** Materials and methods, Line 3 page 3. Please consider changing "study were provided by Shi et al. (2012)." By previously presented in Shi et al., 2012

**Author's Response:** Many thanks. We have modified this sentence following your suggestion. Please refer to Line 12 Page 3.

**12. Referee's comment:** Line 13 page 3: and did not complete around mid-Septermber. Please reword.

**Author's Response:** Thank you very much for pointing out this mistake. We have deleted the "r" from the mis-spelled "Septermber". Please refer to Line 23 Page 3.

**13. Referee's comment:** Line 13 page 3 "that the cambial cells of… started and ceased in… Please be so kind to indicate what started, cell division, cell growth, activity, etc.

**Author's Response:** Thank you for pointing out this unclear demonstration. It is the "activity" that cambial cell started. Please refer to Line 25 Page 3.

**14. Referee's comment:** Line 20 page 3, Due to the characteristics of the ring anatomy, Earlywood and latewood…

**Author's Response:** Many thanks. We have modified this sentence following your suggestion. Please refer to Line 29-30 Page 3.

**15. Referee's comment:** Line 10 page 4, please use "by means of" instead of "via" otherwise "through consecutive iterations"

**Author's Response:** Thank you for your suggestion. We used "by means of" instead of "via". Please refer to Line 20 Page 4.

**16. Referee's comment:** Line 12, see Osborn and colleagues, (1997).

**Author's Response:** We accept your suggestion. This error has been corrected in the

revised manuscript. Please refer to Line 22 Page 4.

**17. Referee's comment:** Line 13, EPS computed on multiple samples per tree will be inflated creating a wrong result (inflated value) please indicate if the index was calculated on single trees or multiple samples per tree.

**Author's Response:** Thank you very much for the suggestion. In the original manuscript, we used the RCSsignalFree software to calculate the running Rbar and EPS based on the core numbers automatically. This did cause inflated EPS values due to the unequal number of cores per tree. In the new revision, we used the effective chronology signal (Rbar$_{eff}$) and the number of trees to calculate the running EPS with the function "rwi.stats.running" in R package "dplR" version 1.6.9 (Bunn et al., 2018). Please refer to Line 25-33 Page 4.

**18. Referee's comment:** Line 27 page 4. Please consider that the application of the principal component analysis is to reduce the amounts of variables of an analysis, rather than assess similarity between variables. Cluster analysis can be used to assess degrees of similarity between datasets.

**Author's Response:** Thank you for your suggestion. In fact, we wanted to use the variance explained by the first eigenvector to estimate degree of similarity among detrended ring-width series just as used in Trouet et al. (2006). We reworded the "principal component" as "the variance explained by the first eigenvector", please refer to Line 6-7 Page 5.

**19. Referee's comment:** Line 2 page 5: SPEI and PDSI, please see the comment above on presenting both indices in the introduction.

**Author's Response:** Thank you for your suggestion. Please refer to the response for **comment 9**.

**20. Referee's comment:** Line 5 page 5, please reword sentence "…and calculate the duration factors…" I do not understand what the authors mean.

**Author's Response:** Thank you very much for your suggestion. We reworded the sentence as "Here we used the scPDSI instead of PDSI because it has solved the PDSI problems in spatial comparisons by calculating the duration factors (**weighting coefficients for the current moisture anomaly and the previous drought severity**) based on the characteristics of the climate at a given location (Wells et al., 2004)**"**. Please refer to Line 19 Page 5.

**21. Referee's comment:** Line 13 page 5, please be so kind to reword: three times the word "reconstruction" in one sentence makes it difficult to follow.

**Author's Response:** Thank you very much for this suggestion. We changed the second "reconstruction" to "it", and the third to "time series". Please refer to Line 28 Page 5.

**22. Referee's comment:** Line 26 page 5, please remove "this" before EASMI and "is"

after it.

 **Author's Response:** Thank you for your suggestion. We moved the reason for choosing EASMI to the introduction, and this sentence was not presented in the new revision. Please refer to Line 30 Page 2 to Line 3 Page 3.

**23. Referee's comment:** Line 29 page 5. Please change "restored" for "adjusted"

 **Author's Response:** Many thanks. We have changed the word as your suggestion. Please refer to Line 4 Page 7.

**24. Referee's comment:** Line 10 page 7. Please change "manifest" for "assess"

 **Author's Response:** Thank you very much for this suggestion. The word has been modified. Please refer to Line 24 Page 7.

**25. Referee's comment:** Line 13 page 7, please provide proper citation and names for software Matlab RM and Surfer 10.

 **Author's Response:** Thank you for your suggestion. We have added the version of Matlab, and cited the corresponding publisher for the two software. Please refer to Line 27-28 Page 7.

**26. Referee's comment:** Line 24 page 7. The positive correlation with PDSI indicates dry conditions as favorable for tree growth. Do I get that right? This means that conditions in the study area are rather too wet, and a moderate drought will be good the tree growth. Is this reasonable for an area of thin soils and well drained?

 **Author's Response:** Please refer to the response for **comment 3**.

**27. Referee's comment:** Line 15 page 8, it says "from September of two years earlier to May of last May". Please reword.

 **Author's Response:** Thank you for pointing out this mistake. We have corrected the "May of last May" into "May of the previous year". Please refer to Line 30-31 Page 8.

**28. Referee's comment:** Line 5-6 page 9, please reword "Increased water deficiency due to the rising temperature and inadequate rainfall in the 5 early growing season could induce soil water deficiency thus suppressing cell expansion and cell growth in the cambium"

 **Author's Response:** As in the response for **comment 3**, the positive relationship between EWW and scPDSI did indicate a water restriction on tree growth. Therefore, we think the reason we presented here is reasonable. To be consistent with the demonstration in Fritts (1976), we reword the "soil water deficiency" as "water stress", and the "cell expansion and cell growth in the cambium" as "cell division and expansion". Please refer to Line 21-22, Page 9.

**29. Referee's comment:** Line 22, page 9. Restored or adjusted?

 **Author's Response:** Thank you for this suggestion. We used "adjusted" instead of "restored". Please refer to Line 4 Page 10.

**30. Referee's comment:** Line 23 page 9, please add "the" before reconstruction.

   **Author's Response:** Thank you for this suggestion. We have added "the" before "reconstruction". Please refer to Line 5 Page 10.

**31. Referee's comment:** Line 6 page 10. Please change "The possible reasons might be that (1) the seasons that the three reconstructions aimed at are different from ours…" for "The possible reasons might be that (1) the reconstructions aim to different target season"

   **Author's Response:** Thank you for this suggestion. We have modified this sentence following your suggestion. Please refer to Line 20 Page 10.

**32. Referee's comment:** Line 33 page 10: How stable in time is the spatial pattern of the EASM?

   **Author's Response:** Thank you for raising this question. Just as demonstrated in Wang et al., (2008), the EASM is a non-stationary system and could change on interdecadal timescale and may even much longer timescales. Please refer to the revision in Line 13-15 Page 11.

**33. Referee's comment:** Line 25 page 11, please reword and eliminate "etc,"

   **Author's Response:** Thank you for this suggestion. It was done. Please refer to Line 14 Page 12

**Figures:**
**34. Referee's comment:** Figure 1, Southern Asia summer monsoon is not mentioned in the text

   **Author's Response:** Thank you for pointing out this issue. Since the climate of the study area is governed by the East Asian summer monsoon (EASM) as indicated by the boundary of EASM (Please refer to Fig. 1), we focused on the relationship of our reconstruction with EASM in this study. Of course, just as your valuable consideration, the Southern Asian summer monsoon (SASM) may impact our study area (Zhang, 2001). We would analysis the relationship of our reconstruction with SASM, and other large-scale circulation patterns including PDO, AMO, etc in the future.

**35. Referee's comment:** Figure 2 figure text: please add "s" to denote.

   **Author's Response:** Thank you very much for pointing out this mistake. It has been modified.

**36. Referee's comment:** Figure 6 add "d" to shade. Areas

   **Author's Response:** Thank you very much for pointing out this mistake. It has been modified.

**37. Referee's comment:** Figure 9, figure text, citation Macias-Faura et al.","2012) please check for the right format.

**Author's Response:** Thank you for reminding. The comma is needed as required by the Journal.

**38. Referee's comment:** Figure 10, text in the figure: Huaihe River and Yangtze River in the lower left plate is difficult to read.

**Author's Response:** Thank you very much for this suggestion. We have added a white border for each character to make them more recognizable.

**39. Referee's comment:** References Please see the order of the references, and how it should be presented, chronologically or alphabetically see several papers with same first author at different years. Is it authors surname and first name and later co-authors? please check.

**Author's Response:** Many thanks. In this revision, we have checked the order of reference carefully. The found mistakes have been corrected.

**40. Referee's comment:** Reference Din and Dai 1994 is not in the text.

**Author's Response:** There is no "Din and Dai 1994" in the reference list.

**41. Referee's comment:** Good job!

**Author's Response:** Thanks again for your positive comments on our work.

**Reference**

Bunn, A., Korpela, M., Biondi, F., Campelo, F., Mérian, P., Qeadan, F., Zang, C., Buras, A., Cecile, J., Mudelsee, M., Schulz, M., Pucha-Cofrep, D., and Wernicke, J.: Dendrochronology program library in R, R package "dplR" version 1.6.9, CRAN, https://cran.r-project.org/web/packages/dplR/index.html, 2018.

Fritts, H. C.: Tree rings and climate, Academic Press, New York, 567 pp., 1976.

Kidd, C., and Levizzani, V.: Status of satellite precipitation retrievals, Hydrol. Earth Syst. Sci., 15, 1109-1116, https://doi.org/10.5194/hess-15-1109-2011, 2011.

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Trouet, V., Coppin, P., and Beeckman, H.: Annual growth ring patterns in *Brachystegia spiciformis* reveal influence of precipitation on tree growth, 38, 375–382, https://doi.org/10.1111/j.1744-7429.2006.00155.x, 2006.

Wang, B., Wu, Z., Li, J., Liu, J., Chang, C.-P., Ding, Y., and Wu, G.: How to measure the strength of the East Asian Summer Monsoon, J. Climate, 21, 4449–4463, https://doi.org/10.1175/2008jcli2183.1, 2008.

Zhang, R.: Relations of water vapor transport from Indian Monsoon with that over East Asia and the summer rainfall in China, Advances in Atmospheric Sciences, 18, 1005–1007, 2001.

## Response to the Second Referee's Comments

**1. Referee's comment:** In the new version, the authors have made great changes to the paper and the quality has been greatly improved. I'm satisfied with their answers. It's acceptable after modifying the following minor issues:

**Author's Response:** Thank you very much for reviewing our work again. We are glad that you are satisfied with our responses. The problems you pointed out in the revision are valuable, and we have modified carefully as below.

**2. Referee's comment:** I suggest to delete the brackets in the title. That is "Early summer hydroclimatic signals were well captured by tree-ring earlywood width in the eastern Qinling Mountains, central China".

**Author's Response:** Thank you very much for your suggestion. The brackets have been removed.

**3. Referee's comment:** I think you made several wrong corrections in revision process, such as "Based on this relationship, the MJJ scPDSI was reconstructed using a linear regression function with strong statistical parameters over the period 1864–2005", are you sure it is 1864–2005, not 1953–2005? Should "1957-2005" in line 33 of page 4 be "1953-2005"? Please check other similar time period.

**Author's Response:** Thank you very much for pointing out these time intervals that we have not clearly clarified.

The period "1864-2005" indicated the length of our scPDSI reconstruction. Due to the recalculated EPS, the reliable period of the reconstruction has been corrected to "1868-2005". Please refer to Line 22 Page 1 and Line 4 Page 10.

The period "1957-2005" indicated the common period of the four meteorological stations used in this study.

The interval "1953-2005" indicated the instrumental scPDSI used for calibration. The scPDSI was derived from CRU scPDSI 3.25 dataset which used the meteorological stations with a common period starting from the July 1952 (please refer to Table. S4). To get a more accurate estimation for the linear relationship between EWW and scPDSI, we selected the period 1953-2005 instead of 1957-2005 for calibration. Please refer to Line 23-27 Page 5.

We thoroughly checked the time intervals again in the revision. Thanks again for your consideration.

# Early summer hydroclimatic signals were well captured by tree-ring earlywood width in the eastern Qinling Mountains, central China

Yesi Zhao[1,2], Jiangfeng Shi[1,3], Shiyuan Shi[1], Xiaoqi Ma[1], Weijie Zhang[1], Bowen Wang[1], Xuguang Sun[4], Huayu Lu[1], Achim Bräuning[2]

5   [1] School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China
[2] Institute of Geography, Friedrich-Alexander-University Erlangen-Nürnberg, Erlangen 91058, Germany
[3] Laboratory of Tree-Ring Research, University of Arizona, Tucson 85721, USA
[4] School of Atmospheric Sciences, Nanjing University, Nanjing 210023, China

*Correspondence to*: Jiangfeng Shi (shijf@nju.edu.cn)

10   **Abstract.** Tree-ring width (TRW) chronologies could only provide limited amount of moisture-related climatic information in the humid and semi-humid regions of China; thus, it is worth to explore the potentials of the intra-annul tree-ring width indices (i.e., the earlywood width (EWW) and latewood width (LWW)) to provide some additional climatic information. To fulfil this task, TRW, EWW and LWW were measured from the tree-ring samples of *Pinus tabulaeformis* in a semi-humid region, that is, the eastern Qinling Mountains, central China. Their standard (STD) and signal-free (SSF) chronologies were created using different detrending methods including (1) negative exponential function together with linear regression with negative (or zero) slope (NELR), (2) cubic smoothed splines with a 50% frequency cutoff of 67% of the series length (SP67), and (3) age-dependent splines with an initial stiffness of 50 years (SPA50). The results showed that EWW chronologies were significantly negatively correlated with temperature, but positively correlated with precipitation and soil moisture conditions during the current early growing season. Comparatively, LWW and TRW chronologies had weaker relationships with these climatic factors. EWW STD chronology with the detrending method of NELR contained the strongest climatic signal, explaining 50% variance of the May–July self-calibrated Palmer Drought Severity Index (MJJ scPDSI) during the instrumental period 1953–2005. Based on this relationship, the MJJ scPDSI was reconstructed back to 1868 using a linear regression function with strong statistical parameters, and the reconstruction was further validated by comparing with other hydroclimatic reconstructions and historical document records in adjacent regions. This highlighted the potentials of intra-annual tree-ring indices for seasonal hydroclimatic reconstruction in humid and semi-humid regions of China. Furthermore, the reconstruction exhibited a strong in-phase relationship with a newly proposed East Asian summer monsoon index (EASMI) before the 1940s on the decadal and longer timescales, which may be due to the positive response of the local precipitation to EASMI. However, the cause for the weakened relationship after the 1940s is complicated, and cannot be solely attributed to the impacts of precipitation and temperature.

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# 1 Introduction

Most of the existing tree-ring width (TRW) based hydroclimatic reconstructions have been conducted in the regions between the 200-to 600-mm annual precipitation isolines in China (Liu et al., 2018b), close to the northern fringe of Asian Summer Monsoon. Comparatively, there are still a small amount of hydroclimatic reconstructions in the core monsoon region, for example, a few case studies in Southeast China (e.g. Cai et al., 2017; Chen et al., 2016a; Shi et al., 2015), North China (e.g. Chen et al., 2016b; Hughes et al., 1994; Lei et al., 2014; Liu et al., 2002), and the Hengduan mountains in Southwest China (Fan et al., 2008; Fang et al., 2010b; Gou et al., 2013; Li et al., 2016). Since precipitation is spatially variable (Ding et al., 2013), hydroclimatic variations in the monsoon fringe can not completely represent those in the core monsoon region (Liu et al., 2018b). Thus, more hydroclimatic reconstructions are needed in the monsoon region.

Some TRW chronologies within the monsoon region showed weak or unstable hydroclimatic signals (e.g. Li et al., 2016; Shi et al., 2012; Wang et al., 2018), unsuitable to be used for reliable reconstruction. Intra-annually resolved tree-ring width (i.e., earlywood width (EWW) and latewood width (LWW)), however, provided stronger hydroclimatic signals than TRW in some cases (Chen et al., 2012; Zhao et al., 2017a). This might be related to the seasonal movement of monsoon rainbelt which causes restrictions of water availability through the growing season (Liu et al., 2018a). Using EWW and LWW, researchers have successfully conducted reconstructions for seasonal rainfall (Hansen et al., 2017), standardized precipitation evapotranspiration index (SPEI; Zhao et al., 2017b), and streamflow (Guan et al., 2018) within the monsoon region.

The eastern Qinling Mountains are located within the core region of East Asian summer monsoon (EASM), and are characterized by a transitional climate from warm-temperate to subtropical. In this region, Shi et al. (2012) has built four TRW chronologies of *Pinus tabulaeformis* along an elevation gradient from 1200 to 1950 m above sea level (a.s.l.). The TRW chronologies from the two low-altitude sites, Baiyunshan and Longchiman, exhibited a positive response to precipitation and negative response to temperature during early summer, showing some kind of water stress. However, the dendroclimatic potentials of EWW and LWW were not explored.

Meanwhile, tree-growth at an adjacent site was found to be more restricted by the drought index, PDSI (Palmer Drought Severity Index), than precipitation and temperature (Peng et al., 2014). The PDSI monitors the cumulative departure of surface water balance in terms of the difference between the amount of precipitation required to retain a normal water-balance level and the amount of actual precipitation (Palmer, 1965; Wells et al., 2004). In addition, the SPEI, which represents a water balance as the form of difference between precipitation and potential evapotranspiration (Vicente-Serrano et al., 2010), has also been found to strongly limit latewood growth at a well-drained site in the core region of EASM (Zhao et al., 2017a, b). Therefore, the PDSI and SPEI should also be incorporated into the climate-tree-growth relationship assessment.

Recently, a new East Asian summer monsoon index (EASMI) was proposed by Zhao et al. (2015) based on the 200 hPa zonal wind anomalies, which shows a better performance in describing precipitation and temperature variations over East Asia than previous indices. When a strong EASM occurred, the new EASMI indicates abundant precipitation and relatively low temperature over the core region of EASM, particularly around the area of mei-yu/changma/baiu rainband (27.5°–32.5° N,

105°–120° E and 30°–37.5° N, 127.5°–150° E; Fig. 1a), which is the center of the leading mode of EASM precipitation (Wang et al., 2008; Zhao et al., 2015). It is worth to study the response of local hydroclimate to EASM from a long-term perspective in combination with these tree-ring materials and the new EASMI.

Since the TRW of *P. tabulaeformis* in Baiyunshan and Longchiman were mainly restricted by the early summer moisture condition, we hypothesize that the early summer hydroclimatic signals might be strengthened only using EWW, with the exclusion of LWW from TRW. Therefore, the objectives of this study are (1) to verify that EWW is more sensitive to early summer hydroclimatic factors than TRW and LWW for *P. tabulaeformis* at Baiyunshan and Longchiman, (2) to reconstruct early summer hydroclimate variations using EWW, and (3) to tentatively explore the relationship between the reconstructed hydroclimate variability and EASMI of Zhao et al. (2015).

## 2 Materials and Methods

### 2.1 Study sites

Dated tree-ring samples of *P. tabulaeformis* used in this study were previously presented in Shi et al. (2012). They were collected from two sampling sites in Mount Funiu in 2006 and 2008 separately: Baiyunshan (33.63° N, 111.85° E) and Longchiman (33.68° N, 112.05° E; Fig. 1b). The sampling sites are located on mountain tops, where soils are thin and well-drained. The elevations of Baiyunshan and Longchiman range from 1200–1300 m a.s.l. and 1340–1400 m a.s.l., respectively. The regional annual mean temperature and annual total precipitation are 14.1 °C and 822 mm, respectively. The majority part of the annual total precipitation drops during the warm season (Fig. 2). More detailed information of the study sites can be found in Shi et al. (2012).

### 2.2 Tree-ring data

The selected *P. tabulaeformis* is a widely distributed conifer species in North China with the extension from 31° 00′ N to 43° 33′ N, and 103° 20′ E to 124° 45′ E (Xu et al., 1981). Liang et al. (2009) studied the cambial dynamics of *P. tabulaeformis* in its northern distribution limit (43° 14.11′ N, 116° 23.60′ E, 1363 m a.s.l.), and found that the cell division in the cambial zone started within the third week of May and did not complete aroud mid-September. Zeng et al. (2018) found that the cambial cells of mature *P. tabulaeformis* in Northwest China (37° 02′ N, 104° 28′ E, 2456 m a.s.l.) started activity in late spring and ceased in late July to early August. Considering that our sampling sites are located at lower latitudes, the cambial activites of *P. tabulaeformis* in our study may start earlier and ends later than those found in above studies according to the temperature-controlled phenology theory (Chen and Xu, 2012).

*P. tabulaeformis* generally exhibits an abrupt transition from light-colored earlywood to dark-colored latewood (Liang and Eckstein, 2006; Fig. S1), and the transition can occur in mid-July in Beijing (39.9° N, 116.3° E; Zhang et al., 1982). Due to the characteristics of the ring anatomy, the earlywood and latewood segments of annual growth rings can be discriminated visually by the sudden change in cell size, lumen size, and color (Stahle et al., 2009). However, gradual transitions also occur

in a few samples, making the earlywood-latewood boundary difficult to discern. Therefore, only samples with distinct earlywood and latewood segments were used for subsequent measurements (Knapp et al., 2016). In total, 20 cores from 11 trees and 42 cores from 22 trees were selected from Baiyunshan and Longchiman, respectively. EWW and LWW were then measured using a LINTAB5 system at a resolution of 0.001 mm, and TRW was obtained by adding EWW and LWW together.

5 **2.3 Development of tree-ring width chronologies**

Non-climatic growth trends need to be fitted and removed from each "raw" (untreated) EWW, LWW and TRW series, which is known as detrending (Cook et al., 1990). In order to check the effects of detrending methods on the preservation of climatic signals, three detrending methods were selected for comparison. They were negative exponential function together with linear regression with negative (or zero) slope (NELR), cubic smoothed splines with a 50 % frequency cutoff of 67 % of the series

10 length (SP67), and age-dependent splines with an initial stiffness of 50 years (SPA50). NELR is a deterministic method based on the assumption that tree radial growth declines monotonically (Cook et al., 1990). SP67 has a good ability in fitting the potential low-and middle-frequency perturbations contained in ring-width series (Cook et al., 1990). It allows no more than half of the amplitude of variations with wavelength of two-thirds of the length of series being preserved in resulting indices (Melvin et al., 2007). SPA50 specifies annually varying 50 % frequency cutoff parameter for each year by adding the initial

15 stiffness with ring age. In comparison with SP67, it makes the resulting spline become more flexible in the early years and progressively stiffer in later years (Melvin et al., 2007). All raw ring-width series were divided by the estimated growth trends, and the resulting detrended ring-width series were averaged to generate the standard (STD) chronologies using the bi-weight robust mean method (Fig. S2). Since the traditional fitted curves may contain the climatic signals, which is termed as "trend distortion" problem (Melvin and Briffa, 2008), the signal-free (SSF) method is introduced to create the fitted growth curve

20 free of climatic signals by dividing the raw ring-width series by the STD chronology by means of iterations (Melvin and Briffa, 2008). Therefore, the SSF chronologies were also developed for analysis (Fig. S3). The variance of each chronology was stabilized to minimize the effects of sampling depth according to the methods described in Osborn et al. (1997). The temporal extension for all width chronologies in Baiyunshan and Longchiman are 1841–2005 and 1850–2005, respectively. All above processes were performed with the program RCSsigFree Version 45_v2b (Melvin and Briffa, 2008; http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). Since the number of cores per tree in our study are

25 unequal, the signal of each chronology was estimated by the effective chronology signal (Rbar$_{eff}$) which incorporates the effective number of cores, within- and between-tree signals (Briffa and Jones, 1990). Besides, the expressed population signal (EPS), a function of Rbar$_{eff}$ and the number of trees, was used to estimate how well the sample chronology represents the theoretical chronology (Briffa and Jones, 1990; Wigley et al., 1984). The running Rbar$_{eff}$ and EPS for each chronology were

30 calculated over a 51-year window with a 50-year overlap using the function "rwi.stats.running" in R package "dplR" version 1.6.9 (Bunn et al., 2018). The minimum number of common years in any pair of ring-width series required for their correlation was set to 30 (Briffa and Jones, 1990). The reliable period for each chronology was determined based on the generally accepted EPS threshold value of 0.85 (Wigley et al., 1984).

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The width chronologies from the two sampling sites show high degree of coherence as evidenced by their significant positive correlations ($p < 0.001$) during their common period 1850–2005 (Table S1). Moreover, the positive correlations remain significant ($p < 0.001$) after removing the influence of autocorrelations and linear trends (Table S1). This indicates that the two sites share common climatic signals. Therefore, we pooled all raw ring-width series from the two sites, and developed composite STD and SSF chronologies for EWW, LWW and TRW using the three detrending methods as described above (Fig. S4). Statistics for each chronology including the starting year when EPS $\geq$ 0.85, standard deviation, mean sensitivity and first-order correlation coefficient (AR1) are shown in Table S2. In addition, several statistics were calculated to assess the degree of similarity among detrended ring-width series over the common period 1915–2005 (Table S3). These statistics are variance explained by the first eigenvector (Var$_{pei}$), Rbar$_{eff}$, siganl-to-noise ratio (SNR), and EPS (Briffa and Jones, 1990; Trouet et al., 2006).

**2.4 Climate data**

Monthly mean maximum (Tmax), minimum (Tmin) and mean temperature (Tmean), and monthly total precipitation (Pre) were selected from four nearby meteorological stations (Table 1; Fig. 1b). These climate data were obtained from the China Meteorological Administration. Regional temperature values were calculated by directly averaging the temperature time series from the four statioins over their common period 1957–2005. Regional precipitation was produced by firstly deriving the regional averages in terms of percentages, then multiplying the regional mean to transform the resulting series back to millimetre units (Jones and Hulme, 1996). The self-calibrated PDSI (scPDSI) and SPEI were also chosen as the hydroclimatic factors. Here we used the scPDSI instead of PDSI because it has solved the PDSI problems in spatial comparisons by calculating the duration factors (weighting coefficients for the current moisture anomaly and the previous drought severity) based on the characteristics of the climate at a given location (Wells et al., 2004). The regional scPDSI was calculated by averaging the CRU (Climate Research Unit) scPDSI grids (van der Schrier et al., 2013) over the area between 32° N to 34.5° N and 111° E to 112° E (Fig. 1b) where the meteorological stations utilized by CRU dataset were concentrated (Fig. S5; Table S4). The time span of scPDSI was selected as 1953–2005, because the stations used by CRU have a common period starting from July 1952 (Table S4). The SPEI has multi-timescales (Vicente-Serrano et al., 2010). Therefore, we calculated the regional SPEI at three timescales (1-month, 3-month and 12-month) using the R package "SPEI" version 1.7 (Beguería and Vicente-Serrano, 2012). The climatic factors used in SPEI calculation included regional Tmax, Tmin and Pre, which were derived from the four stations mentioned in Table 1. The time span of SPEI is 1957–2005.

In order to validate the reconstruction, we compared it with several hydroclimate time series and historical document records (Table 2), including (1) the June–August PDSI from the No. 370 grid point of the Monsoon Asia Drought Atlas (MADA) at 33.75° N, 111.25° E over the period 1868–2005 (PDSI$_{Cook}$; Cook et al., 2010), (2) the dryness/wetness index (DWI) from the grid point at 33.75° N, 111.25° E over the period 1868–2000 (DWI$_{Yang}$; Yang et al., 2013), (3) reconstructed April–June precipitation based on TRW in Mount Hua over the period 1868–2005 (Pre$_{Chen}$; Chen et al., 2016b), and (4) drought/wet events recorded in historical documents over the period 1868–2005 (He, 1980; Wen, 2006). The DWI dataset were reconstructed

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from the historical documents and modern instrumental May–September precipitation in 120 sites over China (Chinese Academy of Meteorological Sciences, 1981). The dataset classified the degree of dryness and wetness into five grades: very wet (grade 1), wet (grade 2), normal (grade 3), dry (grade 4), and very dry (grade 5). Yang et al. (2013) has interpolated the DWI dataset into 2.5° latitude/longitude grid cells.

5    The EASM circulation was represented by a newly defined EASMI based on the 200 hPa zonal wind anomalies which was less affected by complex weather processes near the surface (Zhao et al., 2015). It was computed as Equation (1):

$$EASMI = Nor\,[u(2.5°–10°\,N, 105°–140°\,E) − u(17.5°–22.5°\,N, 105°–140°\,E) + u(30°–37.5°\,N, 105°–140°\,E)] \quad (1)$$

where Nor and u represent standardization and mean 200 hPa zonal wind, respectively. To understand the possible impacts of local precipitation and temperature (32°–34.5°\,N and 111°–112°\,E) on the relationship between the scPDSI and EASMI, the

10 precipitation and temperature data were extracted from the gridded precipitation dataset Global Precipitation Climatology Centre Version 7 (GPCC v7; Schneider et al., 2015), and gridded temperature dataset Climatic Research Unit Time-Series Version 4.01 (CRU TS 4.01; Harris et al., 2014). The gridded dataset can represent the variations of precipitation and temperature over East China during the 20th century (Wang and Wang, 2017; Wen et al., 2006).

**2.5 Statistical methods**

15 To investigate the climate response of different tree-ring parameters (EWW, LWW, and TRW), we firstly calculated the Pearson correlation coefficients of the STD and SSF tree-ring width chronologies with monthly climate time series. The time window for the correlation analysis spanned from January of two years earlier to October of the current year. Secondly, correlations were calculated between the prewhitened and linearly detrended chronologies and climate time series to evaluate the possible effects of autocorrelations and secular trends. The prewhitening procedure was run with the "ar" funtion in R

20 package "stats" version 3.5.1 (R Core Team, 2018). The appropriate autoregressive order was automatically determined by the Akaike Information Criterion (Akaike, 1974). The linear detrending procedure was performed in Matlab R2016a with the "detrend" function (The MathWorks, 2016). Then, we analyzed the response of different tree-ring parameters to multi-month averaged scPDSI (which had the stronger impacts on tree-growth than other climatic factors; see the results for detail) to find the strongest climate-growth relationship. Finally, we used the wavelet coherence method (Grinsted et al., 2004) to test the

25 temporal stability and possible lags of the climate-growth relationship on different frequency domain.

A simple linear regression model was applied to establish the transfer function using May–July (MJJ) scPDSI as the predictant, and the NELR based EWW STD chronology as the predictor (which had the strongest relationship; see the results for detail) over the period 1953–2005. Temporal stability of the model was tested by splitting the MJJ scPDSI into two sub-periods (1953–1979 and 1979–2005) for calibration and verification using the following statistics: correlation coefficient ($r$), explained

30 variance ($R^2$), reduction of error ($RE$), coefficient of efficiency ($CE$), and the sign-test (Meko and Graybill, 1995). Meanwhile, the possible autocorrelation and trend contained in the regression residuals were evaluated using the Durbin-Watson test ($DW$; Durbin and Watson, 1950) with the "dwtest" function in R package "Lmtest" version 0.9-36 (Hothorn et al., 2018), and the two-sided Cox and Stuart trend test ($CS$; Cox and Stuart, 1955) with the R package "snpar" version 1.0 (Qiu, 2014),

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respectively. A *DW* value of 2 means no first order autocorrelation in the residuals, whereas values larger (less) than 2 are indicative for negative (positive) autocorrelation. The *DW* test has the null hypothesis that the autocorrelation of the residuals is 0. The two-sided *CS* trend test has the null hypothesis that there is no monotonic trend in the residuals. The variance of the MJJ scPDSI reconstruction was adjusted to match the variance of instrumental MJJ scPDSI during the calibration period using Equation (2),

$$Adj\_Rec_i = \frac{(Rec_i - \overline{Rec_{cal}})}{\sigma(Rec_{cal})} \times \sigma(Ins_{cal}) + \overline{Ins_{cal}} \qquad (2)$$

where, the $Rec_i$ and $Adj\_Rec_i$ indicate the reconstructed value and its variance adjusted value for a specific year *i*. The $\overline{Rec_{cal}}$ and $\overline{Ins_{cal}}$ indicate the arithmetic mean of the reconstructed and instrumental values during the calibration period (it is 1953–2005 in this study). The $\sigma(Rec_{cal})$ and $\sigma(Ins_{cal})$ are the corresponding standard deviations.

Spatial correlations were calculated between the reconstructed MJJ scPDSI and CRU scPDSI 3.25 dataset (van der Schrier et al., 2013) using the KNMI Climate Explorer (http://climexp.knmi.nl/start.cgi) to investigate the spatial representativeness of our reconstruction. All the hydroclimatic reconstructions were divided into interannual (< 10 years), and decadal and longer-term components (> 10 years) for comparison, respectively. The decadal and longer components were derived by lowpass filtering the original reconstructions using the the adaptive 10 point "Butterworth" low-pass filter at 0.1 cut-off frequency (Mann, 2008). Then, the interannual components were obtained by subtracting the decadal and longer-term components from the original reconstructions. The low-pass filtering technique has a good ability in preserving trends near time series boundaries (Mann, 2008).

We calculated the MJJ EASMI according to the definition of Zhao et al. (2015) using the 200 hPa zonal wind dataset which were obtained from the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences Twentieth Century Reanalysis V2c (NOAA-20C; Compo et al., 2011) over the period 1868–2005. The relationship between EASMI and our reconstruction was firstly evaluated using the wavelet coherence method (Grinsted et al., 2004). In addition, 21-year moving window correlation analyses were calculated between the decadal-filtered MJJ EASMI, reconstructed scPDSI, and local precipitation to explore the connections of precipitation with scPDSI and EASMI. Moreover, empirical orthogonal function (EOF) analysis and spatial correlation analysis were performed to assess the impacts of the changed leading EASM mode on the relationship between decadal-filtered EASMI and local precipitation. The filtering procedure was conducted using the "Butterworth" low-pass filter (Mann, 2008) as mentioned above. The filtering, EOF and correlation analyses were performed in Matlab R2016a (The MathWorks, 2016) and the plots were drawn with Surfer 10 (Golden Software, 2011).

The significance tests for all observed correlation coefficients were conducted using Monte Carlo method (Efron and Tibshirani, 1986). In detail, modelled time series with the same structure as the original series were produced according to the frequency domain method of Ebisuzaki (1997). Then, correlation coefficients were computed between the modelled time series. The above processes were repeated 1000 times to obtain 1000 modelled correlation coefficients. The significance threshold was

estimated based on the probability distribution of the modelled 1000 correlation coefficients. The procedure was performed using the algorithms of Macias-Fauria et al. (2012).

**3 Results and Discussion**

**3.1 Stronger hydroclimatic signals derived from EWW**

As shown in Fig. 3, the EWW chronologies generated using different detrending and standardization methods were significantly negatively correlated with Tmax, Tmean during May–June, and significantly positively correlated with Pre in May. In terms of the drought indices, all EWW chronologies were significantly positively correlated with the 1-month SPEI in May, 3-month SPEI during May–June, 12-month SPEI during May–October, and scPDSI during April–October. It can be found that EWW showed a much longer-term response to the multi-month SPEI and scPDSI than to precipitation after May. This may be because the summer temperatures still affected the soil water status as reflected by their negative correlations with EWW. Besides, soil has a memory effect on previous drought conditions, and this effect was considered by the multi-month SPEI and scPDSI (Vicente-Serrano et al., 2010; Dai, 2011). The scPDSI had higher correlations with tree-ring width than the SPEI. This indicates that the scPDSI has a better ability than the SPEI in monitoring the influence of soil moisture status on tree growth in our sampling sites, and the reasons remain unknown. However, the significant correlations found between EWW and drought indices during autumn should not be regarded as a real drought impact, as the earlywood growth would terminate in the mid- and late-growing season (Larson, 1969). For LWW, during the current growing season, the highest correlation was found between the NELR based LWW STD and July scPDSI ($r = 0.37$, $p < 0.01$), which was much lower than that found between the NELR based EWW STD and the July scPDSI ($r = 0.62$, $p < 0.01$), indicating that LWW had less sensitivity to the scPDSI. TRW generally exhibited the similar climate response as EWW but with relatively lower correlations. Taking the NELR based STD chronologies as an example, the correlation coefficients between TRW and the monthly scPDSI from May to July were 0.59 ($p < 0.01$), 0.58 ($p < 0.01$), 0.58 ($p < 0.01$), respectively. However, for EWW, the correlation coefficients were 0.66 ($p < 0.01$), 0.66 ($p < 0.01$) and 0.62 ($p < 0.01$). The above response patterns were also revealed by the correlation coefficients between the prewhitened and linearly detrended series (Fig. 4), indicating that autocorrelations and secular trends in the tree-ring width chronologies and climate time series have limited effects on the relationships.

Significant climate-growth relationships were also observed prior to the current growing season. For example, most of EWW and LWW chronologies exhibited negative response to Tmax and Tmean during the late summer and early autumn of last year (Figs. 3–4). This may be ascribed that high temperatures in the late growing season of last year could enhance soil water evaporation, thus inducing moisture stress and limiting the accumulation of photosynthetic products for the next year tree-growth (Peng et al., 2014). The influence of moisture status prior to the current growing season can also be reflected by the significant positive correlations between LWW and drought indices from September of two years earlier to May of the previous year. However, EWW had lower correlations with these monthly drought indices. A possible explanation may be that the interannual variations of EWW were mainly contributed by the moisture status of the growth year.

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Since the impacts of scPDSI on tree-growth can last for several months, we analysed the responses of various tree-ring width parameters to the multi-month averaged scPDSI. The strongest climate-growth relationship was found between the NELR based EWW STD chronology and the MJJ scPDSI ($r = 0.707$; $p < 0.01$; Fig. S6). Meanwhile, correlation coefficients derived from the methods SP67 and SPA50 were 0.67 ($p < 0.01$) and 0.68 ($p < 0.01$), respectively, which were lower than that based on NELR method (Fig. S6). This may be because the downward trend in MJJ scPDSI were better preserved using the NELR detrending method (Fig. S7). In addition, correlation coefficient between the NELR based EWW SSF chronology and the MJJ scPDSI was 0.705 ($p < 0.01$), which was quite close to that using the traditional STD method, indicating that the effects of so-called "trend distortion" in our tree-ring series were limited.

We further tested the temporal stability and possible lags (leads) in the relationships between NELR based STD chronologies and the MJJ scPDSI on different frequency domain (Fig. 5). It can be found that EWW generally showed high degree of coherence with the MJJ scPDSI on all timescales (2- to 18-year) except the periodicities between 3.5- and 6.5-year. Different from EWW, LWW only varied in-phase with the MJJ scPDSI but with some lags during the period from 1970s to 1990s on the timescales lower than 12-year. Moreover, LWW was inversely correlated with the MJJ scPDSI during the 1960s on the periodicities of 4- to 6-year. TRW showed an unstable relationship and certain lags to the MJJ scPDSI on the periodicities of 6- to 11-year. Therefore, it can be concluded that EWW has the most stable relationships with the MJJ scPDSI than LWW and TRW.

Previous studies based on TRW has evidenced that moisture status of the current growing season could strongly affect the radial growth of *P. tabulaeformis* (e.g. Cai and Liu, 2012; Cai et al., 2014; Cai et al., 2015; Chen et al., 2014; Fang et al., 2010a; Fang et al., 2012b; Li et al., 2007; Liang et al., 2007; Liu et al., 2017; Song and Liu, 2011; Sun et al., 2012). Fast radial growth of *P. tabulaeformis* usually happens in the early growing season (Liang et al., 2009; Shi et al., 2008; Zeng et al., 2018). Increased water deficiency due to the rising temperature and inadequate rainfall in the early growing season could induce water stress thus suppressing cell division and expansion (Fritts, 1976), and resulting in the formation of narrow earlywood bands. The less sensitivity of LWW to moisture status of the current growing season may be ascribed to that the moisture restrictions on tree growth was alleviated in the rainy season (July–August; Fig. 2). Meanwhile, the response sensitivity of TRW to moisture status of the current growing season was not as strong as EWW, although they shared a similar climatic response pattern because EWW represents the majority of TRW (on average, the portion of EWW of TRW accounts for 65.8%).

**3.2 MJJ scPDSI reconstruction using NELR based EWW STD chronology**

Based on the above analyses, we selected the MJJ scPDSI as the target for hydroclimate reconstruction, and the NELR based EWW STD chronology as the predictor (Fig. 6a). The transfer function was estimated using a simple linear regression model as expressed in Equation (3):

$$\text{MJJ scPDSI} = 4.74\text{EWW} - 4.32; (R^2 = 0.5, n = 53, p < 0.001) , \hspace{1cm} (3)$$

The model explains 50 % of the actual MJJ scPDSI variance over the period of 1953–2005. The calibration-verification tests show that $r$, $R^2$ and the sign-test are significant at the 0.01 level, and that $RE$ and $CE$ values are positive (Table 3). In addition,

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the *p*-value generated from *DW* and *CS* tests are larger than 0.05, indicating that there are no autocorrelations and long-term trends in the regression residuals (Table 3; Fig. 6b). All test results confirm that the model is valid (Cook et al., 1999; Fritts, 1976).

Based on the above model, the MJJ scPDSI of the study region was reconstructed back to 1868 (Fig. 6c). We adjusted the
5  variance of the reconstruction to match the variance of instrumental MJJ scPDSI during the calibration period (1953–2005). Spatial correlation analysis indicates that the reconstruction most strongly represents Central China, including the western part of Henan, the northern part of Hubei, and the southern part of Shaanxi provinces (Fig. 1a).

### 3.3 Comparing the reconstructed MJJ scPDSI with other reconstructions and historical documents

On the interannual timescale (Figs. 7a–c), our reconstruction is significantly correlated with the $PDSI_{Cook}$ ($r = 0.37$; $p < 0.01$;
10  1868–2005), and $Pre_{Chen}$ ($r = 0.52$; $p < 0.01$; 1868–2005). On the decadal and longer timescales, our reconstruction is significantly correlated with all other reconstructions (Figs. 7e–f). The common drought periods occurring in the 1870s and the 1920s were reflected in our reconstruction. These two drought periods were frequently observed in North and West China (Cai et al., 2014; Chen et al., 2014; Fang et al., 2012a; Kang et al., 2013; Liang et al., 2006; Liu et al., 2017; Zhang et al., 2017).

15  However, it should be noted that our reconstruction has some mismatches with others. On the interannual timescale, our reconstruction is not significantly correlated with the $DWI_{Yang}$ over the whole period 1868–2000 ($r = -0.06$; $p = 0.64$; Fig. 7b). This probably due to the historical documents have limited ability in capturing the high frequency climatic variations (Zheng et al., 2014). On the decadal and longer timescales, our reconstruction varied out-of-phase with $PDSI_{Cook}$ during the period from the late 1940s to the early 1960s (Fig. 7d), weakly correlated with $DWI_{Yang}$ after the 1940s (Fig. 7e), and leads $Pre_{Chen}$
20  during the period of 1900s–1930s (Fig. 7f). The possible reasons might be that (1) the reconstructions aim to different target season (June–August for $PDSI_{Cook}$, May–September for $DWI_{Yang}$, and April–June for $Pre_{Chen}$ which is before the rainy season); (2) the $DWI_{Yang}$ after the 1940s was calculated using instrumental May–September precipitation and the chronology of Chen et al. (2016b) also reflects precipitation, while the scPDSI is influenced not only by precipitation but also temperature and previous drought conditions; and (3) in the MADA network, there are still limited tree-ring sites around our sampling sites,
25  which may cause some difference on local scale.

We also compared the dry and wet events derived from our reconstruction with those recorded in historical document records. The moderately to severely dry (wet) events are defined based on the scPDSI values less than –2 (larger than 2) according to Palmer (1965). It can be found that all the dry events and 70 % of the wet events can be verified by corresponding descriptions in historical documents (Table 4). While, there are still some mismatches between our reconstruction and the historical records.
30  For example, no relevant document record is found for the year 1983 when an extreme wet event is shown in our reconstruction. In addition, some historical events are not reflected in our reconstruction, such as the wet event in 1963 and the dry event in 1942 (Wen, 2006). These mismatches may reflect the uncertainties of historical documents records and tree-ring.

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### 3.4 Connections with EASMI

The reconstructed MJJ scPDSI and EASMI in general exhibit an in-phase relationship before the 1940s on the decadal and longer timescales (Fig. 8). This in-phase relationship was further verified after conducting an 21-year moving window correlation analysis on the decadal-filtered scPDSI and EASMI (Fig. 9a, b and e). As EASM direclty drives precipitation rather than the scPDSI, we compared the EASMI with the local precipitation (32° N to 34.5° N and 111° E to 112° E). It was found that the local precipitation also exhibit the similar variation as the scPDSI and EASMI before the 1940s (Fig. 9a, b and c). Therefore, the in-phase relationship between the decadal-filtered EASMI and scPDSI before the 1940s may be ascribed to the fact that a stronger EASM could induce enhanced the local precipitation, thus increasing the soil moisture content. However, interestingly, the correlation between the local precipitation and EASMI weakend after the 1940s, and even became negative since the 1970s (Fig. 9e). We attributed this unstable relaitonship to the nature of EASMI. In fact, the EASMI was desigened to capture the leading mode of EASM precipitation variability, whose largest loading is in general located at the mei-yu/changma/baiu rainband (Zhao et al., 2015). In other words, the mei-yu/changma/baiu rainfall has the most robust relationship with the EASMI. Moreover, although the leading pattern of EASM precipitation can change on interdecadal timescale and may even much longer timescales (which is still elusive due to the limited paleo-precipitation record), the unique importance of mei-yu/changma/baiu in EASM most likely remains (Wang et al., 2008). Therefore, due to the change of EASM precipitation pattern, the precipitation outside of the mei-yu/changma/baiu rainband could be in-phase, out-of-phase and uncorrelated with mei-yu/changma/baiu rainfall (Wang et al., 2008), thus manifesting an unstable relationship with EASMI. The EASM experienced an abrupt shift in the late 1970s, which caused a change of the leading mode of EASM precipitation (Wang, 2001; Ding et al., 2008). We demonstrated how this mode change affects the relationship between EASMI and precipitation in the eastern Qinling Mountains. As shown in Fig. 10a, the anomalies of the decadal-filtered MJJ precipitation exhibited similar variations over the Yangtzer River basin and Yellow-Huaihe River basins during 1901–1978, but they were divided by the Yangtze River, showing a dipole pattern during 1979–2005 (Fig. 10b). The south of the Yangtze River basin (27°–30° N) were the loading centres during both periods, and the decadal-filtered MJJ precipitation over this area were well captured by the designed EASMI as manifested by their significant positive correlations ($p < 0.1$; Figs. 10c–d). On the contrary, the decadal-filtered MJJ precipitation over the north of the Yangtze River, including our sampling sites, varied out-of-phase with those over the south of the Yangtze River basin after the late 1970s, thus being negatively correlated with the EASMI. The weakened scPDSI-EASMI relationship after the 1940s cannot be solely attributed to the change of EASM precipitation mode, because the scPDSI also showed weakened relationship with the local precipitation simultaneously (Fig. 10f). It cannot be ascribed simply to that the variations of scPDSI became dominated by temperature either, as no stably enhanced scPDSI-temperature relationship was found (Fig. 10f). This may be because the scPDSI is not a simple formula based on precipitation and temperature, but a complex function incorporating previous drought conditions and current moisture departure (Wells et al., 2004). In addition to the precipitation and temperature, the available energy, humidity and wind speed can also affect the

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scPDSI via controlling evapotranspiration (Sheffield et al., 2012). Therefore, a variety of climate data is required to identify the specific cause for the weakened relationship. While, this would be difficult due to the limited climate records.

**4 Conclusions**

Besides TRW, climatic responses of EWW and LWW were also explored for the tree-ring samples of *P. tabulaeformis* in the eastern Qinling Mountains, Central China. Regardless of the detrending and standardisation methods used, the resulting EWW chronologies are more sensitive to early summer soil moisture conditions (scPDSI) than LWW and TRW during the instrumental period 1953–2005. The MJJ scPDSI (1868–2005) reconstructed from the NELR based EWW STD chronology captures the past early summer hydroclimatic fluctuations, further validated by other proxy-based reconstructions and historical document records in adjacent regions. This indicates that EWW has great potentials to reconstruct early summer hydroclimatic conditions in this area. Moreover, on the decadal and longer timescales, the reconstruction showed a strong in-phase relationship with the EASMI before the 1940s, which may be related to the positive response of the local precipitation to EASM. Our finding in this study is different from that found at a well-drained site in South China, where strongest moisture signals were contained in LWW with a different tree species (Zhao et al., 2017a, b). Therefore, more EWW and LWW related studies should be conducted in terms of tree species differences, different environmental conditions, in humid and semi-humid regions of China, that provides a possibility to understand EASM variations at longer time periods beyond the meteorological records.

**Data availability**

The tree-ring data used in this study are available on request (shijf@nju.edu.cn). DWI, precipitation reconstruction, and dry/wet events recorded in historical documents are available from corresponding authors or publications. MADA is available from https://www.ncdc.noaa.gov/paleo-search/study/10435. The 200 hPa zonal wind dataset of NOAA-20c is available from https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.html and https://rda.ucar.edu/datasets/ds628.1/. The gridded dataset CRU scPDSI 3.25 is available from https://crudata.uea.ac.uk/cru/data/drought/. The gridded precipitation dataset GPCC v7 is available from https://opendata.dwd.de/climate_environment/GPCC/html/fulldata_v7_doi_download.html. The gridded temperature dataset CRU TS 4.01 is available from https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.01/cruts.1709081022.v4.01/tmp/.

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**Table 1.** Characteristics of climate data.

| Climate data | Source | Longitude (° E) | Latitude (° N) | Elevation (m a.s.l.) | Temporal cover |
|---|---|---|---|---|---|
| Tmax, Tmean, Tmin, Pre | Luanchuan (LC) meteorological station | 111.6 | 33.8 | 751 | 1957–2005 |
| | Xixia (XX) meteorological station | 111.5 | 33.3 | 250 | 1957–2005 |
| | Ruyang (RY) meteorological station | 112.5 | 34.2 | 311 | 1957–2005 |
| | Nanzhao (NZ) meteorogical station | 112.6 | 33.6 | 198 | 1956–2005 |
| scPDSI | CRU scPDSI 3.25 (van der Schrier et al., 2013) | 111–112 | 32–34.5 | — | 1953–2005 |
| SPEI | Calculated in R using the SPEI package with the Tmax, Tmin and Pre data (Beguería and Vicente-Serrano, 2012) | — | — | — | 1957–2005 |

**Table 2.** Long-term hydroclimatic reconstructions and East Asian summer monsoon index (EASMI) selected for comparion with the reconstructed MJJ scPDSI.

| Time series | Source | Longitude (° E) | Latitude (° N) | Temporal cover |
|---|---|---|---|---|
| June–August PDSI | Monsoon Asia Drought Atlas (MADA, Cook et al., 2010) | 111.25 | 33.75 | 1868–2005 |
| April–June precipitation in Mount Huashan (HS) | Chen et al., 2016 | 110.08 | 34.48 | 1868–2005 |
| Dryness/wetness index (DWI) | Yang et al., 2013 | 111.25 | 33.75 | 1868–2000 |
| EAMSI | Calculated using the 200 hPa zonal wind anomalies (NOAA-20c; Compo et al., 2011) according to the definition of Zhao et al. (2015) | — | — | 1868–2005 |

**Table 3.** Statistics for split calibration-verification of the regression model.

| Calibration period | $r$ | $R^2$ | DW value (p-value) | CS p-value | Verification period | RE | CE | Sign-test |
|---|---|---|---|---|---|---|---|---|
| Full period (1953−2005) | 0.71** | 0.50** | 2.03 (0.53) | 0.85 | — | — | — | — |
| Early half (1953−1979) | 0.68** | 0.46** | 2.02 (0.49) | 1 | Late half (1979−2005) | 0.53 | 0.53 | 22+/5−** |
| Late half (1979−2005) | 0.73** | 0.54** | 2.02 (0.50) | 1 | Early half (1953−1979) | 0.46 | 0.45 | 21+/6−** |

** $p < 0.01$; $r$, Pearson correlation coefficient; $R^2$, explained variance; DW, Durbin-Watson test; CS, Cox and Stuart trend test; RE, reduction of error; and CE, coefficient of efficiency.

**Table 4.** Moderately to severely dry (scPDSI ≤ –2) and wet (scPDSI ≥ 2) events derived from the MJJ scPDSI reconstruction and corresponding descriptions from historical documents.

| Event type | Year | scPDSI | Description |
|---|---|---|---|
| Dry | 1879 | –3.61 | A mega-drought occurred has caused a great famine over Henan, Shaanxi and other provinces in North China in the early Guangxu reign (1876–1879)[a] |
| | 1900 | –2.24 | Severe drought from spring to Autumn over Henan and Shaanxi |
| | 1923 | –2.28 | Drought over Henan and Shaanxi |
| | 1926 | –2.33 | No harvest at Ruyang (West Henan) due to severe drought |
| | 1929 | –2.53 | Summer drought over Henan and Shaanxi |
| | 1994 | –2.12 | Severe drought occurred in April, May and July over west Henan |
| | 1995 | –2.10 | Intensified drought severity since April 22 over Henan |
| | 2000 | –2.94 | The drought from Feburary to May is the worst one since 1950 over Henan |
| Wet | 1869 | 2.31 | Flood in summer and autumn over Henan |
| | 1883 | 2.62 | Persistent rainfall in summer at Shanxian and Mianchi (Northwest Henan) |
| | 1885 | 3.07 | Flood in summer at Lingbao and Shanxian (Northwest Henan) |
| | 1894 | 3.06 | Not available |
| | 1895 | 2.11 | Flood over the Qinhe River (Northwest Henan) in summer |
| | 1898 | 3.77 | Severe flood in summer at Lushi (Northwest Henan), Shangnan (Southeast Shaanxi) and Danjiang (Northwest Hubei) |
| | 1905 | 2.26 | Persistent rainfall in spring and summer over Henan |

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| 1906 | 3.65 | Heavy rainfall in summer over Henan |
| 1910 | 2.05 | Flood in summer and autumn over Henan |
| 1911 | 3.84 | Heavy rainfall in summer over Henan |
| 1912 | 2.01 | Heavy rainfall and flood in summer over Nanyang (Southwest Henan) |
| 1933 | 2.51 | Heavy rainfall in summer over Henan and Shaanxi |
| 1934 | 3.11 | Summer rainfall over Henan, South Shaanxi and Northwest Hubei |
| 1936 | 3.72 | Not available |
| 1944 | 2.38 | Flood over Henan; Rainstorm in Zhenan (Southeast Shannxi) on July 8; The Tianhui Channel (Southeast Shaanxi) was destroyed by flood on May 13 |
| 1948 | 2.81 | Wheat loss caused by summer rainfall |
| 1949 | 2.95 | Not available |
| 1973 | 2.97 | Not available |
| 1980 | 2.07 | Rainfall in June is higher than usual for most regions over Henan |
| 1983 | 4.15 | Not available |
| 1984 | 2.33 | From June to September, there are 5 large-scale rainstorms over Henan |
| 1990 | 2.32 | Not available |

[a] Historical description of the 1879 drought event is cited from He (1980), and others from Wen (2006)
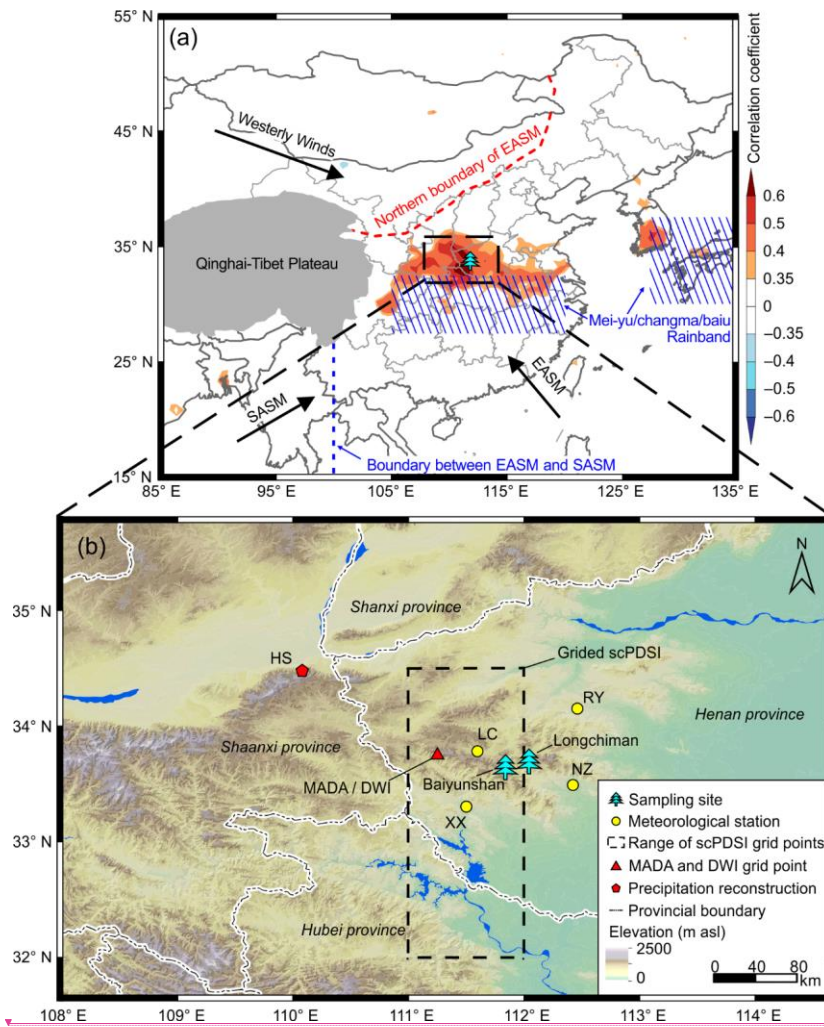
**Figure 1.** Map of the study region. **(a)** Location of the sampling site (tree symbol), and the spatial correlations between the May–July (MJJ) scPDSI reconstruction and the gridded scPDSI dataset (van der Schrier et al., 2013) during the period 1953–2005. The color bar indicates the correlation coefficient. The blue dashed line (100° E) indicates the boundary between East
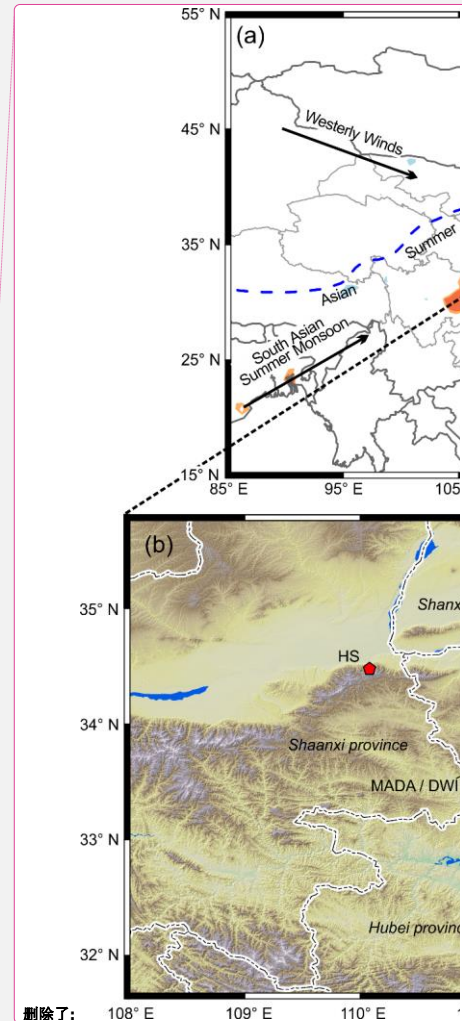
Asian summer monsoon (EASM) and South Asian summer monsoon (SASM; Tang et al., 2010). The red dashed line indicates the northern boundary of EASM (Chen et al., 2018). The blue shaded area represents the mei-yu/changma/baiu rainband (Zhao et al., 2015). **(b)** Partial enlargement of the study region. The circles indicate the locations of the four meteorological stations (LC: Luanchuan, XX: Xixia, RY: Ruyang, and NZ: Nanzhao). The triangle indicates the location of selected grid data from the datasets Monsoon Asia Drought Atlas (MADA; Cook et al., 2010) and Dryness/Wetness Index (DWI; Yang et al., 2013). The pentagon indicates a tree-ring width based precipitation reconstruction in Huashan Mount (HS, Chen et al., 2016b). The dashed rectangle indicates the gridded scPDSI obtained from the gridded scPDSI dataset (van der Schrier et al., 2013).

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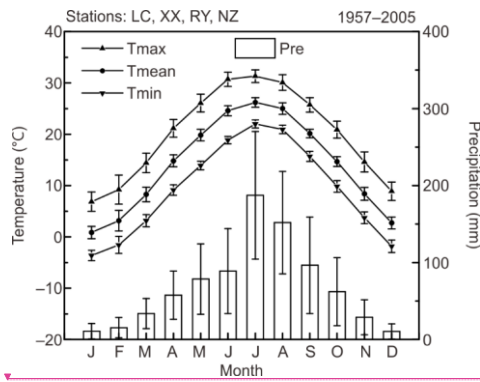
**Figure 2.** Monthly maximum, mean, minimum temperature (Tmax, Tmean, Tmin), and total precipitation (Pre) averaged from the four selected meteorological stations (LC, XX, RY, NZ) during the period 1957–2005. Error bar denotes ± one standard deviation.

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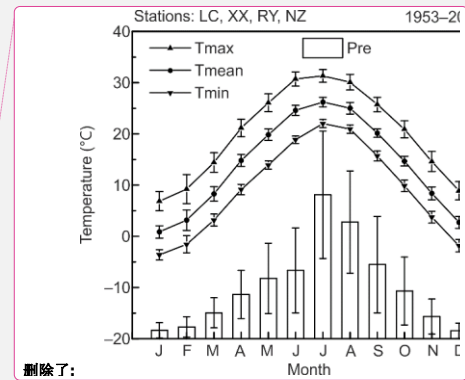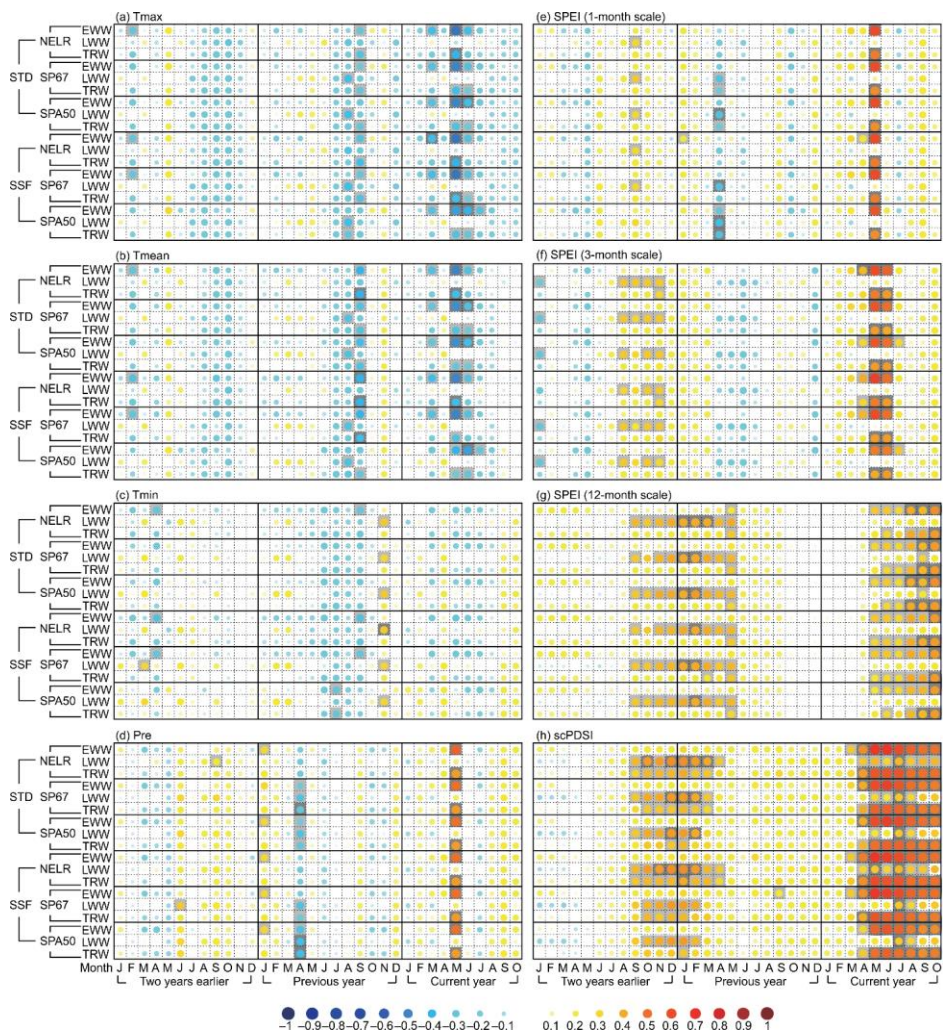
**Figure 3.** Matrix plots for the correlation coefficients between tree-ring width chronologies and monthly climate time series

from January of two years earlier to October of the current year. The climatic factors are monthly **(a)** maximum temperature

(Tmax), **(b)** mean temperature (Tmean), **(c)** minimum temperature (Tmin), **(d)** total precipitation (Pre), **(e)** SPEI of 1-month scale, **(f)** SPEI of 3-month scale, **(g)** SPEI of 12-month scale, and **(h)** scPDSI. EWW, LWW, and TRW indicate the earlywood width, latewood width, and total tree-ring width, respectively. The correlation analyses were conducted during the period 1953–2005 for the scPDSI, and 1957–2005 for the other climatic factors. NELR, SP67, and SPA50 indicate the three detrending methods: (1) negative exponential function together with linear regression with negative (or zero) slope (NELR), (2) cubic smoothed splines with a 50 % frequency cutoff of 67 % of the series length (SP67), and (3) age-dependent splines with an initial stiffness of 50 years (SPA50). STD and SSF indicate the two standardization methods "standard" and "signal-free", respectively. The correlation coefficients are reflected by the colorful and different-size circles, which can be referred to the color bar as shown at the bottom of the figure. The squares filled with light and dark gray color indicate that the correlation coefficients are statistically significant at the 0.05 and 0.01 level, which are tested using the Monte Carlo method (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012).
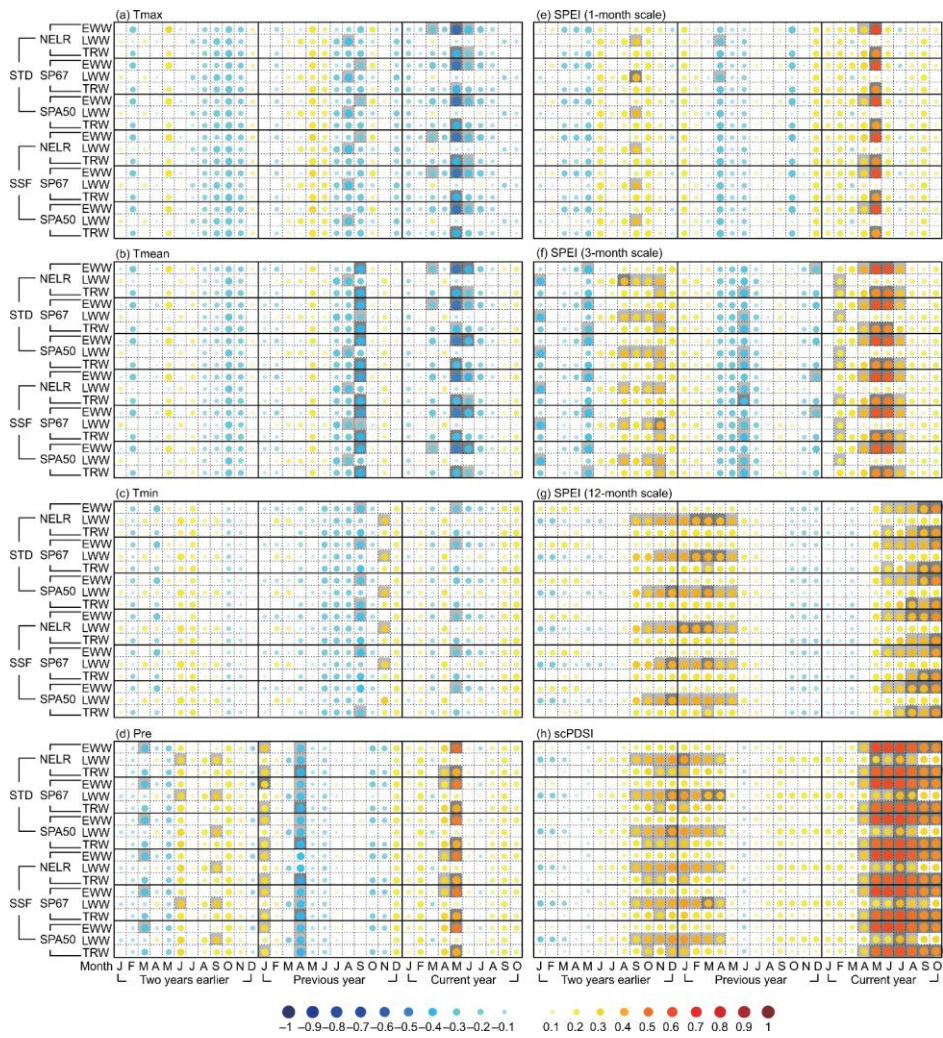
**Figure 4.** Correlation coefficients between the prewhitened and linearly detrended tree-ring width chronologies and climate time series. The explanations and legends are the same as Figure 3.
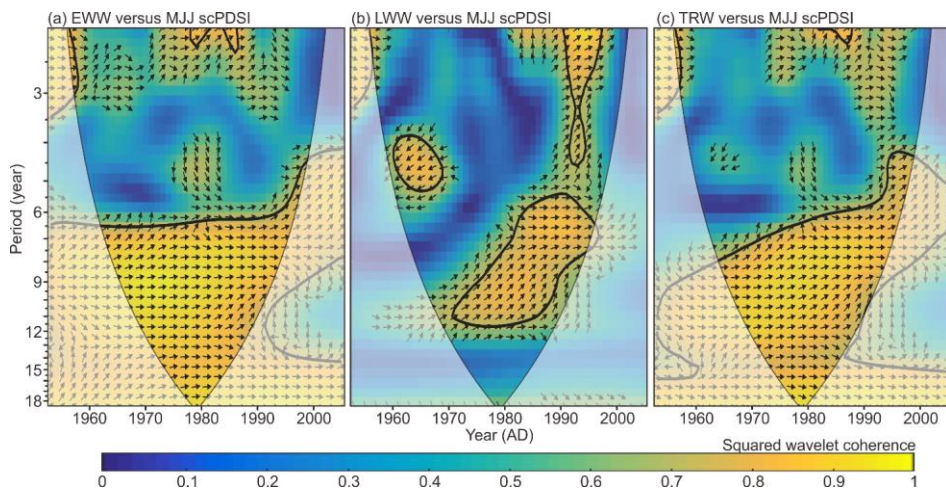
**Figure 5.** Squared wavelet coherence and phase relationship between the NELR based tree ring-width STD chronologies and MJJ scPDSI. **(a–c)** represent the results for EWW, LWW, and TRW, respectively. The color bar indicates the squared wavelet coherence. The arrows indicate the phase relationship with in-phase (anti-phase) pointing right (left), and MJJ scPDSI leading (lagging) tree-ring width with 90° pointing straight up (down). The thick contour indicates the 5% significance level against red noise. The cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.
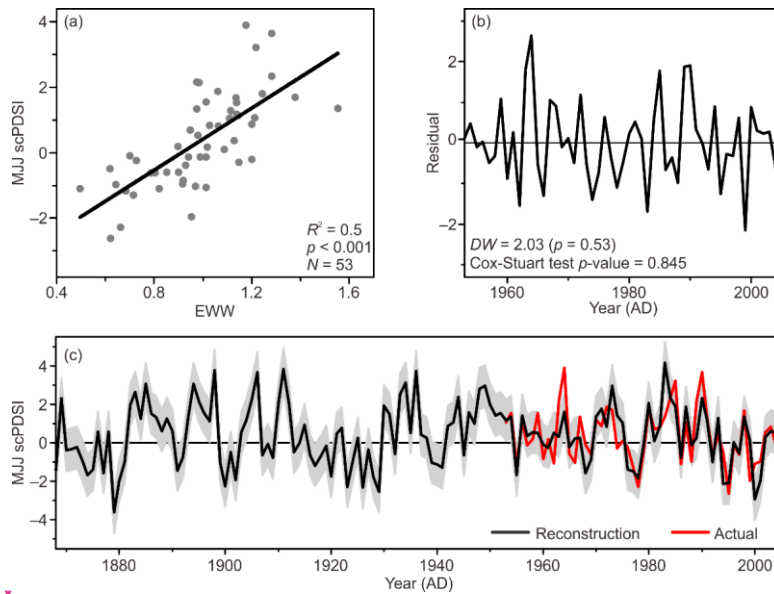
**Figure 6.** MJJ scPDSI reconstruction using NELR based EWW STD chronology. **(a)** Scatter diagram during the period 1953–2005, and **(b)** the resulting residuals. **(c)** MJJ scPDSI reconstruction (black line, after variance adjusted) and instrumental MJJ scPDSI (red line). Shaded area denotes the uncertainties of reconstruction in the form of ± 1 root mean square error.
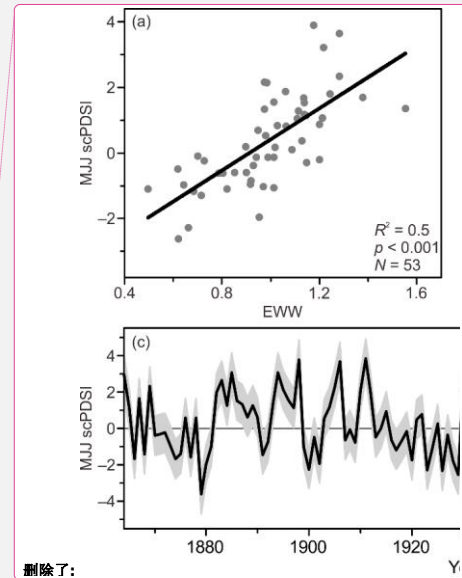
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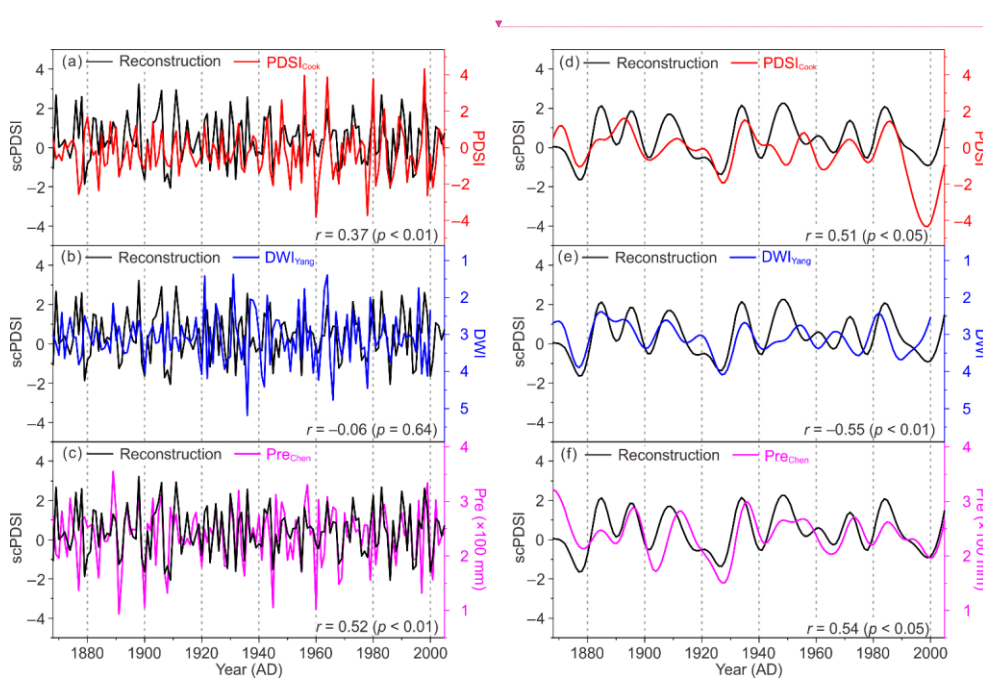
**Figure 7.** Comparison of the reconstructed MJJ scPDSI (black line) with other hydroclimatic reconstructions in adjacent regions on the interannual (left panels), and decadal and longer timescales (right panels). The referenced reconstructions are **(a**, **d)** June–August PDSI of MADA NO. 370 point (Cook et al., 2010), **(b, e)** reversed DWI (Yang et al., 2013), and **(c, f)** TRW based April–June precipitation (Pre) reconstruction (Chen et al., 2016b). The interannual and decadal and longer fluctuations were separated using the adaptive 10 point "Butterworth" low-pass filter with 0.1 cutoff frequency (Mann, 2008). *r* represents the Pearson correlation coefficient between the reconstructed MJJ scPDSI and other hydroclimatic reconstruction over their common period. The significance level for all correlation coefficients were tested using the Monte Carlo method (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012).

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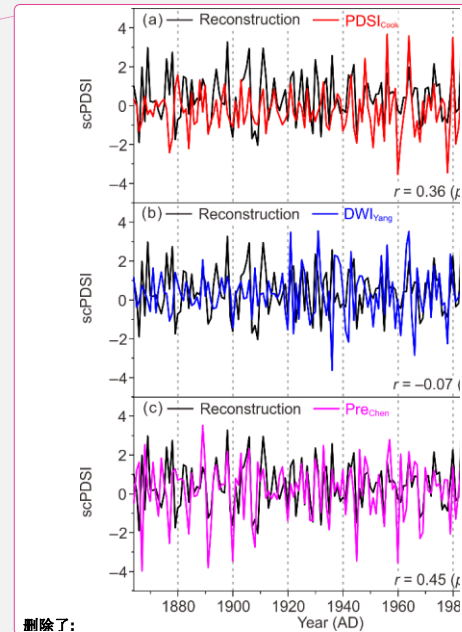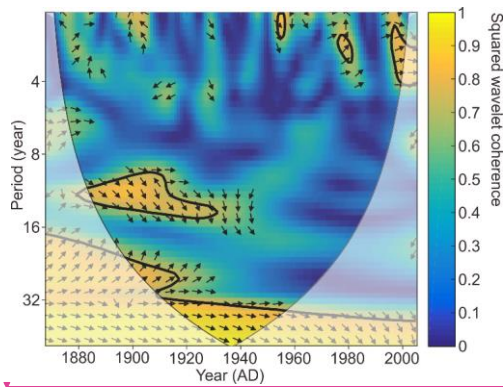
**Figure 8.** Squared wavelet coherence and phase relationship between the reconstructed MJJ scPDSI and EASMI (Zhao et al., 2015). The color bar indicates the squared wavelet coherence. The arrows indicate the phase relationship with in-phase (anti-phase) pointing right (left), and EASM leading (lagging) scPDSI with 90° pointing straight up (down). The thick contour indicates the 5 % significance level against red noise. The cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.

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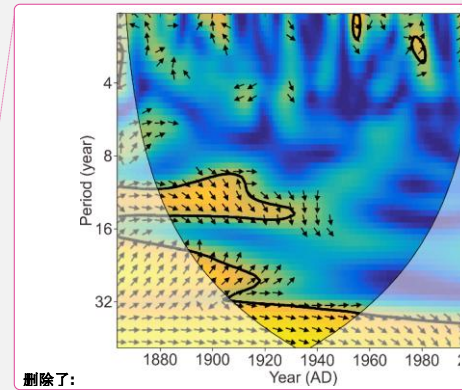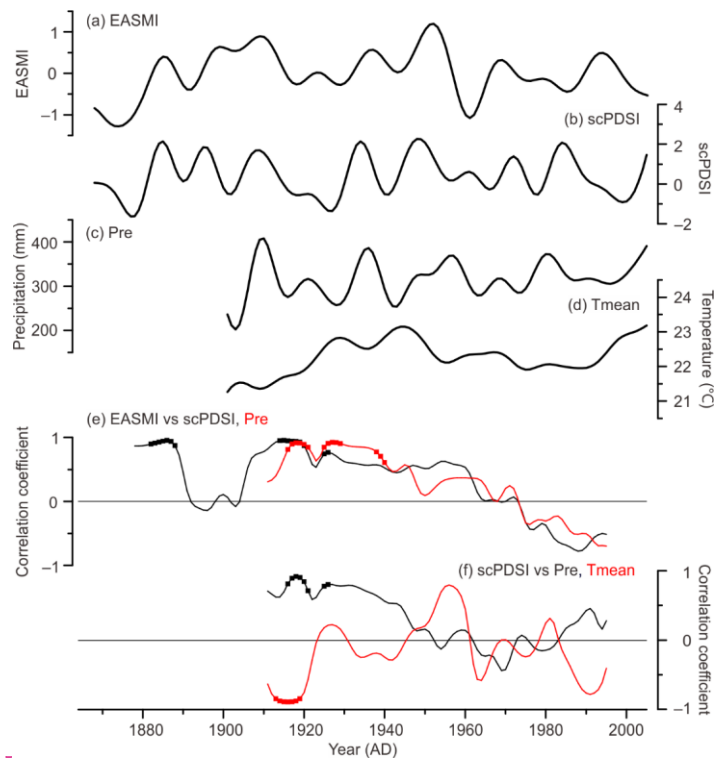
**Figure 9.** Comparison between the decadal and longer fluctuations of May–July **(a)** EASMI (Zhao et al., 2017), **(b)** reconstructed scPDSI, **(c)** precipitation (Pre; GPCC v7; Schneider et al., 2015), and **(d)** mean temperature (Tmean; CRU TS 4.01; Harris et al., 2014) over the reconstructed area. **(e)** 21-year moving Pearson correlation coefficients of the decadal-filtered EASMI with scPDSI (black), and Pre (red). **(f)** 21-year moving Pearson correlations of the decadal filtered scPDSI with Pre (black), and Tmean (red). The decadal and longer fluctuations were derived using the adaptive 10 point "Butterworth" low-pass filter with 0.1 cutoff frequency (Mann, 2008). Statistically significant ($p < 0.05$) correlations are denoted as squares, which were tested using the Monte Carlo method (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012).

**Figure 10. (a–b)** The leading empirical orthogonal function (EOF) modes of decadal filtered May–July GPCC Precipitation anomalies for the periods 1901–1978 (left panel) and 1979–2005 (right panel). The color bar indicated the EOF values. **(c–d)** Spatial correlations between the decadal filtered May–July EASMI defined by Zhao et al. (2015) and Precipitation (Pre) for the periods 1901–1978 (left panel) and 1979–2005 (right panel). The color bar indicates the correlation coefficient. The dot indicates that the correlation is statistically significant ($p < 0.1$) which was tested using the Monte Carlo method (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012). The decadal and longer fluctuations of precipitation were derived using the adaptive 10 point "Butterworth" low-pass filter with 0.1 cutoff frequency (Mann, 2008). The tree symbol denotes the study region.

## Supplement

**Table S1.** Correlation coefficients between the tree–ring width chronologies from the two study sites, Baiyunshan and Longchiman, over their common period 1850–2005.

| Chronologies | Detrending method | | |
|---|---|---|---|
| | NELR | SP67 | SPA50 |
| EWW STD | 0.63 / 0.59 | 0.64 / 0.60 | 0.62 / 0.57 |
| LWW STD | 0.40 / 0.51 | 0.46 / 0.49 | 0.46 / 0.47 |
| TRW STD | 0.58 / 0.58 | 0.60 / 0.62 | 0.61 / 0.63 |
| EWW SSF | 0.64 / 0.60 | 0.57 / 0.53 | 0.55 / 0.49 |
| LWW SSF | 0.43 / 0.54 | 0.37 / 0.51 | 0.35 / 0.47 |
| TRW SSF | 0.57 / 0.57 | 0.50 / 0.54 | 0.50 / 0.54 |

Note: The correlation coefficients before (after) the slashes are for the original (prewhitened and linearly detrended) STD and SSF chronologies. All correlation coefficients are statistically significant at the 0.001 level based on Monte Carlo test (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012).

**Table S2.** Descriptive statitics of the composite STD and SSF tree–ring width chronologies when EPS ≥ 0.85.

| Detrending method | Chronology | Starting year when EPS ≥ 0.85 | Standard deviation | Mean sensitivity | First-order autocorrelation |
|---|---|---|---|---|---|
| NELR | EWW STD | 1868 | 0.238 | 0.225 | 0.348 |
|  | LWW STD | 1877 | 0.25 | 0.221 | 0.421 |
|  | TRW STD | 1871 | 0.221 | 0.200 | 0.458 |
| SP67 | EWW STD | 1871 | 0.235 | 0.222 | 0.354 |
|  | LWW STD | 1877 | 0.247 | 0.227 | 0.38 |
|  | TRW STD | 1871 | 0.218 | 0.200 | 0.439 |
| SPA50 | EWW STD | 1867 | 0.234 | 0.223 | 0.328 |
|  | LWW STD | 1875 | 0.245 | 0.225 | 0.384 |
|  | TRW STD | 1866 | 0.215 | 0.200 | 0.42 |
| NELR | EWW SSF | 1868 | 0.245 | 0.226 | 0.382 |
|  | LWW SSF | 1875 | 0.263 | 0.221 | 0.451 |
|  | TRW SSF | 1868 | 0.227 | 0.200 | 0.479 |
| SP67 | EWW SSF | 1868 | 0.245 | 0.225 | 0.397 |
|  | LWW SSF | 1875 | 0.255 | 0.226 | 0.404 |
|  | TRW SSF | 1871 | 0.227 | 0.201 | 0.48 |
| SPA50 | EWW SSF | 1867 | 0.234 | 0.207 | 0.418 |
|  | LWW SSF | 1875 | 0.246 | 0.214 | 0.426 |
|  | TRW SSF | 1866 | 0.214 | 0.191 | 0.459 |

Note: All statistics were calculated using the R package "dplR" version 1.6.9 (Bunn et al., 2018).

**Table S3.** Statitics of the detrended ring-width series over their common period 1915–2005.

| Detrending method | Chronology | $Var_{pc1}$ | $Rbar_{eff}$ | SNR | EPS |
|---|---|---|---|---|---|
| NELR | EWW STD | 0.386 | 0.443 | 25.878 | 0.963 |
| | LWW STD | 0.328 | 0.358 | 18.175 | 0.948 |
| | TRW STD | 0.384 | 0.433 | 24.806 | 0.961 |
| SP67 | EWW STD | 0.427 | 0.492 | 31.452 | 0.969 |
| | LWW STD | 0.353 | 0.400 | 21.702 | 0.956 |
| | TRW STD | 0.422 | 0.481 | 30.104 | 0.96 |
| SPA50 | EWW STD | 0.411 | 0.471 | 29.007 | 0.967 |
| | LWW STD | 0.341 | 0.384 | 20.315 | 0.953 |
| | TRW STD | 0.404 | 0.459 | 27.607 | 0.965 |
| NELR | EWW SSF | 0.399 | 0.456 | 27.291 | 0.965 |
| | LWW SSF | 0.317 | 0.346 | 17.252 | 0.945 |
| | TRW SSF | 0.393 | 0.439 | 25.492 | 0.962 |
| SP67 | EWW SSF | 0.453 | 0.520 | 35.298 | 0.972 |
| | LWW SSF | 0.366 | 0.417 | 23.308 | 0.959 |
| | TRW SSF | 0.441 | 0.504 | 33.033 | 0.971 |
| SPA50 | EWW SSF | 0.474 | 0.539 | 37.994 | 0.974 |
| | LWW SSF | 0.352 | 0.399 | 21.627 | 0.956 |
| | TRW SSF | 0.431 | 0.491 | 31.354 | 0.969 |

Note: The common period for the tree–ring width dataset was calculated with the "common.interval" function in R package "dplR" version 1.6.9 (Bunn et al., 2018) based on a trade–off between the maximum number of series and years. The statistics, $Var_{pc1}$, $Rbar_{eff}$, SNR, and EPS represent the variance explained by the first eigenvector, effective chronology signal, signal–to–noise ratio, and expressed population signal, respectively. The $Var_{pc1}$ was calculated using the Program ARSTAN40c (Cook and Krusic, 2006), and the other statistics were calculated using the R package "dplR" version 1.6.9 (Bunn et al., 2018).

**Table S4.** The meterological stations utilized by CRU dataset (http://www.cru.uea.ac.uk/data) located

in the area between latitudes 32° N and 34.5° N, and longitudes 111° E and 112° E.

| Meteorological station | Longitude (°E) | Latitude (°N) | Climatic factor | Temporal cover |
|---|---|---|---|---|
| Lushi | 111.03 | 34.05 | Precipitation | 1952.07–2013.12 |
| | | | Temperature | 1952.07–2016.12 |
| Laohekou | 111.73 | 32.43 | Precipitation | 1933.02–1933.11; 1934.01–1935.06; 1935.08–1935.12; 1936.08–1938.07; 1950.06–2005.06; 2005.08–2013.12 |
| | | | Temperature | 1951.01–2016.12 |
| Yunxian | 111.8 | 32.9 | Precipitation | 1933.03–1938.05; 1938.07–1947.10; 1950.03–1990.12; 1991.05; 1991.07–1991.08 |

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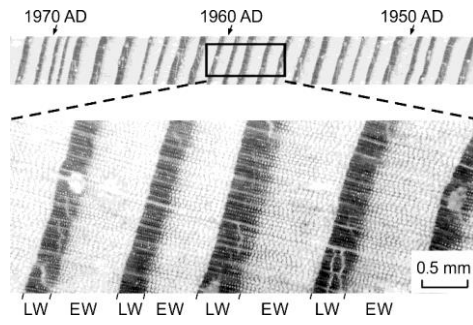
**Figure S1.** Scanned photograph of a section of *P. tabulaeformis* tree–ring sample (LCM0118A). The distinct earlywood (EW) and latewood (LW) segments can be identified by inspection under a microscope.
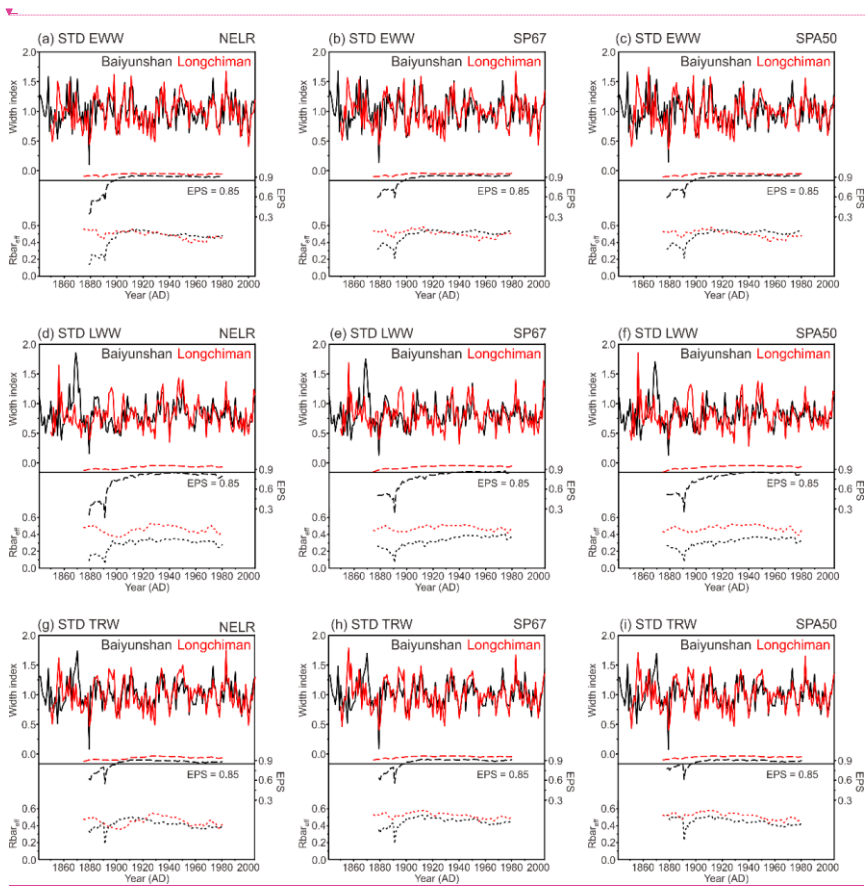
**Figure S2.** Standard tree-ring width chronologies (solid curve) generatued using three kinds of detrending methods for **(a–c)** earlywood width (EWW), **(d–f)** latewood width (LWW), and **(g–i)** total tree–ring width (TRW) at the two study sites, Baiyunshan (black) and Longchiman (red). The three kinds of detrending methods are: (1) negative exponential function together with linear regession with negative (or zero) slope (NELR), (2) cubic smoothed splines with a 50 % frequency cutoff of 67 % of the series length (SP67), and (3) age-dependent splines with an initial stiffness of 50 years (SPA50). The dashed and dotted curves denote the running expressed population signal (EPS) and effective chronology signal (Rbar_eff), respectively. The horizontal line indicates the threshold EPS value of 0.85. The running EPS and Rbar_eff values were calculated over a 51–year window.
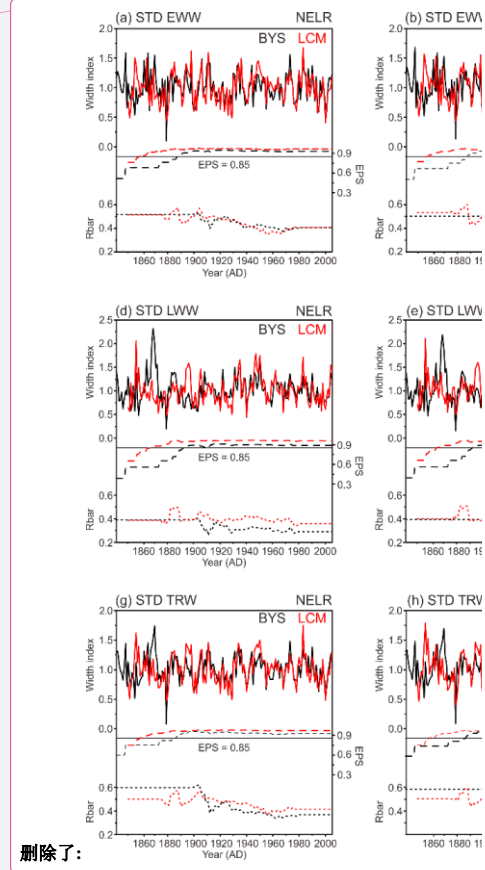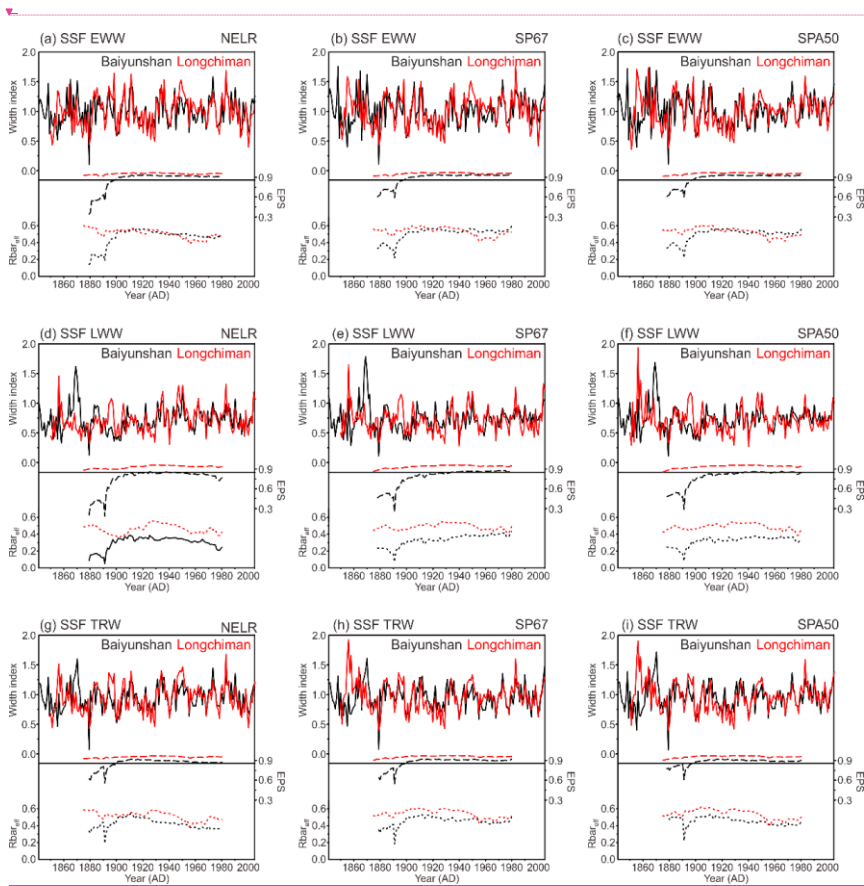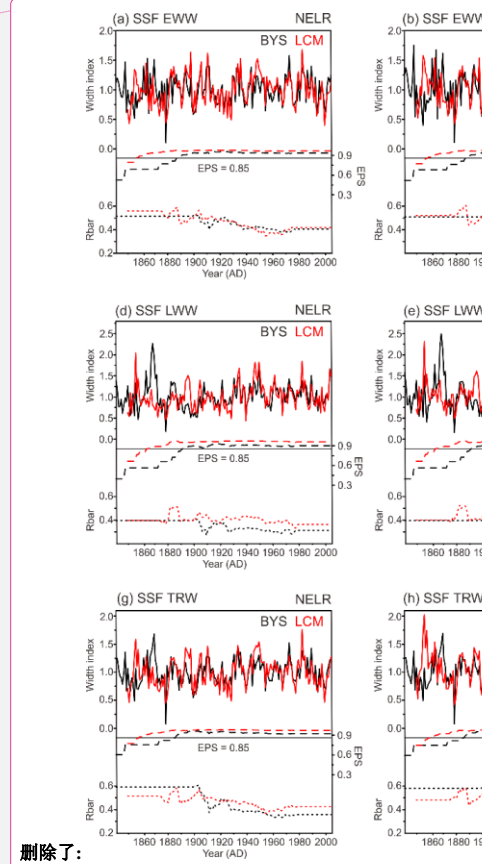
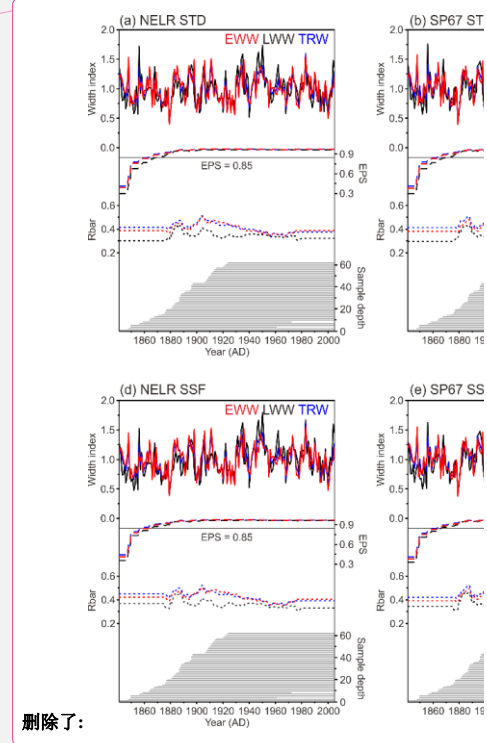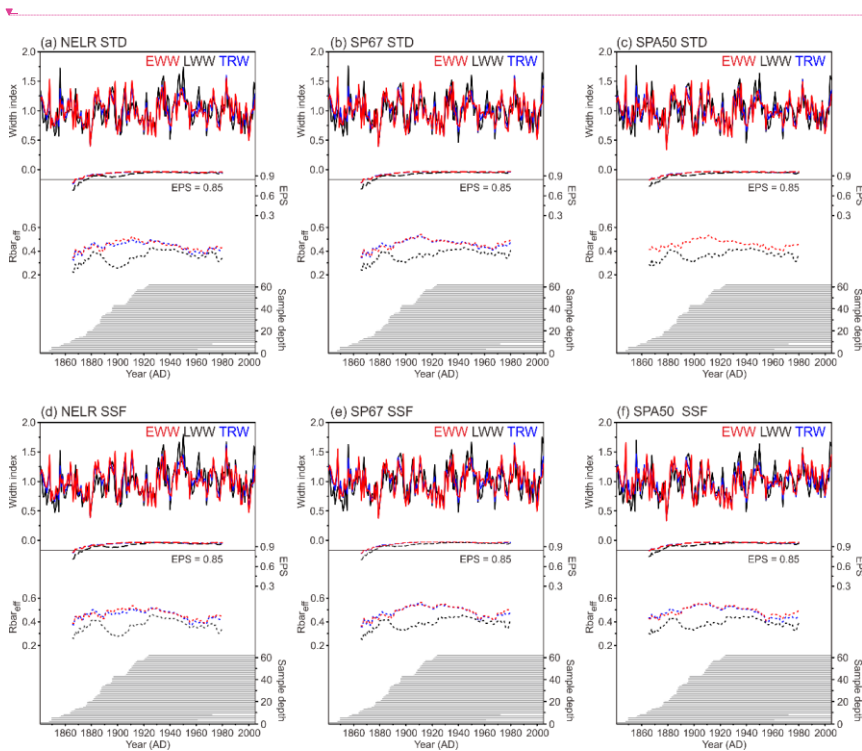删除了：
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**Figure S3.** The same as Figure S2, but for the signal-free (SSF) chronologies.

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**Figure S4.** Composite **(a–c)** STD and **(d–f)** SSF tree-ring width chronologies for EWW (red), LWW (black), and TRW (blue) generated using the merged tree–ring samples from the two study sites, Baiyunshan and Longchiman, based on three kinds of detrending methods. The detrending methods are: (1) negative exponential function together with linear regression with negative (or zero) slope (NELR), (2) cubic smoothed splines with a 50 % frequency cutoff of 67 % of the series length (SP67), and (3) age-dependent splines with an initial stiffness of 50 years (SPA50). The dashed and dotted curves denote the running expressed population signal (EPS) and effective chronology signal ($Rbar_{eff}$), respectively. The horizontal line indicates the threshold EPS value of 0.85. The running EPS and $Rbar_{eff}$ values were calculated over a 51–year window. The segement plot indicated the sample depth (core).
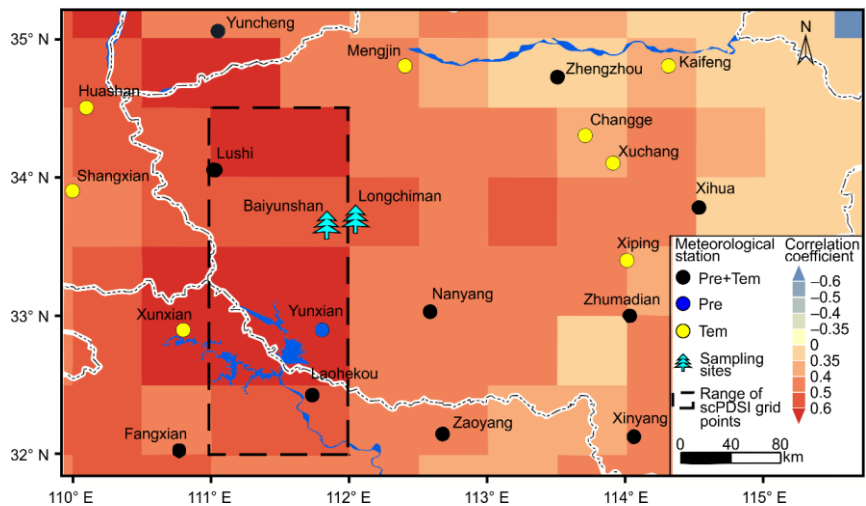
**Figure S5.** Spatial distribution of the meteorological stations included in the CRU dataset (http://www.cru.uea.ac.uk/data) around the tree-ring sampling sites, Baiyunshan and Longchiman. Black cycles represent the meteorological stations that provide both precipitation and temperature data. While, blue (yellow) cycles represent those that only provide precipitation (temperature) data. The dashed rectangle indicates the range of scPDSI grid points used for calibration in this study. The color patches denote the spatial correlation coefficients between May-July scPDSI and NELR based EWW STD chronology.

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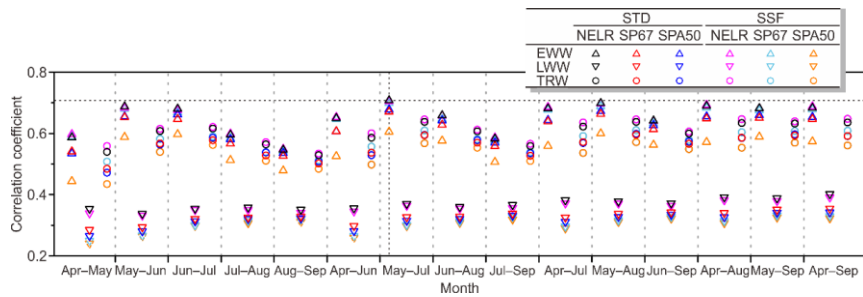
**Figure S6.** Correlation coefficients between the tree-ring width chronologies and multi-month averaged scPDSI (April to September of the current year). The up triangle, down triangle, and circle indicate the chronologies of EWW, LWW, and TRW, respectively. The color black, red and blue indicate the STD chronologies generated using the detrending methods NELR, SP67, and SPA50, respectively. The color magenta, cyan, and orange indicate the SSF chronologies generated using the detrending methods NELR, SP67, and SPA50, respectively. The dashed symbol indicates that the correlation does not reach the 0.05 significance level, which were tested using the Monte Carlo method (Efron and Tibshirani, 1986; Macias-Fauria et al., 2012).
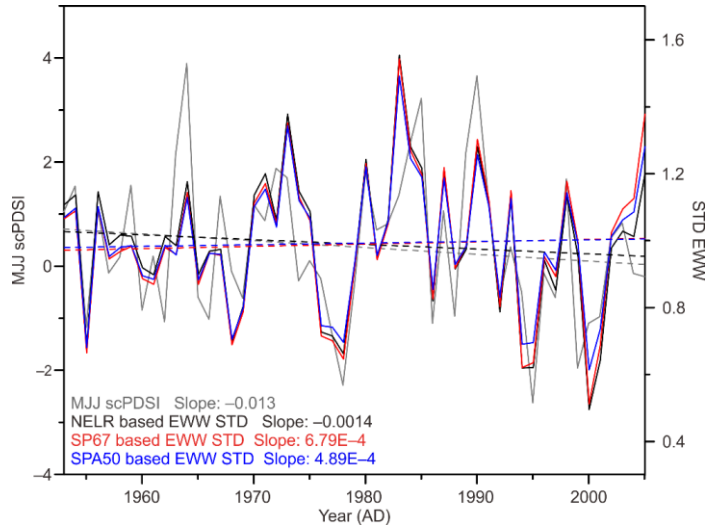
**Figure S7.** Comparisons between the MJJ scPDSI (gray) and EWW STD chronologies generated using the detrending methods NELR (black), SP67 (red), and SPA50 (blue) during the period 1953–2005. The corresponding linear trends are indicated by the dashed lines, and the slope statistics are labelled in the bottom left corner of the figure.

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