



Positive covariance between temperature and precipitation affects dendroclimatological reconstructions

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ABSTRACT

Living and relict Qilian juniper (*Juniperus przewalskii* Kom.) trees from the northeastern Tibetan Plateau offer an exceptional high-resolution paleoclimate archive spanning centuries to millennia. However, the co-occurrence of different climate signals exhibited by the same trees and chronologies may challenge the interpretation, and even reliability, of dendroclimatological reconstructions. Here, we analyse temperature and precipitation measurements from 60 meteorological stations northeast of the Tibetan Plateau between 1139 and 3663 m asl. We find that summer temperature and precipitation are positively correlated at higher elevations, while they tend to reveal inverse relationships at lower elevations. We also show that anthropogenic warming has led to wetter conditions at higher elevations but drier conditions at lower elevations. Our results further suggest that tree ring-based hydroclimate reconstructions from semi-arid Asian mountain systems are localised representations, which are usually not captured by gridded climate data.

1. Introduction

With an area of over 2.5 million square kilometres and an average elevation exceeding 4000 m asl, the Tibetan Plateau and surrounding mountain regions in central Asia host approximately 100,000 km² of glaciers, an extensive permafrost zone and the headwaters of numerous large rivers, including the Yangtze, Yellow and Mekong. Known as the world's largest 'Water Tower' (Yao et al., 2012, 2022), the region provides hydrological resources for nearly 40% of the global human population (Huang et al., 2023). The Tibetan Plateau also exerts a strong influence on large scale climate dynamics through land-ocean-atmosphere couplings (An et al., 2001; Lee et al., 2013). The elevation and extent of the plateau influence the westerly jet stream (Yang et al., 2002) and the Asian monsoon system (Wu et al., 2012; Lu et al., 2021). Despite much research, it remains unclear how anthropogenic climate change is affecting the hydrological cycle of the Tibetan Plateau and

surrounding high mountain systems (Wang et al., 2021), because the interaction between the Asian monsoon and westerly circulation is complex and long meteorological observations at high elevations are sparse. High-resolution proxy data are therefore needed to compare recent trends and extremes against past natural changes.

Despite mounting evidence for – and mechanistic understanding of – elevation-dependent warming (Mountain Research Initiative EDW Working Group, 2015; You et al., 2020; Miller et al., 2021), it is less clear how precipitation patterns are affected by elevation (Napoli et al., 2019), and how possible changes might be season- and region-specific. Meteorological observations in high mountain systems typically cover short time spans, which may prevent them from capturing trends and extremes in precipitation, particularly snowfall. This likely accounts for the varying conclusions reached in different studies (Pepin et al., 2022). Warmer and wetter summers at higher elevations of semi-arid mountain systems in central Asia suggest a thermal amplification of convective

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airflow, cooling beyond dew point temperatures, and enhanced condensation and precipitation events (Cui et al., 2024). At the seasonal scale, high summer temperature means at lower elevations under continental climate conditions typically correspond to low summer precipitation totals (i.e., increased cloud cover), while low summer temperatures correspond to high precipitation totals (i.e., decreased cloud cover). This is because warm summers are usually associated with reduced cloud cover and less rainfall, whereas cold summers tend to have more cloud cover and increased rainfall. A northward shift of the Asian monsoon system and alternations of westerly airmasses, however, would affect water vapour fluxes and moisture content on the Tibetan Plateau (Chen et al., 2008).

Dendrochronology, and especially its subdiscipline of dendroclimatology, both have long traditions in China (Wu and Zhan, 1991). Published almost half a century ago, Cho et al. (1978) estimated summer temperatures for the past millennium from slow-growing Qilian juniper (*Juniperus przewalskii* Kom.) from the northeastern Tibetan Plateau (Fig. 1A). Since then, nearly 200 paleoclimate studies have been published based on new or existing tree-ring width chronologies from this species and region (Fig. 1A; Supplementary Inventory S1) (Gao et al., 2025). While publications are relatively scarce until 2000, their sharp increase afterwards demonstrates the growing importance of this natural proxy archive (Büntgen et al., 2025a, 2025b; Gao et al., 2025). The average chronology length of 1048 years, with individual timespans ranging from 147 to 4650 years, exceeds the typical chronology lengths found in most other regions. Millennial-scale Qilian juniper tree-ring chronologies have been established for at least seven subregions of the northeastern Tibetan Plateau (Fig. 2). Careful development of these

exceptional composite records was only possible because of the tremendous lifespan of some individual trees exceeding 2000 years (He et al., 2019), as well as the precise cross-dating of living and relict wood, including well-preserved in situ dry-dead snags, archaeological remains and historical construction timbers.

Notable in this body of research is the range of climate signals retrieved from the annual tree-ring widths of Qilian junipers (Fig. 1B). Temperature and precipitation were reconstructed 72 and 62 times, respectively, while 52 studies reported other hydroclimate variables, such as drought, streamflow and relative humidity. Temperature and precipitation reconstructions from Qilian junipers have been published at similar frequencies since the 1970s but works reporting other hydroclimate signals have emerged since 2007 (Gao et al., 2025), when gridded drought indices became available for much of Asia (Dai et al., 2004; Cook et al., 2010). A closer look at the individual tree-ring chronologies or network compilations in the 151 herein reviewed publications reveals that there is no general relationship between site elevation and the reconstructed climate signal for most of the studies (Fig. 1C), except for those sites below 3400 m asl that were predominantly used for hydroclimate and precipitation reconstructions.

The observed inconsistency in climate signals by a single species from the same region, and in some cases even by the same specimens, suggest that temperature and precipitation operate not independently from each other and the final reconstruction parameter was simply defined by the highest proxy-target correlation (i.e., either temperature or precipitation), or temperature and precipitation are meteorologically independent yet, can be reconstructed from the same proxy. Motivated by this conceptual and empirical ambiguity, deeper investigation of the

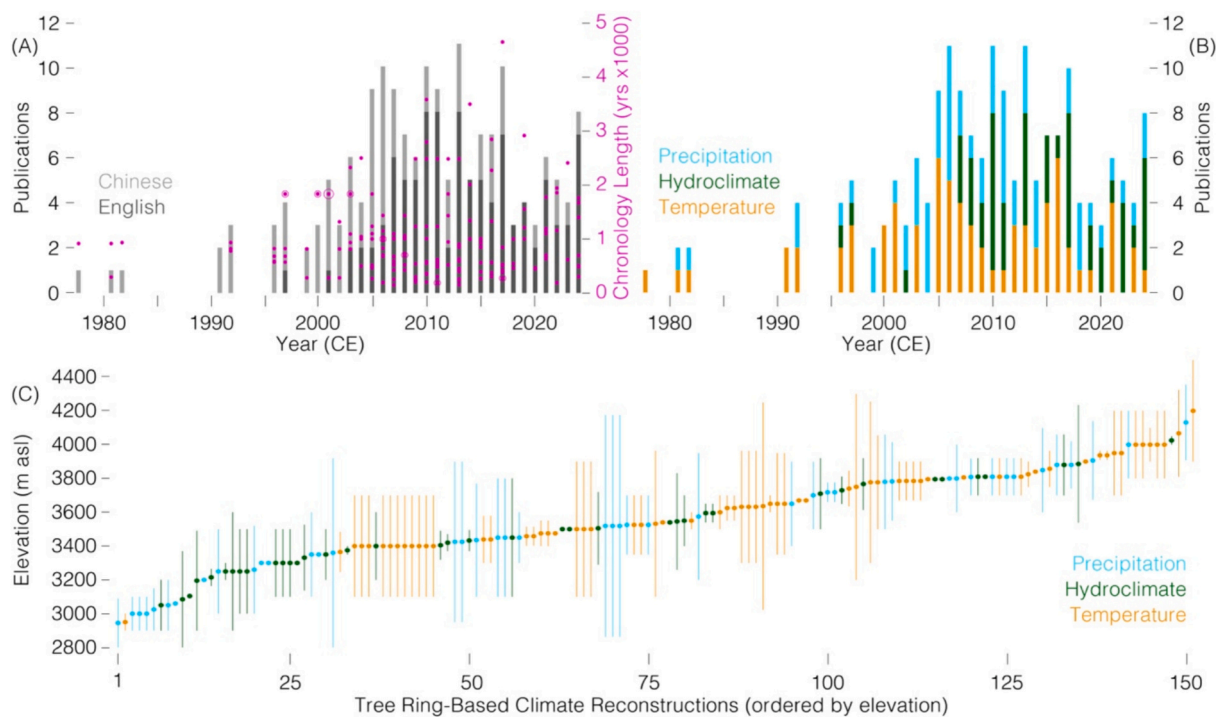


Fig. 1. Overview of 174 scientific publications in which Qilian juniper tree-ring width chronologies from the northeastern Tibetan Plateau were used for climate reconstructions. (A) Annual distribution of 174 publications from 1978 to 2024 and separated into 75 and 99 studies written in Chinese and English (light and dark grey), respectively (Supplementary Inventory S1). The inventory of Qilian juniper (*Juniperus przewalskii* Kom.) tree-ring width chronologies used to reconstruct temperature, precipitation or hydroclimate (e.g., indices of drought, streamflow and relative humidity) is based on the search criteria “Juniperus przewalskii”, “Sabina przewalskii”, “Qilian juniper” and “Qilian yuanbai”, in Web of Science (WoS) and the China National Knowledge Infrastructure (CNKI). Purple dots indicate the length of individual chronologies (right y-axis), and circles indicate those chronologies that were used in more than one publication per year. (B) Climate target of the published reconstructions: temperature (72, orange), precipitation (62, blue), and hydroclimate (52, green), with the latter being a combination of the first two and can include records of streamflow and relative humidity. Slight differences in the number of publications between A and B result from individual publications reporting more than one climate target (see Supplementary Inventory S1 for details). (C) Elevational distribution of individual and multiple tree-ring chronologies used in 151 publications that provide relevant information. Dots refer to mean elevation, vertical lines to elevation ranges of the samples collected, and colours to the reconstructed climate signal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

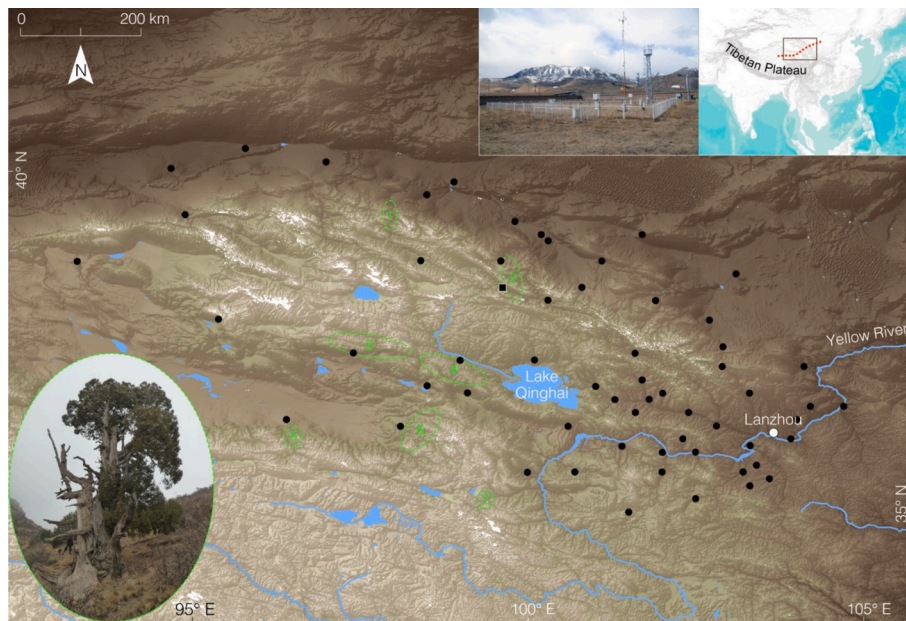


Fig. 2. Location of the Qilian Mountains on the northeastern Tibetan Plateau. Topographic map (lighter = higher with glaciers in white) shows the location of 60 meteorological stations (black dots) and seven regions from which >1000-year-long Qilian juniper tree-ring chronologies have been developed (green dashed ovals; 1 = Jiuquan, 2 = Qilian, 3 = Delingha, 4 = Wulan and Tianjun, 5 = Nuomuhong, 6 = Dulan, 7 = Animaqing). The bottom photo shows living and relict Qilian juniper trees, while the upper photo shows the Yeniugou climate station at 3314 m asl (indicated by a black square north-northwest of Lake Qinghai). Almost all stations represent rural settings. The inset map shows the study area on the northeastern Tibetan Plateau (rectangle), and the dashed line on the inset map shows the modern limit of the Asian summer monsoon (Chen et al., 2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relationship between temperature and precipitation and possible changes in the covariance of both meteorological parameters with elevation is needed. A better understanding of climate variations in high mountain systems is not only crucial for assessing the reliability of tree ring-based reconstructions, but also for modelling changes in the hydrological cycle, plant growth, and vegetation composition under projected anthropogenic warming (Mountain Research Initiative EDW Working Group, 2015; You et al., 2020; Miller et al., 2021).

Here, we use meteorological station data from the wider region of the northeastern Tibetan Plateau to quantify how relationships between temperature and precipitation may, or may not, change with elevation. We then assess if the northeastern Tibetan Plateau is experiencing different climate trends than its surrounding lowlands. Drawing on our results from the meteorological measurements, we explain why tree-ring chronologies from the Tibetan Plateau and comparable high-elevation environments might be used simultaneously to reconstruct temperature and precipitation or hydroclimate at limited spatial extent. We then discuss the implications of elevation-dependent precipitation changes for plant growth, vegetation composition, snow cover, glacier extent, and river runoff in semi-arid mountain systems. Finally, we contend that a warming-induced increase in convectively driven summer precipitation at high elevations is likely to persist in the Anthropocene, with substantial implications for the hydrological cycle of ‘Water Towers’ that are vital resources for ecological and societal systems on large spatial scales across Asia.

2. Data and methods

We extracted monthly precipitation, as well as minimum, mean and maximum temperature measurements in the wider region of the northeastern Tibetan Plateau from the Chinese Meteorological Administration (<https://data.cma.cn/>). The network of 60 meteorological stations spans roughly 35–40° North and 95–105° East (Fig. 2), including the Qilian mountains with important tributaries of the Yellow River on the northeastern Tibetan Plateau. The instrumental stations are

evenly distributed between 1139 and 3663 m asl (Fig. 3A). Most of them became operational in the 1950s, and more than 80% of the records cover the period 1958–2014 continuously. Pearson's correlation coefficients between temperature means and precipitation totals were calculated for each meteorological station using two windows of high summer (June–August; JJA) and warm season (April–September; A-S), and three periods of early 1958–1986, late 1986–2014 and full 1958–2014 coverage. The mean difference in correlation coefficients between the 30 lowest and 30 highest meteorological stations was calculated (Fig. 4), and a two-sample *t*-test was used to assess statistical significance. A linear regression model was used to calculate temporal trends in all meteorological parameters between 1958 and 2014, for which slopes were calculated for the original and normalized timeseries (i.e., *z*-scores with a mean of zero and standard deviation of one).

All analyses were repeated with gridded 0.5° x 0.5° temperature and precipitation data from the Climatic Research Unit (CRU TS v. 4.08; Harris et al., 2020), and a comparable, though independent product from China (0.025° x 0.025°; Zhao et al., 2019). The gridded temperature and precipitation data were selected to best represent the location of each meteorological station. We also calculated first differences for all data to see if detrended timeseries reveal the same results (Fig. S1).

3. Results

We find significant negative correlations between high summer June–August (JJA) temperature and precipitation at the majority of stations below circa 2300 m asl ($p < 0.01$) (Fig. 3B), whereas positive correlations dominate at higher elevations. The Theil-Sen slope estimator suggests that all positive slopes are significant ($p < 0.05$) (Fig. 3B). A similar pattern is obtained when using data spanning the longer warm season from April–September (A-S), for which the inverse association at lower elevations is weaker but the synchronous temperature-precipitation behaviour at higher elevations is stronger. Negative correlations for JJA (A-S) at lower elevations range from -0.20 to -0.62 (0.00 to -0.42), whereas positive correlations at higher

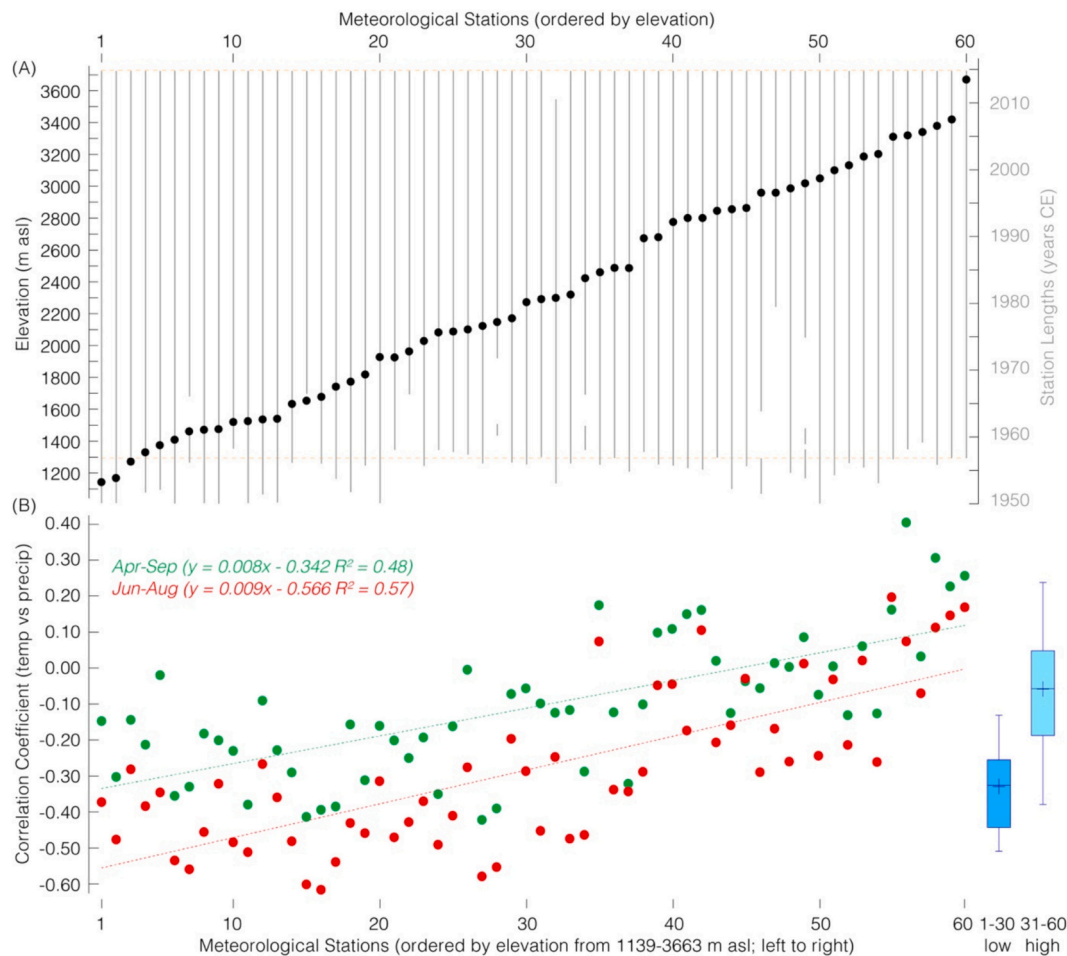


Fig. 3. Characteristics of meteorological stations and the relationship between temperature and precipitation on the eastern Tibetan Plateau. (A) Elevational distribution of 60 meteorological stations between 1139 and 3663 m asl (black dots), with a mean and median elevation of 2300 and 2277 m asl, respectively (see Fig. 2 for spatial distribution). Grey vertical lines represent the length of station recordings, and horizontal orange dashed lines indicate the period 1958–2014 for which 83% of meteorological stations have continuous readings. (B) Correlation coefficients between temperature means and precipitation totals at each of the 60 meteorological stations, calculated over 1958–2014 for three-month (June–August; red) summer and six-month (April–September; green) warm season intervals (see Fig. S1 for detrended data and Fig. S2 for comparison against gridded data). Correlations above (below) 0.26 (–0.26) are significant at the 0.05 confidence level. Dashed lines are linear trends of the seasonal correlation coefficients, and boxplots emphasise significant differences in temperature-precipitation covariance between the 30 lowest and 30 highest meteorological stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

elevations range from 0.0 to 0.21 (0.0 to 0.41). A similar pattern of negative (positive) correlations between temperature and precipitation at lower (higher) elevations is obtained when using detrended timeseries (Fig. S1).

Splitting the 120 correlation pairings into two groups of 60, each including either the 30 lowest or the 30 highest instrumental stations, reveals significant correlation differences ($p < 0.05$) (Fig. 3B). The elevation-dependent covariance between temperature and precipitation is, however, not seen when using gridded indices instead of the original 60 meteorological stations (Fig. S2). It should be further noted that we found no latitudinal effect on the relationship between temperature and precipitation (Fig. S3). These findings reinforce the effect of elevation and exclude possible biases from northward shifts of the Asian monsoon system. Tests for longitudinal effects were limited by the occurrence of many stations at lower elevations in the eastern part of study region.

Robustness of the observed covariance between temperature and precipitation, and its elevation dependence, is corroborated by minimum and maximum temperatures and by repeating the analysis for two equally long early and late sub-periods (Fig. 4A). The individual correlation pairings calculated over 1958–1968, 1958–2014 and 1986–2014, as well as using two seasons and minimum, mean and maximum

temperatures range from –0.75 to 0.72 ($p < 0.01$). The range of correlations with minimum temperatures is wider and more positive than that of maximum temperatures. The average difference in correlations from the 30 lowest and highest stations is larger for JJA than A-S, especially during the early split period. The mean difference in all correlation pairings from the 30 lowest and 30 highest stations is 0.23 (Fig. 4B), with minimum and maximum correlation differences of 0.10 (max A-S late period) and 0.37 (mean JJA early period), respectively. There is no systematic change in elevation-dependency between the early, late and full calculation periods.

Independent of their elevation, the 60 temperature records show positive trends between 1958 and 2014 (Fig. 5A), with a mean warming of approximately 0.4 °C per decade across all sites and elevations (Fig. S4A), corresponding to a warming relative to each station's inter-annual variability of around 0.5 standard deviation per decade (Fig. 5A). While the recent increase in both high summer and warm season temperatures is significant across the wider region of the northeastern Tibetan Plateau at all elevations ($p < 0.01$), there is no evidence for elevation-dependent warming. The observed long-term trends in high summer and warm season precipitation totals, however, suggest that only the meteorological stations at high elevations have recorded wetter

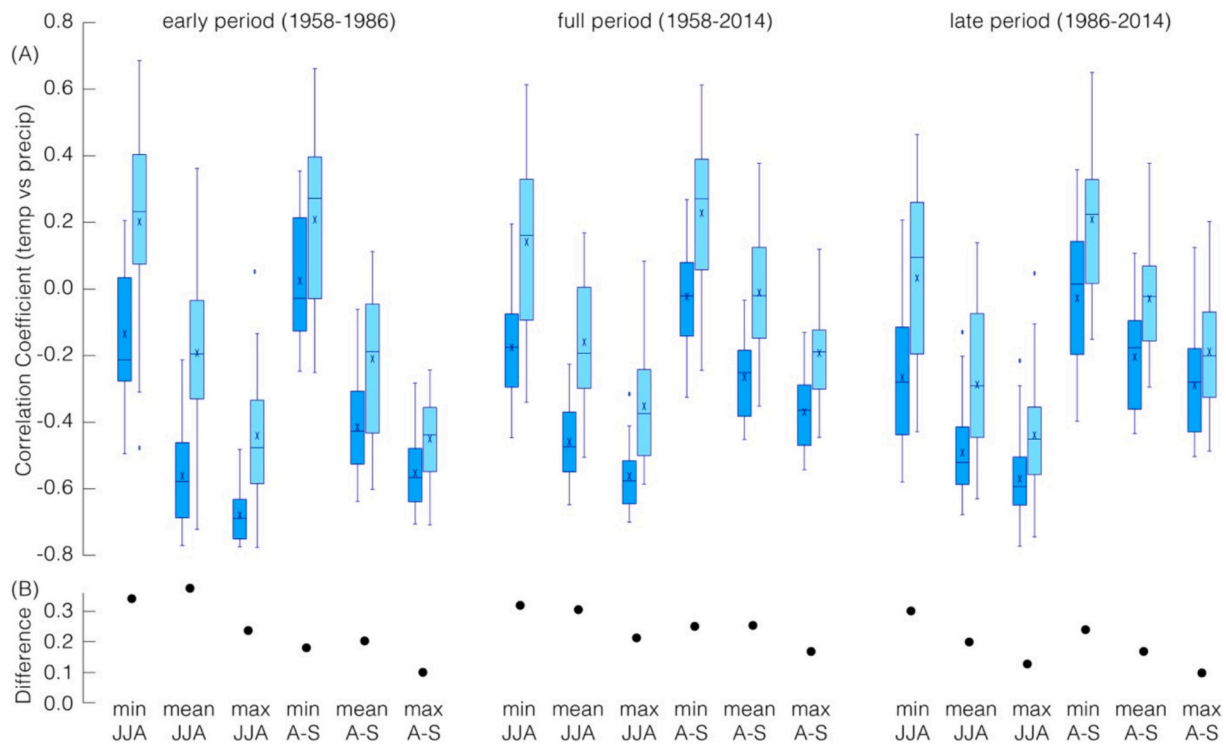


Fig. 4. Elevation-dependent covariance between temperature and precipitation. (A) Differences in temperature-precipitation covariance between the 30 lowest (dark blue) and 30 highest (light blue) meteorological stations, calculated over early (1958–1986), full (1958–2014) and late (1986–2014) split periods for minimum, mean and maximum temperatures and three-month (June–August; JJA) summer and six-month (April–September; A-S) warm season intervals. (B) Mean difference in correlation coefficients of the 18 temperature-precipitation pairings, which are all significant at the 0.05 level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

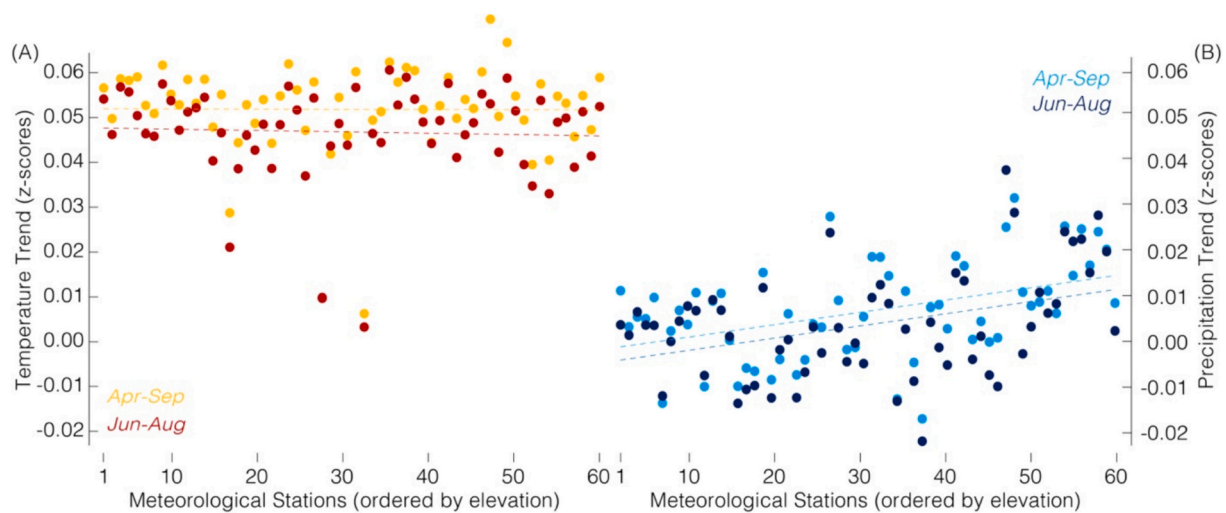


Fig. 5. Long-term trends in temperature and precipitation at meteorological stations ordered by elevation. Relative changes (i.e., trend slopes expressed as standard deviation units per year) in summer (June–August) and warm season (April–September) (A) mean temperature and (B) precipitation totals recorded by the 60 meteorological stations between 1958 and 2014. All timeseries were normalized to have a mean of zero and standard deviation of one (see Fig. S4 for absolute changes in °C and mm per decade).

(and thus likely also colder) conditions (Fig. 5B). However, the surrounding lowland areas of the northeastern Tibetan Plateau became slightly drier. The wetting trend at higher elevations can be up to 18 mm per decade during the warm season from A-S and up to 14 mm for the shorter high-summer JJA window (Fig. S4B). The long-term warming is less significant when using 0.5° latitude by 0.5° longitude gridded indices (CRU TS v. 4.08; Harris et al., 2020) closest to the meteorological stations (Fig. S5A). The gridded high-resolution climate product also

lacks significant elevation-dependency in precipitation trends over 1958–2014 (Fig. S5B), thus does not reproduce the station-based evidence for increasingly wet-cold mountains and dry-hot lowlands of the northeastern Tibetan Plateau.

4. Discussion and conclusions

The observed increase in high summer and warm season

precipitation with elevation and over time suggests that tree-ring chronologies from high-elevation sites in the region of the Tibetan Plateau, as well as in other semi-arid mountains of inner Eurasia (e.g., Karakorum, Pamir, Taurus, Tian Shan and Zagros), and likely also in the western US and South America (e.g., Sierra Nevada and Andes), could reveal significant positive correlations with both temperature means and precipitation totals. Wherever increasing temperatures at larger scales cause wetter rather than drier conditions, dendroclimatologists might experience difficulties in distinguishing between more than one dominant growth controlling factor. If the same tree-ring chronology reveals significant positive correlations with temperature and precipitation (when both variables behave similarly and exhibit positive covariance), attribution of the final reconstruction to a single climate parameter might be subjective and the reasoning must be communicated clearly to avoid potential misinterpretation by secondary data users. Hydroclimate reconstructions are usually robust if high temperatures and low precipitation (or low temperatures and high precipitation) jointly cause dry (or wet) conditions (Fritts, 1976). However, where temperature and precipitation positively co-vary during the growing season, their opposing effects on tree growth are likely to complicate the reconstruction of a distinct, singular climatic signal.

The overall climate sensitivity of tree growth will likely decline under warmer and wetter conditions (Fig. 6). Such a scenario might bias the variance and amplitude of tree ring-based climate reconstructions (Büntgen et al., 2022). Moreover, the spatial validity of precipitation and hydroclimate reconstructions might be limited if the underlying tree-ring chronologies come from semi-arid mountain systems, because the recorded trends and extremes in summer climate likely differ from those in the surrounding lowlands (Fig. 6). If mountains get wetter but lowlands get drier (Fig. 6), tree-ring chronologies from the Asian ‘Water Towers’ are unlikely to be representative of the functioning and productivity of inner Eurasian steppe environments. This caveat may be particularly relevant for streamflow reconstructions that extrapolate hydrological variability of high mountain systems across the surrounding lowland areas (Chen et al., 2023).

Limited availability of meteorological observations from high elevations influences correlations with gridded climate data, because lowland weather stations dominate and conditions at higher elevations are not accurately represented. This caveat is particularly severe for spatially constrained summer precipitation. Despite the global

availability and many other advantages of gridded climate products (Harris et al., 2020), such interpolated data may not capture important behaviours such as regional wetting trends at higher elevations (Fig. S5B compared with Fig. 5B), or elevation-dependence in the temperature-precipitation relationship (Fig. S2 compared with Fig. 3B). This is not unexpected because the gridded CRU dataset does not consider elevation-dependence when it interpolates temperature or precipitation anomalies across grid cells (Harris et al., 2020). In fact, elevation dependence is incorporated only in the baseline climatology (and, for precipitation, this translates into elevation dependence in absolute values but not in values expressed relative to the baseline climatology). In simple terms, grid cell anomalies are calculated as a weighted average of station anomalies without considering the elevation difference between stations and the grid cell. This method is used because, in most mountain regions, weather stations are too sparse to represent the full range of elevations accurately. More and better meteorological station measurements from high elevation sites and refined gridding algorithms are therefore needed to improve the quality of gridded datasets.

A wetter alpine zone will have implications for vegetation functioning and productivity and thus carbon capture (Feldman et al., 2024). While our findings are consistent with independent evidence for a recent enhancement of tree growth in the Tian Shan mountains (Wang et al., 2024), it remains unclear if anthropogenic climate change will continue to enhance sub-alpine forest growth in semi-arid mountain systems. Instead, a decoupling in the rate of future warming and less wetting may cause additional drought stress at the cold distribution limit of tree growth (Galván et al., 2015). A shift in the predominant growth response of high-elevation trees from temperature to moisture has been reported for the southeastern Tibetan Plateau (Chen et al., 2025). Aside from the risk of drought-induced growth declines, the benefits of increased biomass production and carbon sequestration may be offset by the association of higher stem growth with faster tree turnover, and shorter carbon residence time: “grow fast but die young” (Büntgen et al., 2019).

Further to the effects on tree growth, forest productivity, carbon storage, and climate reconstruction, there are ecological, hydrological and societal consequences of a warming-induced increase in precipitation at higher elevations (Fig. 6). The position and proportion of sub-alpine and alpine vegetation cover is likely to change, with diverse implications for animal populations and biodiversity via trophic



Fig. 6. Possible causes and consequences of rising summer precipitation in semi-arid mountain systems. Conceptual framework for understanding the orographic modification of convective summer precipitation in semi-arid mountain systems and comparison with their surrounding lowland areas under generally cooler, pre-industrial climate conditions and typically warmer, anthropogenic climate conditions (left and right sides, respectively). The diagram also illustrates that rising precipitation totals enhance tree growth, but potentially decreases growth sensitivity to interannual climate variability, and that the climatological difference between wetter high mountain systems and their drier surrounding lowland areas were likely smaller during colder conditions in the past and become larger under recent anthropogenic warming, with implications for vegetation composition, snow cover, glacier extent, and river runoff in the Asian ‘Water Towers’, the main hydrological resource for much of inner Eurasia’s steppe environment.

interactions (Büntgen et al., 2014). Moreover, lightning during extreme precipitation events and thunderstorms is expected to increase wildfire risk (Pérez-Invernón et al., 2023). Increased river runoff from the ‘Water Towers’ would benefit hydroelectric power generation and agricultural production, amongst others. Hydrological changes on the northeastern Tibetan Plateau are particularly relevant for irrigation systems along the Yellow River (Fig. 2), where farming has a long tradition intertwined with the rise and fall of Chinese dynasties (Qin et al., 2025).

While the hydroclimatic future of Asian ‘Water Towers’ remains uncertain (Yao et al., 2022), our results imply that it is likely misleading to focus on the expected warming without anticipating changes in precipitation. Given the importance of accurate predictions of water supply for almost two billion people, we argue for the establishment of more and better equipped monitoring networks in mountain regions, and a drive towards open data access. Regional atmosphere-cryosphere-hydrology models would also benefit from improvements, and empirical and theoretical evidence should be combined to enhance water management at national and trans-boundary scales. Refining the predictability of hydrological resources is particularly relevant since the erratic nature of warming-induced convective summer precipitation is likely to cause growing threats from flash floods, debris flows, landslides, and glacial lake outburst floods, with cascading downstream implications for hydropower and settlements (Borga et al., 2014; Thackeray et al., 2022; Martínez-Villalobos and Neelin, 2023; Büntgen et al., 2025a, 2025b).

Consistent with model projections for high mountain systems (Kad et al., 2023; Chen et al., 2024), our findings on elevation-dependent precipitation changes emphasise how little is known about the hydrological cycles of the Asian ‘Water Towers’ on which ecosystems and societies in the drier lowlands depend. Worldwide, we are aware of just a handful of high-elevation meteorological summit observatories in continuous operation since the second half of 19th or early-20th century, of which three are in the European Alps (Grosser St. Bernhard and Jungfrauoch in Switzerland, and Sonnenblick in Austria), and one each in the Pyrenees (Pic Du Midi in France) and Tatra (Lomnický štít in Slovakia). There is thus an urgent need for new stations to be established, gridded climate datasets to be refined, proxy-based reconstructions to be developed, and model simulations to be improved for quantifying hydroclimate changes in complex mountain terrain.

CRedit authorship contribution statement

Linlin Gao: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Tatiana Bebchuk:** Writing – original draft, Investigation, Conceptualization. **Clive Oppenheimer:** Writing – original draft. **Timothy J. Osborn:** Writing – original draft, Methodology, Investigation, Data curation. **Jan Esper:** Writing – original draft, Conceptualization. **Mirek Trnka:** Methodology, Investigation, Funding acquisition. **Xiaohua Gou:** Supervision, Methodology. **Yang Deng:** Methodology, Investigation. **Ulf Büntgen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2026.105496>.

Data availability

All data used in this study are either freely available (<https://data.cma.cn/> and <https://climexp.knmi.nl>) or included in the online supplement.

References

- An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since late Miocene times. *Nature* 411, 62–66.
- Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M., 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. *J. Hydrol.* 518, 194–205.
- Büntgen, U., Jenny, H., Liebhold, A., Mysterud, A., Egli, S., Nievergelt, D., Stenseth, N.C., Bollmann, K., 2014. European springtime temperature synchronizes ibex horn growth across the eastern Swiss Alps. *Ecol. Lett.* 17, 303–313.
- Büntgen, U., Krusic, P.J., Piermattei, A., Coomes, D.A., Esper, J., Myglan, V.S., Kirilyanov, A.V., Camarero, J.J., Crivellaro, A., Körner, C., 2019. Limited capacity of tree growth to mitigate the global greenhouse effect under predicted warming. *Nat. Commun.* 10, 2171.
- Büntgen, U., Piermattei, A., Crivellaro, A., Reing, F., Krusic, P.J., Trnka, M., Torbenson, M., Esper, J., 2022. Common era tree-line fluctuations and their implications for climate reconstructions. *Glob. Planet. Chang.* 219, 103979.
- Büntgen, U., Oppenheimer, C., Farinotti, D., Nahtz, T., Esper, J., 2025a. The 2025 Blatten disaster in the Swiss Alps followed exceptional warming and highlights the vulnerability of people and heritage in glaciated landscapes. *Commun. Earth Environ.* 6, 994.
- Büntgen, U., Trnka, M., Hulme, M., Esper, J., 2025b. Climate data for climate action. *NPJ Clim. Act.* 4, 9.
- Chen, F., Yu, Z., Yang, M., Ito, E., Wang, S., Madsen, D.B., Huang, X., Zhao, Y., Sato, T., Birks, H.J.B., Boomer, I., Chen, J., An, C., Wünnemann, B., 2008. Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian Monsoon history. *Quat. Sci. Rev.* 27, 351–364.
- Chen, F., Man, W., Wang, S., Esper, J., Meko, D., Büntgen, U., Yuan, Y., Chen, F., He, D., Hadad, M., Hu, M., Zhao, X., Roig, F., Fang, O., Chen, Y., Zhang, H., Shang, H., Yu, S., 2023. Southeast Asian ecological dependency on Tibetan plateau streamflow over the last millennium. *Nat. Geosci.* 16, 1151–1158.
- Chen, R., Duan, K., Shi, P., Shang, W., Yang, J., He, J., Meng, Y., Dou, M., Li, L., 2024. Amplification of warming-wetting in high mountains and associated mechanisms during the 21st century in Xinjiang, Central Asia. *Clim. Chang.* 177, 177.
- Chen, S., Duan, X., Li, Z., 2025. Forest growth dependency shifts from temperature to moisture in southeastern Tibetan Plateau. *Ecol. Front.* 45, 433–443.
- Cho, C.T., Hu, C.-S., Chang, H.-K., Chao, C., Wang, Y.-S., Liu, K.-Y., 1978. Tree rings of Kilienshan region, and changes of the climate during the recent thousand years in China. *J. Lanzhou Univ.* 2, 145–157.
- Cook, E.R., Anchukaitis, K.J., Buckley, B.M., D’Arrigo, R.D., Jacoby, G.C., Wright, W.E., 2010. Asian monsoon failure and megadrought during the last millennium. *Science* 328, 486–489.
- Cui, W., Galarneau, T.J., Hoogewind, K.A., 2024. Changes in mesoscale convective system precipitation structures in response to a warming climate. *J. Geophys. Res. Atmos.* 129, e2023JD039920.
- Dai, A., Trenberth, K.E., Qian, T., 2004. A global dataset of palmer drought severity index for 1870–2002: Relationship with soil moisture and effects of surface warming. *J. Hydrometeorol.* 5, 1117–1130.
- Feldman, A.F., Konings, A.G., Gentile, P., Cattray, M., Wang, L., Smith, W.K., Biederman, J.A., Chatterjee, A., Joiner, J., Poulter, B., 2024. Large global-scale vegetation sensitivity to daily rainfall variability. *Nature* 636, 380–384.
- Fritts, H.C., 1976. *Tree Rings and Climate*. Academic Press, New York, USA.
- Galván, J.D., Büntgen, U., Ginzler, C., Grud, H., Gutiérrez, E., Labuhn, I., Camarero, J. J., 2015. Drought-induced weakening of growth-temperature associations in Mediterranean high-elevation forests. *Glob. Planet. Chang.* 124, 95–106.
- Gao, L., Bebchuk, T., Gou, Xiaohua, Büntgen, U., 2025. China’s growing relevance in dendrochronology and paleoclimatology. *NPJ Clim. Act.* 4, 83.
- Harris, I., Osborn, T.J., Jones, P., 2020. Lister d version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* 7, 109.
- He, M., et al., 2019. Recent advances in dendroclimatology in China. *Earth Sci. Rev.* 194, 521–535.
- Huang, J., et al., 2023. Global climate impacts of land-surface and atmospheric processes over the Tibetan Plateau. *Rev. Geophys.* 61, e2022RG000771.
- Kad, P., Ha, K.-J., Lee, S.-S., Chu, J.-E., 2023. Projected changes in mountain precipitation under CO₂-induced warmer climate. *Earth’s Future* 11, e2023EF003886.

- Lee, S.S., Lee, J.Y., Ha, K.J., Wang, B., Kitoh, A., Kajikawa, Y., Abe, M., 2013. Role of the Tibetan plateau on the annual variation of mean atmospheric circulation and storm-track activity. *J. Clim.* 26, 5270–5286.
- Lu, M., Yang, S., Wang, J., Wu, Y., Jia, X., 2021. Response of regional Asian summer monsoons to the effect of reduced surface albedo in different Tibetan plateau domains in idealized model experiments. *J. Clim.* 34, 7023–7036.
- Martinez-Villalobos, C., Neelin, J.D., 2023. Regionally high risk increase for precipitation extreme events under global warming. *Sci. Rep.* 13, 5579.
- Miller, J.R., Fuller, J.E., Puma, M.J., Finnegan, J.M., 2021. Elevation-dependent warming in the Eastern Siberian Arctic. *Environ. Res. Lett.* 16, 024044.
- Mountain Research Initiative EDW Working Group, 2015. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Chang.* 5, 424–430.
- Napoli, A., Crespi, A., Ragone, F., Maugeri, M., Pasquero, C., 2019. Variability of orographic enhancement of precipitation in the alpine region. *Sci. Rep.* 9, 13352.
- Pepin, N., et al., 2022. Climate changes and their elevational patterns in the mountains of the world. *Rev. Geophys.* 60, e2020RG000730.
- Pérez-Invernón, F.J., Gordillo-Vázquez, F.J., Huntrieser, H., Jöckel, P., 2023. Variation of lightning-ignited wildfire patterns under climate change. *Nat. Commun.* 14, 739.
- Qin, C., et al., 2025. Persistent humid climate favored the Qin and Western Han dynasties in China around 2200 years ago. *Proc. Natl. Acad. Sci. USA* 122, e2415294121.
- Thackeray, C.W., Hall, A., Norris, J., Chen, D., 2022. Constraining the increased frequency of global precipitation extremes under warming. *Nat. Clim. Chang.* 12, 441–448.
- Wang, T., Zhao, Y., Xu, C., Ciais, P., Liu, D., Yang, H., Piao, S., Yao, T., 2021. Atmospheric dynamic constraints on Tibetan plateau freshwater under Paris climate targets. *Nat. Clim. Chang.* 11, 219–225.
- Wang, T., Bao, A., Xu, W., Zheng, G., Du, W., Yu, T., Huang, X., Gao, Z., Bao, J., Stoffel, M., De Maeyer, P., De Wulf, A., 2024. Does Central Asian forest growth benefit from a warming-wetting climate? Insights from tree-ring records. *Environ. Res. Lett.* 19, 064037.
- Wu, X., Zhan, X., 1991. Tree-ring width and climatic change in China. *Quat. Sci. Rev.* 10, 545–549.
- Wu, G., Liu, Y., He, B., Bao, Q., Duan, A., Jin, F., 2012. Thermal controls on the Asian summer monsoon. *Sci. Rep.* 2, 404.
- Yang, S., Lau, K.M., Kim, K.M., 2002. Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Clim.* 15, 306–325.
- Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Yang, X., Duan, K., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Chang.* 2, 663–667.
- Yao, T., et al., 2022. The imbalance of the Asian water tower. *Nat. Rev. Earth Environ.* 3, 618–632.
- You, Q., Chen, D., Wu, F., Pepin, N., Cai, Z., Ahrens, B., Jiang, Z., Wu, Z., Kang, S., AghaKouchak, A., 2020. Elevation dependent warming over the Tibetan Plateau: patterns, mechanisms and perspectives. *Earth Sci. Rev.* 210, 103349.
- Zhao, H., Huang, W., Xie, T., Wu, X., Xie, Y., Feng, S., Chen, F., 2019. Optimization and evaluation of a monthly air temperature and precipitation gridded dataset with a 0.025° spatial resolution in China during 1951–2011. *Theor. Appl. Climatol.* 138, 491–507.