

Summer hydroclimate variations in Northeast China during the period of 1568–2021

Yucheng LIU^{1,2}, Wenling AN^{1*}, Zhipeng WU³, Chenxi XU^{1,2*} & Zhengtang GUO^{1,2}

¹State Key Laboratory of Lithospheric and Environmental Coevolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

²College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

³Earth and Climate Research Center, Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve 1348, Belgium

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Abstract The causes of recent dry-wet changes in the East Asian summer monsoon (EASM) area remain unclear, and attribution analysis to anthropogenic influences is hindered by the lack of long-term hydroclimate record. In this study, we build up a tree ring oxygen isotope chronology in Northeast China, which is the longest to date (1568–2021), and use it to reconstruct summer relative humidity (RH) variations in the northern edge of the EASM region. The reconstruction reveals that Northeast Asia experienced dry conditions during the Little Ice Age (LIA), followed by wet conditions in the Current Warm Period (CWP). On the centennial timescale, the warming caused by the increased greenhouse gases since the Industrial Revolution appears to have strengthened the EASM and facilitated a more humid Northeast Asia. Recent drought events in Northeast Asia since the 1950s are not unprecedented compared with those during the LIA. Recent drought is likely influenced by the positive phase of the Pacific Decadal Oscillation (PDO), the negative phase of the Atlantic Multidecadal Variability (AMV), and anthropogenic aerosol emissions. These findings suggest that recent hydroclimate variations likely reflect a complex interplay between natural forcing mechanisms and competing anthropogenic influences, with warming-induced EASM strengthening potentially moderating what would otherwise be more severe drought conditions.

Keywords East Asian summer monsoon, Tree-ring oxygen isotopes, Northeast Asia, Summer relative humidity, Recent drought

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1. Introduction

The East Asian summer monsoon (EASM) is one of the most dynamic and significant circulation systems in Asia, transporting a large amount of water vapor to East Asian (Song et al., 2014; Zhang, 2015). In the context of global warming, hydroclimate changes in the East Asian monsoon region are related not only to changes in EASM precipitation (Wilcox et al., 2015; Lee et al., 2017), but also to changes in temperature

(Duan et al., 2022; Guo et al., 2025). Distinguishing the hydroclimate changes under different temperature backgrounds in the EASM region is critical for future climate projections.

Northeast Asia is located on the northern edge of the EASM, and thus regional hydroclimate changes are sensitive to monsoon strength (Tang et al., 2006; Zhu et al., 2018). Previous studies have documented a significant aridification trend in this region over the past six decades, predominantly attributed to enhanced evapotranspiration under global warming (Guo et al., 2025). However, some studies found that Northeast Asia is experiencing a wetting trend from

* Corresponding authors: Chenxi XU (cxxu@mail.iggcas.ac.cn), Wenling AN (wlan@mail.iggcas.ac.cn)

1961 to 2020, especially from 1999 to 2020, due to increased EASM-related precipitation (Wang et al., 2024; Jiang et al., 2024). Earth System Model projections consistently indicate a progressive wetting trend under future warming scenarios due to increased precipitation (Chen et al., 2022; Wang et al., 2022; Katzenberger and Levermann, 2024). These apparent discrepancies likely stem from multiple factors, including observational dataset selection, temporal coverage limitations, and inherent uncertainties in climate model parameterizations, collectively constraining our understanding of regional hydroclimate dynamics.

Paleoclimatic reconstructions demonstrate that the Current Warm Period (CWP, 1850–present) represents an unprecedented thermal anomaly within the Common Era, exceeding historical temperature variability documented in both hemispheric (Mann et al., 2008) and global-scale (Neukom et al., 2019) reconstructions. In association with the global temperature change, EASM precipitation has changed significantly, as evidenced through multi-proxy analyses spanning decadal to centennial timescales (Paulsen et al., 2003; Zhang et al., 2008; Xu et al., 2023). The Little Ice Age (LIA) is the cold period in the last millennium (Neukom et al., 2019). Therefore, high-resolution hydroclimate reconstructions covering the LIA and CWP provide the opportunity for systematic evaluation of hydroclimatic responses under different background states. The long-term history of hydroclimate variability provides a foundational baseline for assessing whether contemporary climate variability remains within the thresholds of natural fluctuations. Comparative studies of hydroclimate under varying thermal regimes are critical for advancing our understanding of East Asian monsoon variability and its governing mechanisms (Chen et al., 2014; Duan et al., 2022).

Tree ring oxygen isotope ($\delta^{18}\text{O}$) in monsoonal Asia is a promising proxy to reconstruct historical hydroclimate variations (Xu et al., 2024). Long-term tree ring $\delta^{18}\text{O}$ -based hydroclimatic reconstructions have improved our understanding of the EASM (Nakatsuka et al., 2020; Yang et al., 2021; Xu et al., 2023; Zhao et al., 2024; Qin et al., 2024). However, existing investigations mainly focused on western China and the South Asian monsoon domain, while the Northeast China region, situated within the East Asian monsoon marginal zone, remains broadly understudied. Previous studies reconstructed summer relative humidity in Northeast China since 1752, which covered a limited hydroclimate in the LIA (Liu et al., 2022). The tree-ring $\delta^{18}\text{O}$ sequences obtained from the LIA play an irreplaceable role in identifying the contributions of natural and anthropogenic factors to modern hydroclimate anomalies. Therefore, we developed a regional tree ring $\delta^{18}\text{O}$ record covering the LIA and the CWP, which enables us to reconstruct changes in RH in Northeast Asia. This reconstruction allows us to place recent droughts within the long-term context of pre-in-

dustrial variability and to evaluate the influence of natural and anthropogenic influences on the EASM.

This study aims to understand the summer hydroclimate variations in Northeast China. First, we establish a 454-year tree ring $\delta^{18}\text{O}$ series which is significantly correlated with summer (June–September) relative humidity. Then, we reconstruct the summer relative humidity in Northeast China. Finally, we discuss the characteristics of hydroclimate variability in Northeast China and the possible mechanisms.

2. Materials and methods

2.1 Study area and climate data

Tree ring samples were collected from the Laobai Mountain (44°06'N, 128°03'E) in Jilin Province, Northeast China (Figure 1a, 1b). According to meteorological records from nearby Jilin station (43°57'N, 126°28'E, 183.4 m a.s.l., 1951–2019 AD), the mean annual temperature in this region is 4.9°C, and the annual precipitation is 551 mm, approximately 89% of the annual precipitation (492.4 mm) occurs during the months of June–September. During this period, the mean temperature and relative humidity (RH) are 19.9°C and 75.3%, respectively (Figure 1c). The sampling site is dominated by coniferous species, including *Pinus koraiensis*, *Picea jezoensis*, and *Abies nephrolepis*; alongside broadleaf trees such as *Juglans mandshurica*, *Fraxinus mandshurica*, and *Acer mono* (Bu et al., 2003). The local soil composition primarily comprises dark brown soil, brown coniferous forest soil, podzolic soil typical of mountain grasslands, and swamp soil. The hydroclimate of this region in summer is mainly influenced by the EASM. The differences in sea-land heating directly affect the intensity of the East Asian monsoon, which influences humidity variations in this region (Han et al., 2015).

2.2 Tree-ring sampling and oxygen isotope measurements

To obtain a longer tree-ring oxygen isotope chronology, here we supplemented the work of Liu et al. (2022) by collecting older tree-ring samples from Laobai Mountain, specifically from Korean pines. A total of 43 trees (85 cores) were sampled and dated using standard dendrochronological methods (Stokes and Smiley, 1996). Four cores (LBS08b, LBS25b, LBS27c, and LBS301a) with clear ring boundaries and no false or missing rings were selected for subsequent isotope analysis.

A modified plate method was used to extract α -cellulose, as described by Xu et al. (2011, 2013). A sodium chlorite (NaClO_2) acidified solution was added to remove lignin; a 17 wt.% sodium hydroxide (NaOH) solution was added to remove hemicellulose; and a combination of organic solvents,

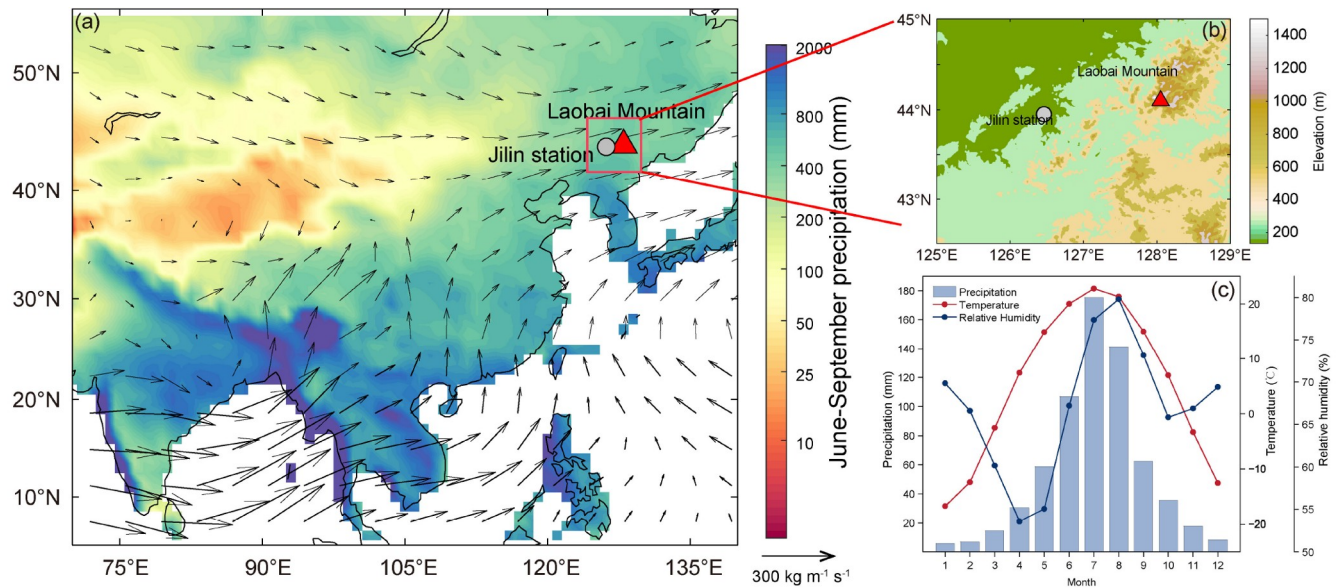


Figure 1 (a) Location of Laobai Mountain (red triangle) and Jilin meteorological station (gray circle). The contours indicate the average summer (June–September) precipitation during 1948–2019 from the Global Precipitation Climatology Center (Becker et al., 2013). Arrows depict the summer average of the transport direction of the vertically integrated water vapor flux ($\text{kg m}^{-1} \text{s}^{-1}$) from 1948 to 2019 based on NCEP/NCAR reanalysis datasets (Kalnay et al., 1996). (b) The geographical information for the sampling site and the meteorological station. (c) The multi-year mean monthly meteorological variables from the Jilin station.

including acetone, toluene, and ethanol, was employed to remove lipids. Oxygen isotope ratios ($\delta^{18}\text{O}$) of the cellulose derived from the tree-ring cores were measured using an isotope ratio mass spectrometer (Delta V Advantage, Thermo Scientific, Germany), interfaced with a pyrolysis-type high-temperature-conversion elemental analyzer (Flash HT, Thermo Scientific, Germany), at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. The $\delta^{18}\text{O}$ values are reported as per mil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) standard: $\delta^{18}\text{O} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000$, where R_{sample} and R_{standard} represent the $^{18}\text{O}/^{16}\text{O}$ isotope ratios for the sample and the standard, respectively. The $\delta^{18}\text{O}$ values of cellulose were determined by comparison against an in-house working standard (Merck cellulose) that was analyzed following each batch of eight samples. The analytical uncertainty, estimated from repeat measurements of the Merck cellulose standard, is estimated to be $\pm 0.20\text{‰}$.

2.3 Data analysis

The relationship between tree ring $\delta^{18}\text{O}$ and climatic parameters from Jilin meteorological station (1951–2019) was analyzed by Pearson correlation. A transfer function was established between RH and the tree-ring $\delta^{18}\text{O}$ series based on a linear regression model, taking two sub-periods (1951–1983, 1984–2015) as the calibration and verification periods to verify the reconstruction function. Pearson's correlation coefficient (r), explained variance (R^2), reduction of error (RE), and the coefficient of efficiency (CE) were used to

evaluate the model. A positive RE (CE) indicates a valid regression model, and higher RE and CE values reflect a more robust regression model (Cook et al., 1999). The mean inter-series correlation (Rbar) and expressed population signal (EPS) were used to test the reliability of the composite series. Rbar represents the average correlation between individual $\delta^{18}\text{O}$ time series, and the EPS was used to test the overall representativeness of the composite series (Wigley et al., 1984).

To verify the reliability of the reconstruction, the final hydroclimate reconstruction was compared with previous reconstructions in the vicinity of the study region, including dryness/wetness index (D/W index) (Yang et al., 2013) and the Palmer drought severity index (PDSI; Cook et al., 2010). A D/W index was employed for comparative analysis with the reconstructed summer RH. The closest gridded PDSI reconstruction from the monsoon Asia drought atlas (MADA) was also used (43.75°–46.25°N, 126.25°–128.75°E) for comparison (Cook et al., 2010). To investigate the influence of temperature on hydroclimate changes, we make comparisons between the reconstructed East Asian summer temperature over the past 600 years (Wang et al., 2023; <https://www.ncdc.noaa.gov/access/paleo-search/study/37057>) and the relative humidity reconstruction. To investigate the influence of internal climate variability, we employed wavelet coherence analysis (WCA) to examine the relationships between our reconstruction and Pacific Decadal Oscillation (PDO) (MacDonald and Case, 2005). The PDO is frequently characterized as a prolonged-El Niño-like mode of climate variability in the Pacific which strongly influences

the inter-decadal climate variability in the EASM region (Zhu and Yang, 2003; Grinsted et al., 2004).

To investigate the decadal-scale variability in the reconstructed summer relative humidity series, we applied a fast Fourier transform (FFT)-based low-pass filtering approach to the dataset. The FFT methodology facilitates the transformation of time-domain signals into their frequency-domain representation, enabling the suppression of high-frequency noise while preserving low-frequency components associated with decadal climatic oscillations (Torrence and Compo, 1998).

To decompose the low-frequency signals of historical hydrological changes, we employed the ensemble empirical mode decomposition (EEMD) method. EEMD is an adaptive noise-assisted signal processing method that effectively suppresses mode mixing by introducing multiple realizations of Gaussian white noise and ensemble averaging, thereby decomposing nonlinear and non-stationary signals into physically meaningful intrinsic mode functions (IMFs) with enhanced stability and interpretability (Wu and Huang, 2009).

To investigate the relationships between the interdecadal and multidecadal hydrological changes and we used the artificial skill method (ASM) to calculate correlation coefficients, termed critical values (CV), between the low-pass filtered series, characterized by strong auto-correlation due to the large reduction in the degree of freedom. The ASM for correlation significance (95% confidence level) addresses this issue and provides a more accurate estimation of the significance, as is also the case when the data are serially auto-correlated.

To investigate the factors driving regional hydroclimate changes, we employed multiple linear regression (MLR) to estimate the contributions of external forcings and the PDO, atlantic multidecadal variability (AMV; Wang et al., 2017) to past hydroclimate changes in this region. MLR has been widely used in detection and attribution studies (Wang et al., 2017; Chen et al., 2023). Prior to the application of MLR in the reconstructed data, all independent variables were smoothed using a 30-year FFT low-pass filter with the following equation:

$$RH = \beta_0 + \beta_1 PDO + \beta_2 AMV + \beta_3 RH_{Solar} + \beta_4 RH_{Volc} + \beta_5 RH_{GHG}, \quad (1)$$

where RH represents the summer RH from all predictors, and RH_i represents the RH from individual-forcing simulations. The predictor matrix incorporated: (1) internal climate variability—AMV and PDO; and (2) external forcings including total solar irradiance (TSI; Steinhilber et al., 2012), atmospheric CO₂ concentrations (Köhler et al., 2017), and global volcanic stratospheric sulfate injection (Gao et al., 2008). The explanatory variance (EV) of the relative contribution was calculated as follows:

$$EV_i = |\beta_i| \times \frac{R^2}{\sum_{i=1}^n |\beta_i|}. \quad (2)$$

3. Results

3.1 Characteristics of the tree-ring $\delta^{18}O$ series

The final tree ring $\delta^{18}O$ chronology, spanning 454 years (1568–2021 CE), exceeds all prior chronologies in temporal extent in Northeast China. The mean $\delta^{18}O$ values of the four trees, spanning the whole period (1568–2021), exhibited a mean value of 26.25‰, which aligns with the previously reported HS $\delta^{18}O$ series (Appendix Figure S1). The Pearson correlations between the selected four cores were significantly positive (Appendix Table S1), with $Rbar = 0.86$ and $EPS > 0.85$ throughout the entire period, demonstrating that the $\delta^{18}O$ series of the four cores record a common regional climate signal. To avoid artificially abrupt increases or decreases in $\delta^{18}O$ resulting from extreme values, we normalized all the individual $\delta^{18}O$ series to produce the regional tree-ring $\delta^{18}O$ series for subsequent analysis (Appendix Figure S1c). The new composite chronology is significantly correlated with the HS $\delta^{18}O$ series ($r = 0.76$, $p < 0.01$, $n = 159$; Liu et al., 2022) during their common period (1822–1860).

3.2 Climate response and summer hydroclimate reconstruction

The regional tree-ring $\delta^{18}O$ series is significantly and negatively correlated with the June–September precipitation ($r = -0.42$, $p < 0.01$) during the period of 1951–2019. The strongest correlation is found between tree-ring $\delta^{18}O$ and June–September RH ($r = -0.74$, $p < 0.001$), and the correlation between their first-order difference series is also significant ($r = -0.73$, $p < 0.001$). The strongest correlation between RH and tree-ring $\delta^{18}O$ values arises from leaf water and soil water isotopic enrichment processes. During stomatal transpiration, evaporative enrichment of $\delta^{18}O$ in leaf water occurs as water vapor diffuses across the leaf-atmosphere boundary layer, which is regulated by RH variations (Roden et al., 2000). Specifically, reduced atmospheric humidity intensifies stomatal water loss, amplifying the evaporative ^{18}O enrichment in leaf water. Concurrently, diminished RH enhances soil water $\delta^{18}O$ enrichment through increased surface evaporation. This isotopically heavier soil water signal is subsequently transported via root uptake into xylem water, and ultimately incorporated into cellulose through isotopic exchange during carbohydrate metabolism preceding cellulose synthesis (Roden et al., 2000; Gessler et al., 2014).

The spatial correlation analysis showed a strong negative correlation between regional tree-ring $\delta^{18}\text{O}$ and RH, precipitation, and SPEI, over Northeast China, Mongolia, the Democratic People's Republic of Korea, the northern parts of Japan, and the Republic of Korea (Figure 2a–2c and Appendix Figure S2). A similar spatial correlation pattern is evident between regional tree-ring $\delta^{18}\text{O}$ and temperature, but with a positive relationship (Figure 2b). These results indicate that our regional tree-ring $\delta^{18}\text{O}$ record can represent regional hydroclimate variations over Northeast Asia.

Based on the above results, we established a linear regression model between the relative humidity from June to September (hereinafter, summer RH) and tree ring $\delta^{18}\text{O}$. The relative humidity variations in summer in Northeast China over the past 454 years (1568–2021) were reconstructed using the transformation function (Figure 3a, 3b). The tree-ring $\delta^{18}\text{O}$ record explained 54% of the total variance of the June–September RH. The cross-validation test indicated that

the model is skillful in reconstructing the regional June–September RH (Table 1), indicating that the transfer function is reliable. Specifically, the reduction of error test (RE) and coefficient of efficiency (CE) values are high and positive. When using 1951–1985 as the calibration period (1986–2019 as the verification period), the RE is 0.686 and the CE is 0.514. The reversed configuration (calibration period: 1986–2019; verification period: 1951–1985) yielded a RE of 0.657 and a CE of 0.422.

3.3 Temporal variation of reconstructed summer RH

The mean reconstructed summer RH is 74.93% and the standard deviation (1σ) is 2.96% during the period of 1568–2021. Extreme wet and dry events are defined as RH values greater than the mean + 1σ (77.9%) and lower than the mean – 1σ (72.0%). During the LIA (~1568–1850), there were 59 extreme dry events and 25 extreme wet events. However, only 8 extreme dry events but 37 extreme wet events are

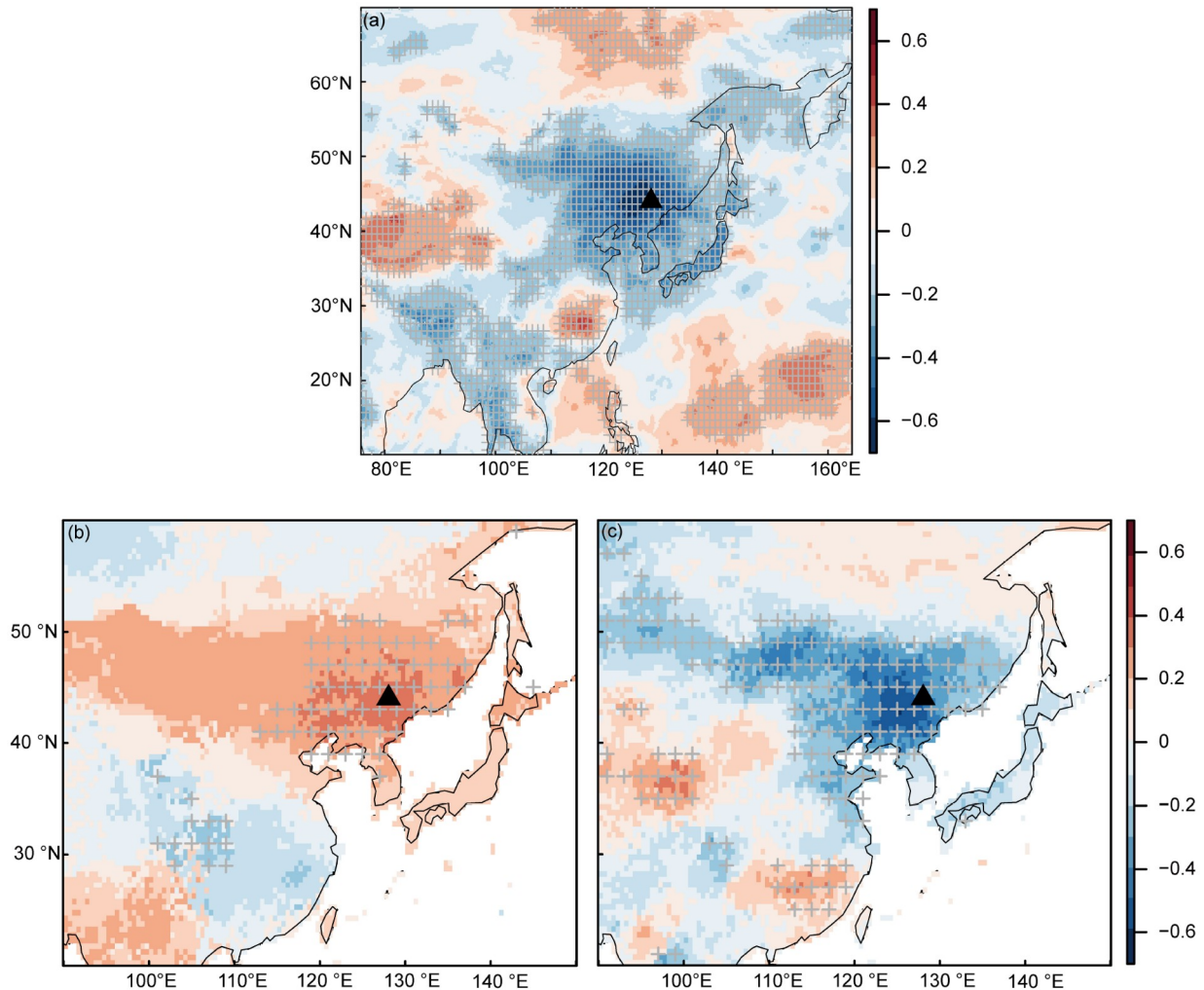


Figure 2 Spatial correlation between $\delta^{18}\text{O}$ values and June–September RH (a), temperature (b), and precipitation (c) during 1951–2019. Gray “+” symbols indicate that the correlation coefficients are significant at the 95% confidence level.

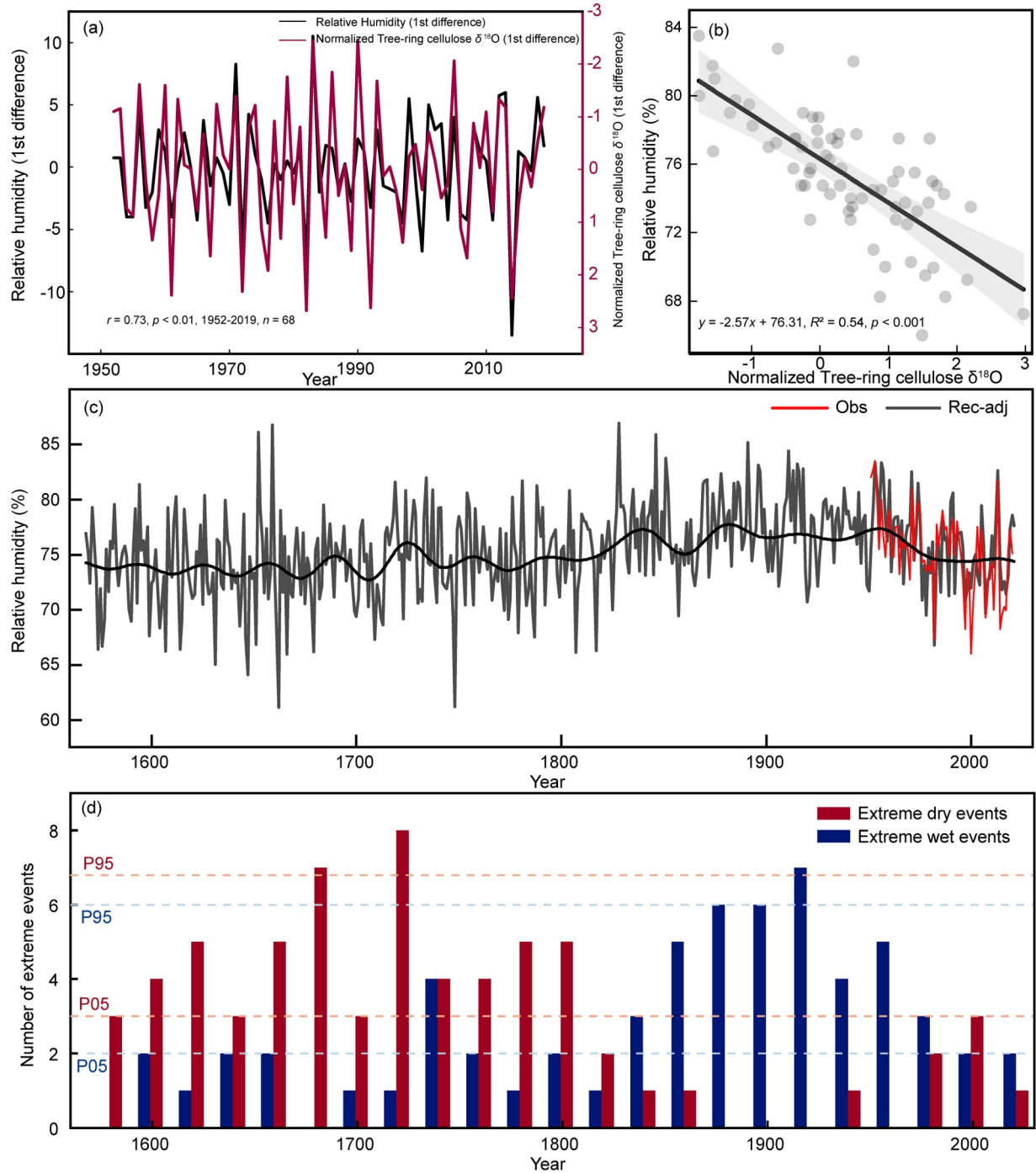


Figure 3 (a) First difference timeseries between $\delta^{18}\text{O}$ and summer RH. (b) The linear relationship between the standardized composite $\delta^{18}\text{O}$ chronology and summer RH (June–September). (c) Reconstructed summer RH in Northeast Asia (gray curve) and observed RH from the Jilin meteorological station (red curve). The dark black curve is the 30-year FFT low-pass filtering on reconstructed RH. (d) The number of extreme dry/wet events per 20 years, derived from our summer RH reconstruction. The yellow/blue short dashed lines indicate the 5% and 95% percentiles of the distribution.

found from 1850 to 2021 (Figure 3d). At low frequencies, our summer RH reconstruction reveals that Northeast Asia was dry during the LIA and wet during the CWP. It is also evident that the mild drought from the 1950s to the present day does not exceed the natural variability in the context of the past 454 years.

3.4 Comparison with other hydroclimate reconstructions

We compared our reconstruction with other moisture reconstructions for this region. Despite differences in proxy, climatic parameters, and the seasonality (e.g., June–Sep-

Table 1 Calibration and verification statistics for 1951–2019^{a)}

Calibration period	R^2	Verification period	r	RE	CE
Full (1951–2015)	0.542 ^{***}	–	–	–	–
Early Half (1951–1985)	0.493 ^{**}	Late Half (1986–2019)	0.744 ^{***}	0.686 ^{***}	0.514 ^{**}
Late Half (1986–2019)	0.553 ^{**}	Early Half (1951–1985)	0.702 ^{***}	0.657 ^{***}	0.422 ^{**}

a) **, $p < 0.01$; ***, $p < 0.001$.

tember in our reconstruction versus June–August in the MADA reconstruction), our RH reconstruction is significantly ($p < 0.01$) correlated with previous hydroclimate reconstructions at high and low frequencies (Appendix Figure S3). On the annual scale, our summer RH reconstruction is significantly correlated with the D/W index derived from historical documents ($r = -0.17$, $n = 432$, $p < 0.01$) and the gridded MADA PDSI data ($r = 0.15$, $n = 438$, $p < 0.01$). On the multidecadal timescale, our reconstruction also shows similar dry and wet changes as the D/W index and average MADA PDSI series. However, our reconstruction reveals greater variability at the centennial scale, with a dry LIA but a wet CWP. Furthermore, there has been a climate trend toward greater aridity since the 1950s.

3.5 Contributions of climate drivers to the reconstructed RH

We conducted MLR analyses to quantify the relative contributions of key climate drivers following established methodologies (Wang et al., 2017; Figure 4). These factors have been consistently identified in prior research as significant modulators of regional humidity variability. The multiple regression analysis employing 30-year low-pass filtering demonstrated a total explained variance of 31% for summer relative humidity variations in the region, with both internal and external forcings collectively contributing. Solar radiation was the primary external forcing, accounting for 9.00% of the explained variance, marginally exceeding CO₂'s contribution (8.90%). Internal forcings demonstrated similar impacts, with the PDO explaining 7.94% of variance and AMV contributing 4.64%. When 60-year low-pass filtering was used, the total explained variance increased to 39%, with TSI (12.5%) and PDO (12.2%) showing enhanced explanatory power, while CO₂ (7.25%) and AMV (6.60%) maintained significant contributions. Both models exhibited robust performance in capturing interdecadal humidity variability during the 1568–1996 period.

4. Discussion

4.1 Dry LIA and wet CWP in Northeast Asia

Our reconstruction indicates that Northeast Asia had an un-

stable and dry climate during the LIA, and a relatively stable and wet climate from the end of the LIA (c.a. the 1820s) to the 1950s (Appendix Figure S4), which was followed by a slightly drying trend until the present (Figure 5a). A dry LIA climate was also documented in nearby Inner Mongolia (Figure 5b; Xiao et al., 2008; Chu et al., 2009; Mao et al., 2021) and in the southern parts of the East Asian monsoon region (Hu et al., 2008; Li et al., 2011). The drought in LIA triggered a series of ecological and agricultural collapses, which exacerbated societal tensions and likely caused the rise of the Qing dynasty and the fall of the Ming dynasty in China (Ren et al., 2024; Chen et al., 2024; Yue et al., 2024). The post-1850s wetting trend is also evident in the records of several moisture-sensitive proxies from Northeast Asia (Zhang et al., 2008; Liu et al., 2011; Li et al., 2017; Mao et al., 2021).

Our results demonstrate that Northeast Asia was relatively dry during cold periods and comparatively wet during warm periods. This warm-wet/cold-dry climatic pattern has been reported on a longer timescale. For example, Northeast Asia experienced a wet MWP, which was the latest warm period (Mao et al., 2021; Lv et al., 2024). Geological records show that Northeast Asia was wet during the mid-Holocene, Quaternary interglacials, and the Miocene and Pliocene, which were characterized by increased precipitation (Ding et al., 1999, 2001, 2024). In contrast, Northeast Asia was dry during cold periods (e.g., Goldsmith et al., 2017; Ding et al., 2024). These findings indicate that the warm-wet/cold-dry climatic pattern of Northeast Asia was stable on decadal to geological timescales.

4.2 Possible external and internal forcings on summer RH in Northeast Asia

The long-term summer RH variations in Northeast Asia may have resulted from a weak EASM during the LIA and a strong EASM during the CWP. It has been suggested that the pressure gradient resulting from the thermal contrast between the Pacific Ocean and the Asian continent is the main driving factor for the variation of the EASM (Cheng et al., 2008). The decrease of solar irradiance during the LIA (Bard et al., 2000; Reimer et al., 2004) may directly or indirectly have led to a decrease in the thermal contrast between the East Asian continent and the North Pacific Ocean, resulting

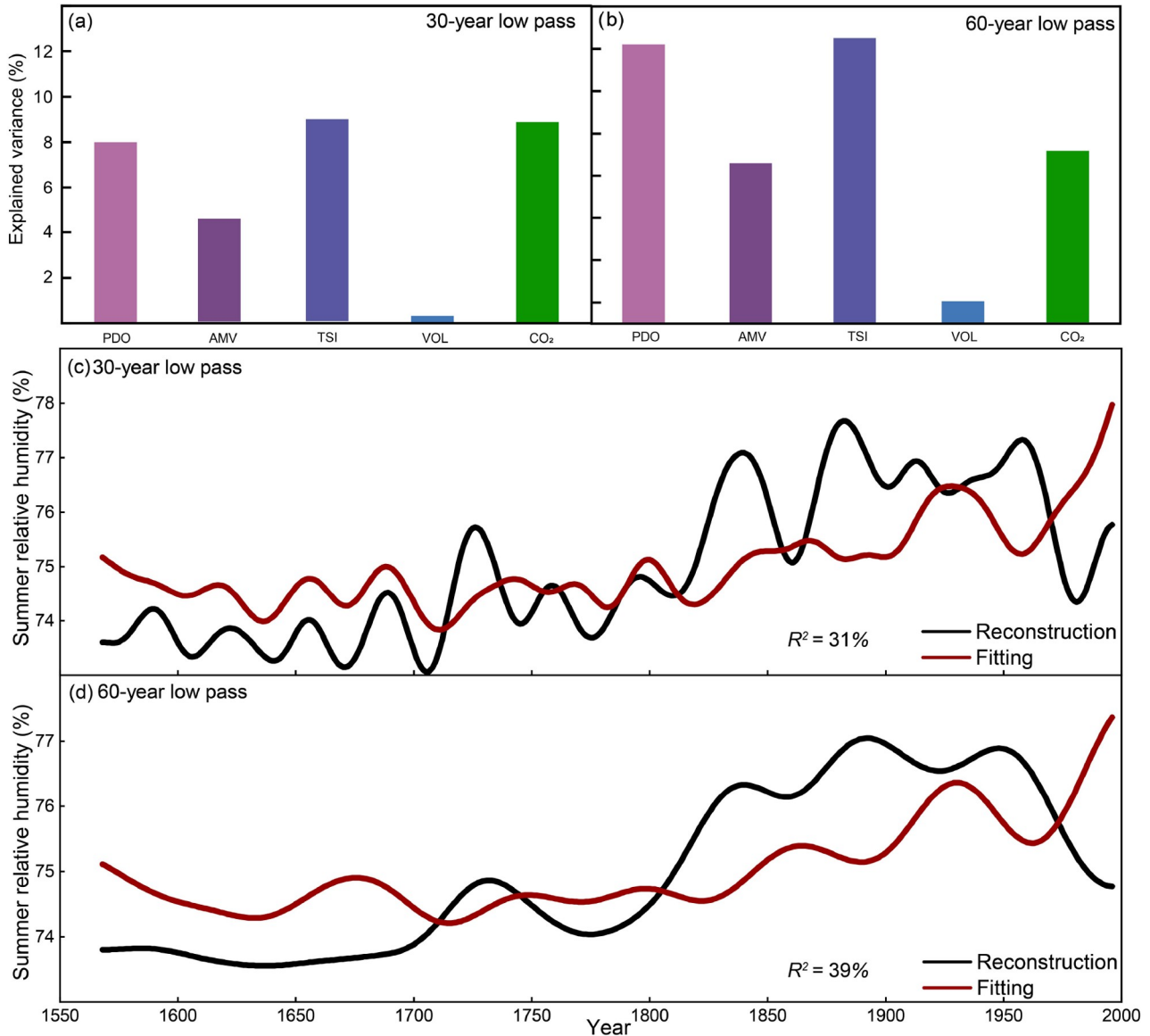


Figure 4 Explained variance (%) of summer relative humidity in the reconstruction for 30-year low pass (a) and 60-year low pass (b). Regional RH changes attributed to PDO, AMV and external forcing determined by multiple linear regression (MLR) from 1568 to 1996 in reconstruction for 30-year low pass (c) and 60-year low pass (d).

in reduced moisture transport from the adjacent North Pacific Ocean, which caused drier conditions in East Asia, including in Northeast China (Chen et al., 2019). Additionally, low solar irradiance likely promotes the southward movement of the East Asian westerly jet (Jiang et al., 2019), leading to drier conditions in northern and western Asia (Zhou et al., 2022). In contrast to the LIA, with the increase in solar radiation and greenhouse gas emissions during the CWP, the East Asian continent has been warming rapidly (Figure 5c; Wang et al., 2023), while the North Pacific Ocean has cooled since ~1875 (Gebbie and Huybers, 2019). This could have led to an increase in the thermal contrast between the East Asian continent and the North Pacific Ocean, and

thus facilitated moisture transport from the Ocean. This is consistent with EASM intensification during global temperature increases in the geological past, which led to a northward shift of the monsoonal rain belt and hence to more precipitation in northeast Asia (Yang et al., 2019). Several studies have predicted that with rising temperatures, the EASM will gradually strengthen and the rain belt will shift further northwards, causing increased precipitation in Northeast Asia (Zou et al., 2024; Chen et al., 2024).

The summer RH variations on decadal to multi-decadal timescales could be related to changes of the PDO, which play a crucial role in modulating the variation of the EASM on an interdecadal timescale (Zhu and Yang, 2003). We

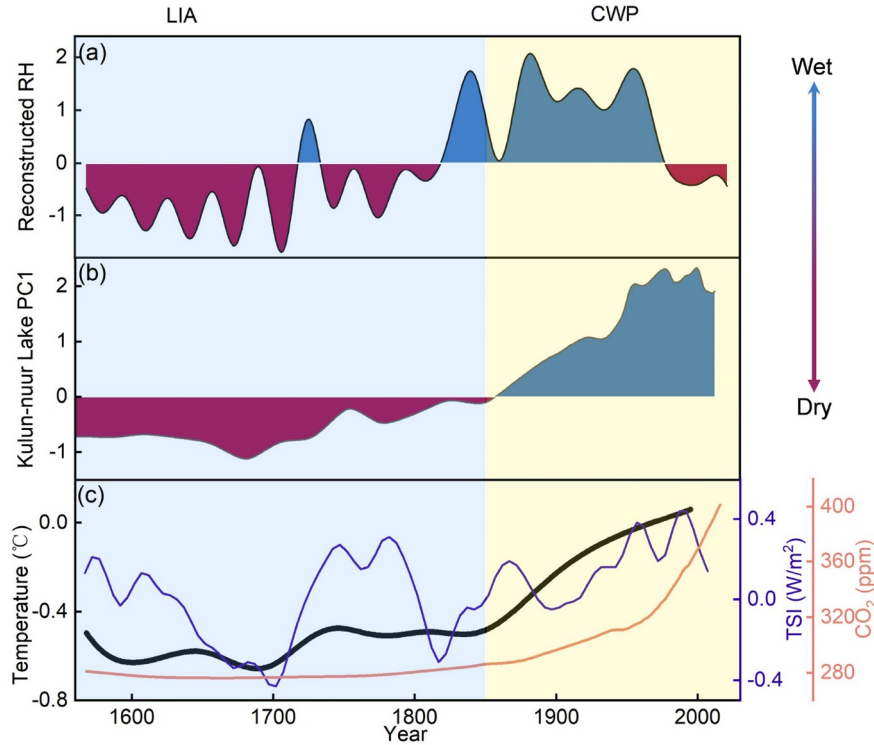


Figure 5 Comparison of reconstructed RH (a) with other proxy indices reflecting dry/wet changes after 30-year FFT low-pass filtering. (b) PC1 of grain size and total organic carbon (TOC) records from Kulun-nuur Lake, indicating moisture variations (Mao et al., 2021). (c) Reconstructed TSI (in blue, Steinhilber et al., 2012), East Asian temperature (in black, Wang et al., 2023), and atmospheric CO₂ (in orange, Köhler et al., 2017).

further used wavelet coherence analysis to examine the relationship between summer RH in Northeast Asia and the PDO. The squared wavelet coherence pattern between both time series reveals a significant correlation between summer RH in Northeast Asia and the PDO in the 40–80-year periodicity band; however, this relationship is non-stationary (Figure 6a, 6b). This summer RH-PDO relationship is supported by the significant negative correlations between both time series on a timescale > 30 years (Figure 6a, CV = −0.41, $p = 0.08$, Ndf = 19). The negative feedback of summer RH to the PDO involves a teleconnection mechanism. During the warm phase of the PDO, the equatorial region of the central East Pacific experiences anomalously high temperatures, while the mid-latitude North Pacific exhibits unusually low temperatures. The negative anomalies in sea-level pressure (SLP) over the North Pacific weakened significantly, while the entire East Asian continent showed pronounced positive SLP anomalies. This phenomenon likely results in the weakening of the EASM (Li et al., 2017; Duan et al., 2022; Hu et al., 2024), subsequently leading to decreased precipitation in Northeast Asia (Zhu and Yang, 2003).

4.3 Recent drought in northeast Asia is not unprecedented

Our reconstruction results reveal a drying trend from the

1950s to the 1990s, which is also recorded in the instrumental data. The result of the reconstruction does not support the notion that recent drought is exceptional within a 454-year context (Figure 7). Compared with the LIA, the drought in recent decades is not comparable in both frequency and intensity (Figure 3d). The drought during this period may have been caused by the weakening of the Northern Hemisphere monsoon. The North Pacific Ocean has undergone significant warming from the 1950s to the present day (Gebbie and Huybers, 2019), a change that may have weakened the land-ocean thermal contrast and consequently diminished the moisture transport associated with the EASM to Northeast Asia. North China and the Sahel also showed a drought trend in the same period (Zou et al., 2005; Epule et al., 2014; Lou et al., 2024). Previous studies have shown that variations in the intensity of the Northern Hemisphere land monsoon (NHLM) and the resulting shifts in water vapor transport significantly impact the precipitation in the Northern Hemisphere (Huang et al., 2019). In Northeast Asia, hydroclimate change may be influenced by PDO, AMV, and anthropogenic aerosol emissions. The positive (negative) phase of the PDO may have contributed to a weakening (intensifying) of the EASM intensity (Hao et al., 2020). The positive (negative) phase of the AMV may have contributed to an intensifying (weakening) of the EASM intensity (Chen et al., 2014). Moreover, the contribution

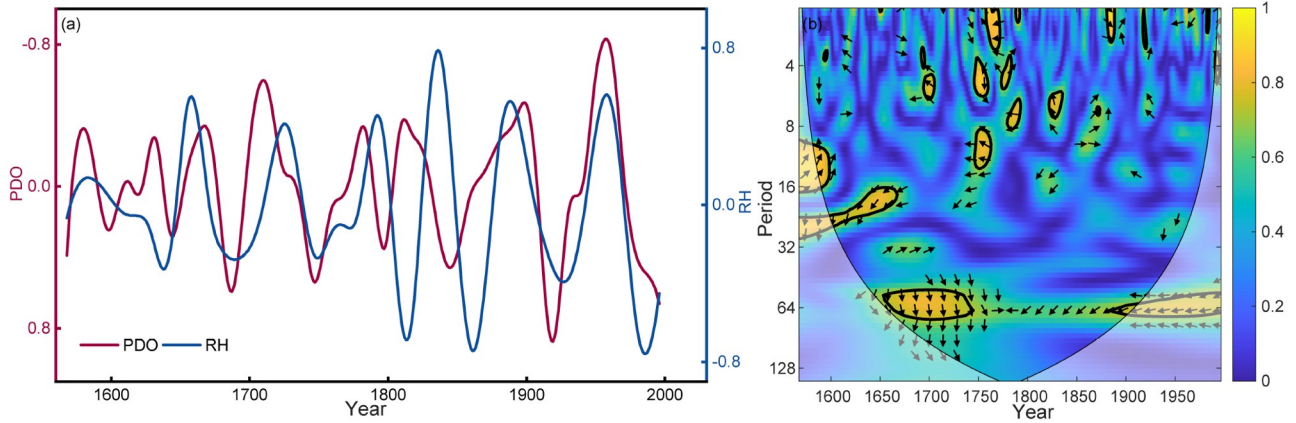


Figure 6 (a) Comparison of the reconstructed summer RH obtained via EEMD decomposition with the Pacific decadal oscillation (PDO) in the 40–80-year periodicity band, where the y-axis for the PDO is inverted, and (b) wavelet coherence plot illustrating the relationship between both series.

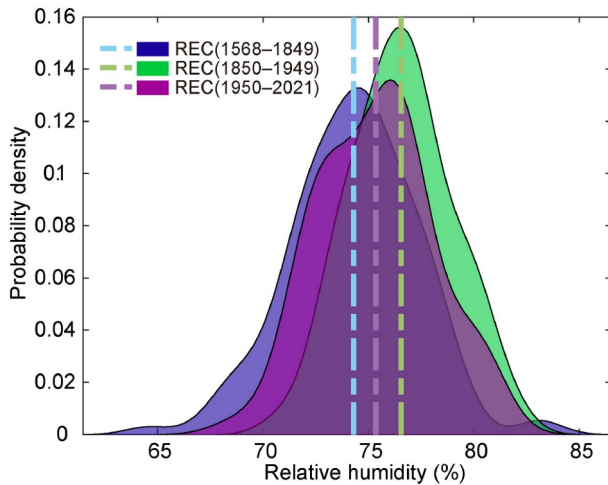


Figure 7 Probability density profiles of summer RH for different periods: 1568–1849 (blue), 1850–1949 (green), and 1950–2021 (purple).

from anthropogenic aerosol emissions should also be considered, which could reduce the warming on land and thus weaken the land-ocean thermal contrast, which weakens the EASM (Liu et al., 2019). Therefore, recent weak droughts could be caused mainly by decreased EASM precipitation rather than the intensification of warming-induced evapotranspiration (Liu et al., 2022). In addition, our reconstruction results also found that Northeast Asia showed a wetter trend since the 2000s, which was consistent with the results of Lou et al. (2024).

5. Conclusions

Our 454-year tree-ring cellulose $\delta^{18}\text{O}$ chronology from Northeast Asia (1568–2021 CE) provides crucial context for assessing recent hydroclimate variations. The reconstruction reveals that Northeast Asia experienced pronounced dry conditions during the LIA, followed by a persistent wetting

trend from the end of the LIA to the 1950s, with only a mild drying trend thereafter. Variations in land-sea thermal contrast driven by temperature fluctuations resulted in arid conditions during the LIA and humid conditions in the CWP. On decadal to multi-decadal timescales, internal climate variability (PDO and AMV) influences hydroclimate changes in Northeast Asia.

The recent drying trend in Northeast Asia (1950s–1990s), though apparent in instrumental records, appears unremarkable when viewed within the 454-year reconstruction of the past; meanwhile, long-term hydroclimatic records indicate that both the frequency and intensity of recent drought episodes fall well within the range of natural variability observed during the LIA. Recent hydroclimate changes is likely influenced by natural climate variability, and potentially modulated by competing anthropogenic influences—with warming-induced strengthening of the EASM partially offsetting the drying effects from Pacific warming and aerosol emissions. This finding underscores the importance of long-term paleoclimate records in properly contextualizing contemporary climate trends and distinguishing anthropogenic signals from natural variability.

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Conflict of interest The authors declare that they have no conflict of interest.

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