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Greening of Eurasia's center driven by low-latitude climate warming

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ABSTRACT

Central Asia, located in the innermost part of the Eurasian continent, has experienced “warming and humidification” in recent decades, with potentially important implications for tree growth in alpine forests, which are critical for regional water reserves. We use nested principal component analysis to assess tree radial growth patterns and reveal significant positive trends since the 20th century across Central Asian alpine forests (0.076 per decade during 1900–2021, $p = 0.003$). Regional hydroclimatic variations affect the greening of these alpine forests, especially with extreme droughts being the most damaging. Growth acceleration is driven by low-latitude warming, which enhances regional temperatures and precipitation. The warming ocean centers alter atmospheric circulation patterns, leading to more moisture being transported to the Central Asian alpine forests, thereby increasing regional precipitation and promoting tree growth. Our model projections indicate that growth rates will continue to rise in the future. However, unprecedented warming may eventually lead to growth deterioration if negative effects, such as insufficient precipitation, occur due to breakdown signs of positive feedback mechanisms, such as moisture transport driven by low-latitude warming. Our study highlights the beneficial, but not unlimited, influences of climate warming on tree growth in Central Asian alpine forests, with implications for the sustainability of water resources. However, as urban and agricultural demands escalate, a holistic, long-term perspective is recommended to mitigate the adverse effects of temperature increases.

1. Introduction

Forest ecosystems are crucial for carbon sequestration, oxygen production, and water conservation, and they have played a major role in the evolution of civilizations; hence, they are invaluable global assets (Foley et al., 2005; Mitchard, 2018; Piao et al., 2020; Paul et al., 2021; Chen et al., 2023a; Zhang et al., 2024). While many regions across the globe have experienced negative impacts from intensifying global warming—manifesting as reduced tree growth due to drought stress, rising temperatures, and elevated evapotranspiration (Allen et al., 2015, 2020; Gradel et al., 2017; Dannenberg et al., 2019; Lian et al., 2021; Marqués et al., 2022)—Central Asia, nestled in the heart of the Eurasian continent and one of the world's driest regions, presents a strikingly different trend. In this unique region, where sparse vegetation and alpine forests are predominantly located in the eastern mountainous zones, tree growth appears to be increasing, defying broader global patterns (Chen et al., 2021a; Zhao et al., 2023). This unexpected growth is particularly significant given the increasing water scarcity the region faces (Mekonnen and Hoekstra, 2016). These alpine forests are not only pivotal for local ecological stability and climatic regulation but also provide critical water resources for agriculture and socio-economic development, as they feed into key inland rivers like the Amu Darya and Syr Darya. Central Asia's location along the historic Silk Road has further amplified its global relevance, fostering cultural exchanges that have been supported by the

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region's distinctive climatic and ecological conditions, including the snow and ice melt in its alpine areas (Frachetti et al., 2017; Chen et al., 2022; Ding et al., 2023). Despite some positive developments, this region continues to face harsh environmental challenges, including the growing threat of agricultural droughts, which are projected to worsen (Greve et al., 2014; Jiang and Zhou, 2023). This paradoxical trend highlights the need for a deeper understanding of the growth dynamics of Central Asian alpine forests, which could provide critical insights for both predicting regional environmental changes and developing targeted, effective strategies for environmental protection in the face of accelerating global climate change.

Since the 1980s, the climate of Central Asia has shifted from "warming and drying" to "warming and humidifying", characterized by increasing precipitation and rising lake levels (Chen et al., 2010, 2023b; Zhang et al., 2022a), which may represent the hydroclimatic background responsible for accelerated vegetation growth. In cold environments, warming can enhance cellular activity and extend the growing season, which is especially beneficial for tree growth at higher altitudes (Pretzsch et al., 2014; Zeng et al., 2019; Chen et al., 2021a; Kang et al., 2023; Zhao et al., 2023). Similar to most of the rest of the world, in Central Asia, where water scarcity is prevalent, increased precipitation is a critical factor in maintaining forest diversity and promoting vegetation expansion (Liu et al., 2022; Wise and Dannenberg, 2022; Chen et al., 2024a). Westerly winds and the South Asian monsoon transport large quantities of water vapor across this region (Chen and Huang, 2012; Huang et al., 2015; Zhao and Zhang, 2016; Chen et al., 2020, 2023b; Ma et al., 2020; Jiang et al., 2021; Li et al., 2023). The westerlies carry moisture from the Atlantic Ocean and the Mediterranean Sea (Guan et al., 2019; Chen et al., 2023b), while the monsoon supplies water vapor from the Indian Ocean and the Arabian Sea (Chen et al., 2021b; Jiang et al., 2021). Together, these sources deliver precipitation derived from distant oceans to the area of elevated topography in Central Asia. Despite significant advancements in understanding hydroclimatic changes in Central Asia, the precise response of alpine forest ecosystems, particularly in relation to the complex interactions between warming and humidification, remains unclear. Furthermore, a key aspect that requires further investigation is the identification of the underlying mechanisms driving this positive feedback, specifically, the factors that contribute to the availability of sufficient moisture and how this may evolve in the future.

Recent advances in dendrochronology have allowed for the collection of an increasing number of tree-ring width sequences from Central Asian alpine forests (Cook et al., 2010; Ahmed et al., 2013; Chen et al., 2016a, 2016b, 2016c, 2016d, 2017a, 2017b, 2022, 2023c; Chen and Yuan, 2016; Taynik et al., 2016; Wang et al., 2017; Zhang et al., 2020; Gao et al., 2022), and combined with the most recent tree-ring samples we have obtained, providing valuable new insights into the growth characteristics and hydroclimatic responses of these forests to climatic warming and humidification. However, the underlying mechanisms driving the observed trends remain largely unexplored. This study seeks to bridge the gap by exploring the relationship between global warming and tree growth in Central Asian alpine forests, leveraging tree-ring data and climate models to project how future hydroclimatic changes may influence forest growth. By using the Coupled Model Intercomparison Project 6 (CMIP6) (Eyring et al., 2016) and the Vaganov-Shashkin-Lite (VS-Lite) model (Tolwinski-Ward et al., 2013), we provide projections of future tree radial growth in the context of climate change, which could inform both ecological restoration efforts and future climate adaptation strategies.

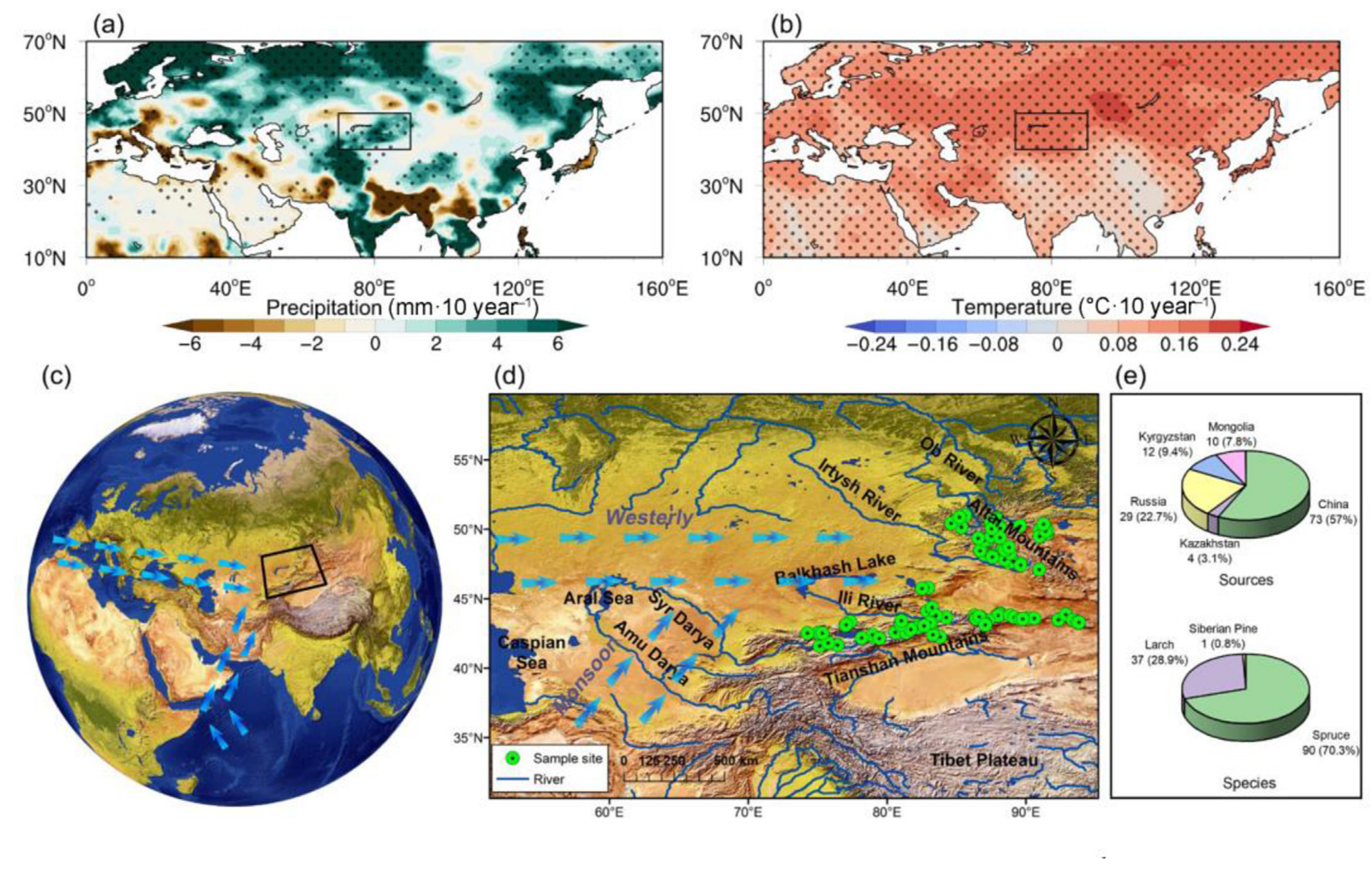

Fig. 1. Trends in **(a)** precipitation and **(b)** temperature since the 20th century. Dotted areas are above the 95% significance level. **(c, d)** Geographic locations of the Central Asian alpine forests and the 128 sampling sites. **(e)** Source countries and tree species for 128 sampling sites.

2. Materials and methods

2.1. Chronology development

We integrated a comprehensive tree-ring network comprising 128 conifer chronologies from the Central Asian alpine forests (Fig. 1 and Table S1). This network includes annual radial growth records for 90 spruce, 37 larch, and 1 Siberian pine, spanning five countries: China (73), Russia (29), Kyrgyzstan (12), Mongolia (10), and Kazakhstan (4), ensuring that each chronology is supported by at least 40 cores from 20 different trees. Specifically, they are from 17 sources, comprising 84 chronologies from 15 published studies (Cook et al., 2010; Ahmed et al., 2013; Chen et al., 2016a, 2016b, 2016c, 2016d, 2017a, 2017b, 2022, 2023c; Chen and Yuan, 2016; Taynik et al., 2016; Wang et al., 2017; Zhang et al., 2020; Gao et al., 2022), 15 chronologies from the International Tree Ring Database (ITRDB) without specified references, and 29 contributed by our research group for the first time. More information, including the exact geographic locations, is given in Table S1.

The unpublished chronologies, mainly collected in the Tianshan and Altai Mountains of Xinjiang, China, between 2006 and 2021, were carefully obtained using an increment borer operated at ∼1.3 m above the ground, followed by systematic labeling and organization. The cores were air-dried, mounted with white latex, and finely sanded with 320–1,000 grit sandpaper to enhance ring visibility. Core imaging utilized an Epson scanner, and the tree-ring widths were measured with 0.001 mm precision using CDendro 9.4 software, while earlier samples were measured with 0.01 mm precision via the Velmex system. Cross-dating accuracy was verified using the COFECHA program (Holmes, 1983), and the ARSTAN program facilitated the detrending and development of the final tree-ring width series (Cook, 1985), employing conservative detrending methods (negative exponential curves). The resulting 128 standardized (STD) chronologies were further analyzed to provide climatic and ecological insights.

2.2. Instrumental hydroclimatic data

The instrumental hydroclimatic data used in this study are as follows.

1) Global monthly surface gridded datasets from the Climate Research Unit (CRU), University of East Anglia, UK (CRU TS4.07) (Harris et al., 2014), with a horizontal resolution of 0.5° × 0.5°, spanning 1901–2022, including precipitation, temperature, and potential evaporation.
2) Global monthly surface gridded runoff dataset from the Institute for Atmospheric and Climate Science of the Eidgenössische Technische Hochschule Zürich, IAC ETH Zürich, Switzerland (G-RUN) (Ghiggi et al., 2021), with a horizontal resolution of 0.5° × 0.5°, spanning 1902–2019.
3) Global monthly surface gridded self-calibrating palmer drought severity index (scPDSI) dataset from the CRU, University of East Anglia, UK (van der Schrier et al., 2013), with a horizontal resolution of 0.5° × 0.5°, spanning 1901–2020.
4) Global monthly surface gridded normalized difference vegetation index (NDVI) dataset from the global inventory monitoring and modeling system (GIMMS) of the National Center for Atmospheric Research (NCAR) (Pinzon and Tucker, 2014), with a horizontal resolution of 0.25° × 0.25°, spanning 1981–2015.
5) Global monthly gridded sea surface temperature (SST) dataset (HadISST1) (Rayner et al., 2003) and sea level pressure (SLP) dataset (HadSLP2r) (Allan and Ansell, 2006) from the Hadley Center of the UK Met Office, UK, with horizontal resolutions of 1° × 1° and 5° × 5°, spanning 1870–2023 and 1850–2019, respectively.
6) Global monthly gridded surface temperature datasets from the National Oceanic and Atmospheric Administration (NOAA) (Vose et al., 2012) and the Goddard Institute for Space Studies of the National Aeronautics and Space Administration (NASA) (Hansen et al., 2010; Lenssen et al., 2019), with horizontal resolutions of 5° × 5° and 1° × 1°, spanning 1880–2022 and 1880–2023, respectively.

2.3. Modeled hydroclimatic data

The community earth system model-last millennium ensemble (CESM-LME), based on the CESM1.1 framework, is a sophisticated model that simulates the interactions among the atmosphere, ocean, land surface, sea ice, and land ice (Hurrell et al., 2013; Otto-Bliesner et al., 2016). With resolutions of ∼2° × 2° for atmospheric and land components and ∼1° × 1° for ocean and sea ice, CESM-LME offers detailed climate simulations. It incorporates internal climate variability and external forcings like solar variability, volcanic eruptions, land use changes, greenhouse gas concentrations, and orbital changes, representing a comprehensive dataset for paleo-hydroclimatic research. This study uses 13 all-forcing ensemble members from CESM-LME, including precipitation, temperature, SLP, winds, and humidity, at 500 hPa. CESM-LME's utility in delineating hydroclimatic changes and mechanisms in High Asia has been validated by previous research (Chen et al., 2020, 2021b, 2023a; Bakhtiyorov et al., 2023), highlighting its importance for regional climate dynamics.

This research utilizes CMIP6 simulations involving 24 different models, encompassing historical data (1850–2014) and future scenarios (SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP5-8.5) (2015–2100) for global monthly surface precipitation and temperature, refined via multi-model ensemble (MME) averaging to enhance signal reliability (Table S2) (Dai et al., 2020; Eyring et al., 2016). We also used a method for downscaling and bias correction, which is used to improve the reliability of future regional climate and environmental predictions (Xu et al., 2021; Chen et al., 2024b). First, both instrumental (CRU TS4.07 and HadISST1) and modeled precipitation and temperature were transformed to a 0.5° × 0.5° resolution using bilinear interpolation, and non-linear trends were extracted for the historical period (1901–2014) using the ensemble empirical model decomposition (EEMD) method (Wu and Huang, 2009). Residuals for MME are scaled in part by the ratio of the standard deviations (SDs) between instrumental and modeled data, followed by the addition of the instrumental non-linear trend. Thereby, downscaling and bias corrections are completed for the historical period, including precipitation, land temperature, and SST. For future climate projections, based on an assessment in Central Asia (Guo et al., 2021), we selected CESM2-WACCM, which is the most effective and accurate, as the standard model to repeat the above operations.

2.4. Nested principal component analysis

128 tree-ring width records, with end dates ranging from 1994 to 2021, were analyzed to extract a common signal of tree radial growth. This was accomplished using nested principal component analysis. Initially, the first principal component (PC1) was derived from the overlapping period (1900–1994) common to all series. Subsequently, the analysis iteratively removed the shortest sequence at each step before extracting the next PC1. A variance correction was then applied to subsequent PC1 extractions based on the variance of the initially derived PC1 (Büntgen et al., 2008; Frank et al., 2007). This process culminated in the splicing of PC1s from each nested interval to construct a new, normalized series. This method effectively mitigates the issues of changing variance and mean values inherent in diminishing chronologies. The resulting sequence, henceforth referred to as PC1, serves as a common signal for tree radial growth in Central Asian alpine forests and is significantly positively correlated with most chronologies, highlighting the robustness of the extracted growth signal (Fig. S1).

2.5. Resistance (R_s) and recovery (R_c) of trees

There is currently no universally accepted method for identifying extreme wet or drought events (Mccabe et al., 2024). In this study, the

PDSI is utilized to categorize wet and dry fluctuations, identifying the top 10% of extreme values as severe, the subsequent 10% as moderate, and the following 10% as mild conditions. Tree resilience to these events is quantified through the concepts of R_s and R_c (Zhang et al., 2022b; Zhao et al., 2023). R_s is defined as the change in the PC1 relative to the period preceding the extreme event. A value of R_s near zero indicates high resistance of tree radial growth to the extreme event. R_c is assessed by the difference in PC1 values post-event relative to the immediate at-event period, with values farther from zero indicating greater recovery. If the combined effect of R_s and R_c approaches zero, this suggests minimal impact of the extreme event on tree growth, implying high resilience to climatic extremes.

2.6. Future projections based on the VS-lite model

The VS-Lite model (Tolwinski-Ward et al., 2013) was employed to simulate tree radial growth in Central Asian alpine forests, utilizing downscaled and bias-corrected CMIP6 data. This model incorporates the “leaky bucket model” from the Climate Prediction Center (CPC) to estimate soil moisture based on monthly temperature and precipitation data and operates under the assumption that precipitation falls exclusively as liquid (Huang et al., 1996). Annually, the VS-Lite model initiates growth simulations with the minimum monthly growth response, factoring in temperature, soil moisture, and regulated by insolation. The day length is fixed for each latitude and does not vary year-to-year; hence, the study area only requires the latitude and monthly precipitation and temperature data to generate a normalized sequence of tree-ring widths. In this case, the temperature response and moisture parameters were calibrated using the Bayesian parameter estimation method, with other parameters set to their default values.

In this study, our initial step involved training simulations of the actual PC1 in the VS-Lite model based on the temperature and precipitation data from the CRU TS4.07 dataset spanning 1901–2021. After well training, we integrated historical and future climate data from CMIP6 into the VS-Lite model to generate continuous simulated PC1s extending from 1901 to 2100. Finally, we scaled the simulated PC1 for the historical period (1901–2014) based on the actual PC1 and adjusted this scaling to the simulated PC1 for the future period (2015–2100), which was used to compare the magnitude of the predicted future changes with the historical period and the actual tree radial growth (Rao et al., 2020).

2.7. Statistical analyses

To identify long-term trends in the tree radial growth and hydroclimatic changes in Central Asian alpine forests, we implemented the linear trend test (Hulme, 1992). The correlation census was used to specify the main climatic variables and month combinations controlling the tree radial growth (Chen et al., 2023d). To understand the regional hydroclimatic changes reflected by PC1, we computed spatial correlation patterns based on the results of the correlation census (Pederson et al., 2014). The effects of extreme wet or drought events on tree growth were further analyzed using the superposed epoch analysis (SEA), which is conducted through a Monte Carlo random sampling method (Haurwitz and Brier, 1981; Adams et al., 2003). If the event occurred, it was set to zero year, while changes were tested for three years before and six years after the event. Additionally, regression analyses were applied to explore the driving mechanisms behind the internal variability of the climate system affecting these hydroclimatic changes (Chen et al., 2023a). Direct interrelationships between hydroclimatic variables and tree radial growth were likewise shown to provide a more comprehensive understanding of the dynamics at play (Zhao et al., 2023; Zhang et al., 2022b).

3. Results

3.1. Tree radial growth trends in Central Asian alpine forests

The warming and humidifying rates of Central Asian alpine forests appear to have increased from around the beginning of the 20th century (Figs. 1a and b, and S2). The trend of increasing tree radial growth occurs in almost all alpine areas, with an average rate of increase of 0.049 per decade (common growth variability) (Fig. 2). PC1, representing the common signal of tree radial growth derived from nested principal component analysis (see Materials and methods), indicates a pronounced trend of increasing growth of 0.076 per decade ($p = 0.003$) (Fig. 2b). Three periods of rapid growth are evident: during 1929–1942 (+0.632), 1949–1972 (+0.377), and 1988–2006 (+0.738); and two periods of decreasing growth rate are evident: during 1906–1923 (−1.088) and 1973–1987 (−0.558). Additionally, over the past 122 years, 7 years of

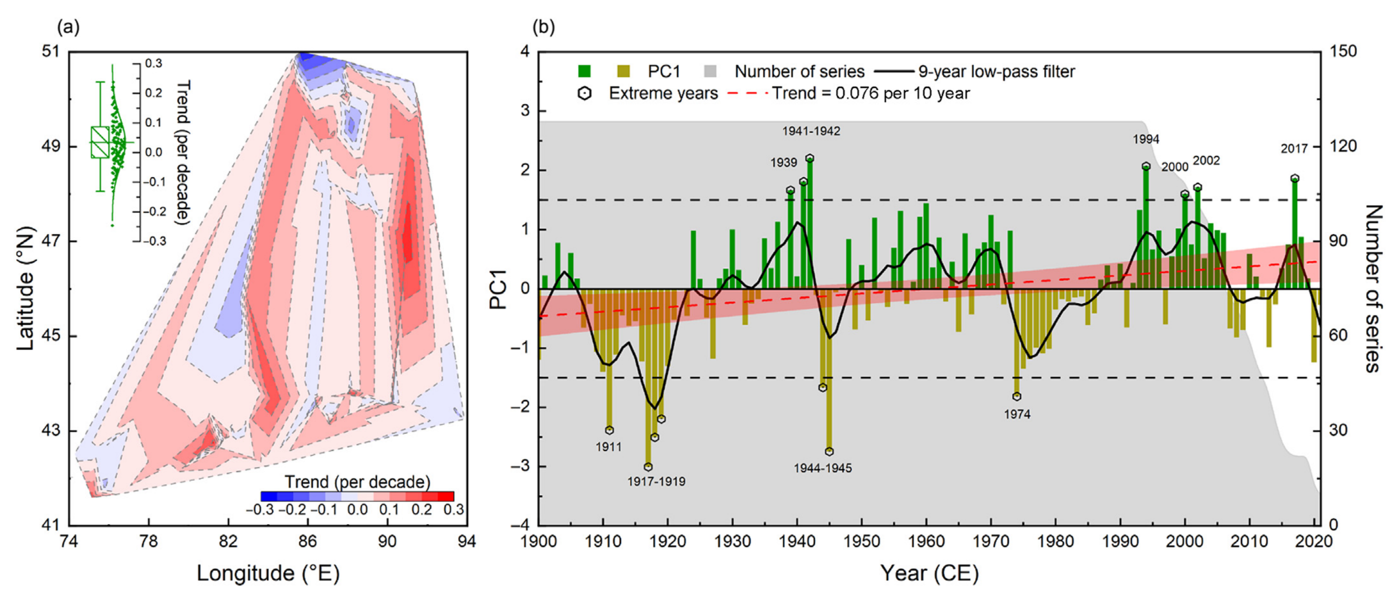

Fig. 2. (a) A spatial contour plot of trends for 128 normalized chronologies since the 20th century. The illustration shows a box-and-whisker plot of trends. The box represents the 25%–75% range, the whiskers extend to the ±1.5 interquartile range (IQR), and the center line represents the mean. The scatter and normal distribution plots are given in parallel. **(b)** Nested first principal component and its 9-year low-pass filtered curve from 1900 to 2021. Extreme years (exceeding the mean by ±1.5 SD), the number of series, and the trend are shown in the plot. The shaded areas denote the 95% uncertainty range.

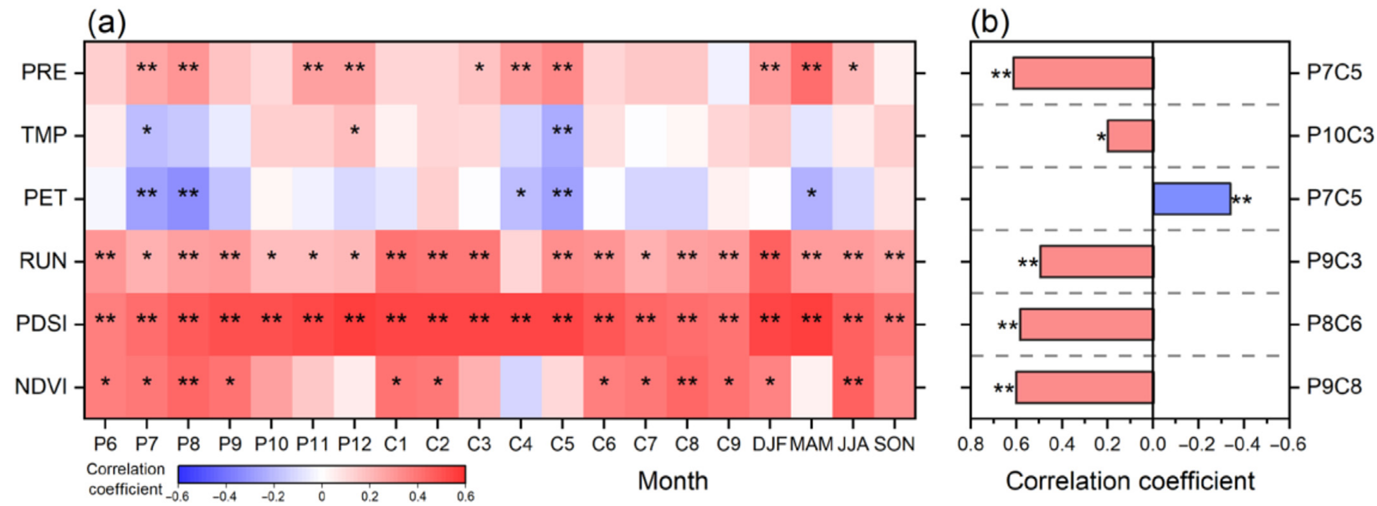

Fig. 3. **(a)** Heatmap of precipitation (PRE), mean temperature (TMP), potential evaporation (PET), runoff (RUN), palmer drought severity index (PDSI), and NDVI in correlation with PC1, respectively. Hydroclimatic data are regional averages for 40°–50° N and 70°–90° E. Correlations are calculated for the years 1901–2021 (PRE, TMP, PET, and PDSI), 1902–2019 (RUN), and 1981–2015 (NDVI). Correlation censuses include previous (P6–P12) and current (C1–C9) years, as well as winter (DJF), spring (MAM), summer (JJA), and autumn (SON). * and ** indicate the results are significant at the 95 % and 99 % levels, respectively. **(b)** Month combinations with the highest correlation coefficients.

extremely fast growth are evident (1939, 1941, 1942, 1994, 2000, 2002, and 2017), and seven years of extremely slow growth (1911, 1917, 1918, 1919, 1944, 1945, and 1974), defined by rates beyond ±1.5 SD of the mean.

3.2. Responses of tree radial growth to hydroclimatic changes

To examine the role of regional hydroclimatic changes in tree radial growth in Central Asian alpine forests, we determined the tree growth–hydroclimatic relationships based on correlation analyses (Fig. 3). Our results reveal that precipitation from the previous July to the current May (P7C5) is the most favorable for tree radial growth in Central Asian alpine forests ($r = 0.616$, $p < 0.01$). Also, there is a positive correlation between tree radial growth and temperature in roughly winter and spring (P10C3) ($r = 0.201$, $p < 0.05$) and a negative correlation in early summer (C4-5). In particular, as the combined reflections of environmental signals, we have observed strong positive responses between tree radial growth and runoff, PDSI, as well as vegetation growth in almost all months, most prominently in P9C3 ($r = 0.497$, $p < 0.01$), P8C6 ($r = 0.587$, $p < 0.01$), and P9C8 ($r = 0.603$, $p < 0.01$), respectively. Spatial response patterns suggest that alpine forests are critically regulated by regional hydroclimates and are important for rivers and ecological dynamics in the wider Central Asia (Fig. 4).

3.3. Resilience of tree radial growth to extreme hydroclimatic events

Tree growth responses to extreme climatic events are crucial for the health and stability of forest ecosystems, particularly in the fragile Central Asian alpine regions. In this study, we employ SEA to investigate the impact of extreme wet and drought events of varying intensities. The results indicate that these associations primarily occur in the year of the event when the PC1 exhibits significantly high or low values (Fig. 5a and b). Following extreme wet or drought events, tree radial growth in Central Asian alpine forests demonstrated a nearly linear correlation with changes in PDSI intensity, as shown in Fig. S3. Specifically, after mild, moderate, and severe wet events, characterized by PDSI values of +1.266, +1.386, and +2.300, respectively, PC1 exhibited corresponding increases of 0.466, 0.390, and 0.872. By contrast, following mild (−0.949), moderate (−1.064), and severe (−1.930) drought events, PC1 decreased by 0.417, 0.427, and 1.444, respectively. Notably, tree recovery was not linearly correlated with the degree of post-event wet or drought recession, with values of −0.435, −0.275, and −0.708 after wet events, and values of +0.635, +0.647, and +0.982 after drought events. These patterns indicate that a water surplus after a wet event still supports increased tree radial growth (Fig. 5c), whereas, after a drought event, the trees showed compensatory growth (Fig. 5d). However, under severe drought conditions, the potential for this compensatory growth is significantly reduced, making it difficult for tree radial growth to recover to its prior state (Fig. 5d).

3.4. Linkages with large-scale atmospheric circulations

The relationship between tree radial growth in Central Asian alpine forests and temperatures at lower latitudes demonstrates influences from lower latitudes that may impact tree growth even more significantly than local temperature variations (Fig. 4b). This observation caused us to focus on the impact of large-scale warming signals, particularly from low-latitude regions. Our analyses confirm that moderate temperature increases in these lower latitudes are beneficial for tree growth in Central Asia (Fig. 6a–c). The temporal scope of our study spans the range from the previous July to the current June, encompassing a full hydrologic year. This suggests that temperature increases in low-latitude regions (30°S–30°N), particularly around the Indian Ocean (15°S–35°N, 30°E–130°E), the central-east Pacific Ocean (20°S–20°N, 90°W–180°), and the Atlantic Ocean (30°S–30°N, 0°–80°W), contribute significantly to tree radial growth in these forests. Since the 20th century, changes in precipitation and PC1 were more closely linked to the above three circum-oceanic regions and to the entire low-latitude region, including original and first-order difference data. These relationships are all statistically significant at the 1‰ level (Fig. S4). Additionally, spatial correlation analyses between PC1 and SLP demonstrated the significant impact of low-latitude climate variations on tree growth (Fig. 6d). The significant contributions of large-scale sea-air interactions are also supported by results based on paleo-hydroclimate modeling (Fig. 7).

3.5. Future projections

Utilizing downscaled and bias-corrected CMIP6 data (Fig. S5) (Eyring et al., 2016; Xu et al., 2021), we employed the VS-Lite model (Tolwinski-Ward et al., 2013) to project tree radial growth in Central Asian alpine forests under anticipated future climatic conditions. Initially, the model was trained with precipitation and temperature data from CRU

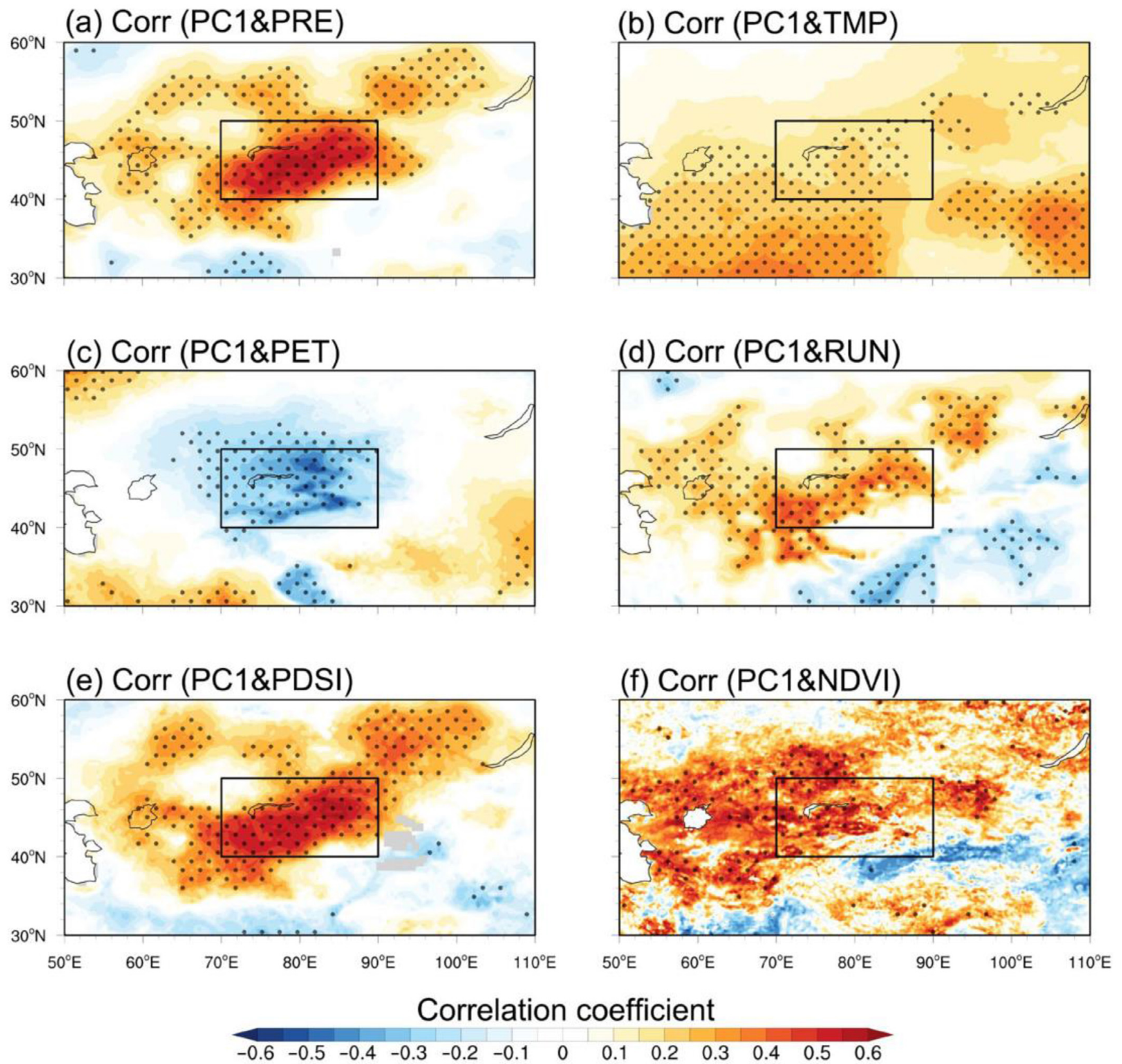

Fig. 4. Spatial correlation patterns between PC1 and **(a)** precipitation, **(b)** temperature, **(c)** potential evaporation, **(d)** runoff, **(e)** PDSI, and **(f)** NDVI using the month combinations with the highest correlations in Fig. 3. Dotted areas are above the 95% significance level.

TS4.07 (Harris et al., 2014), which showed an acceptable performance ($r = 0.513, p < 0.001$) (Fig. 8a). The calibrated model was then applied to continuous tree growth projections spanning from 1901 to 2100 based on CMIP6 data, with appropriate scaling used to make reasonable comparisons between the past and future (Rao et al., 2020) (Figs. 8b and S6). The congruence between simulated and actual PC1 trends (0.074 per decade vs. 0.076 per decade) during the historical period reveals the robustness and validity of our projections. With projections extending into future scenarios characterized by continued warming and humidification (Fig. S5), our results indicated continued upward trends in tree radial growth. Specifically, growth rates are projected to accelerate to 0.133, 0.142, 0.218, and 0.337 per decade under the SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5 scenarios, with these trends being statistically significant ($p < 0.001$), as shown in Fig. 8b.

4. Discussion

4.1. Growth enhancement and responses under warming and humidification

A well-documented climatic shift from “warming and drying” to “warming and humidification” has occurred in Central Asia since the 1980s (Chen et al., 2010, 2023b; Zhang et al., 2022a). In particular, this phenomenon seems to have started earlier in the Central Asian alpine forests (Figs. 1a and b, and S2). Concomitantly, the tree radial growth in the Central Asian alpine forests showed a similar significant increase. Our findings reveal that the regional hydrological cycle, represented by precipitation, has a strong effect on the tree radial growth in these alpine forests, especially at the beginning of the growing season (Figs. 3 and 4a). As the principal moisture source for vegetation growth, precipitation is

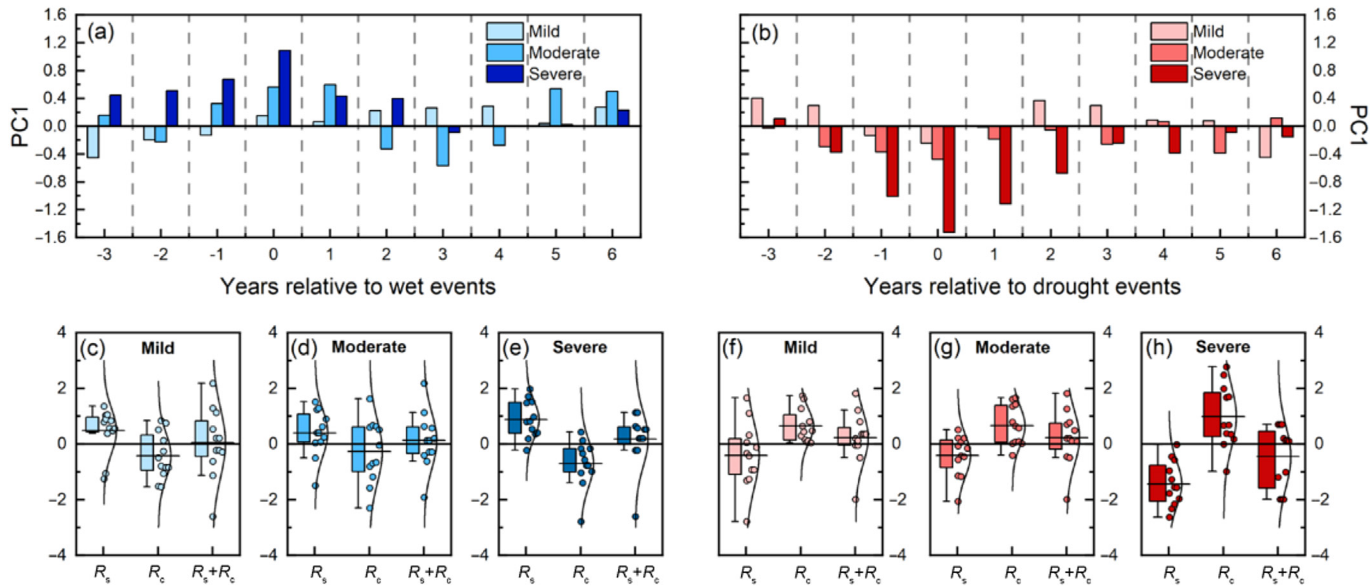

Fig. 5. Results of the SEA assessing the responses of tree radial growth to mild, moderate, and severe **(a)** wet or **(b)** drought years. R_s, R_c, and their sum ($R_s + R_c$) of tree radial growth under **(c)** mild, **(d)** moderate, and **(e)** severe wet years as indicated by box-and-whisker plots. **(f–h)** are the same as **(c–e)** but correspond to drought events. R_s quantifies the growth deviation in the event year from the year prior to the wet/dry events, serving as an indicator of the event's immediate impact—values further from zero denote greater effects. Conversely, R_c measures the growth change from the event year to the year after wet/dry events, serving as an indicator of growth recovery—values further from zero denote more effective recovery. The cumulative effect of R_s and R_c ($R_s + R_c$), when closer to zero, suggests the minimal impact of the event. The box of the box-and-whisker plot represents the 25%–75% range, the whiskers extend to ±1.5 IQR, and the center line represents the mean. To the right are the scatter and normal distribution plots.

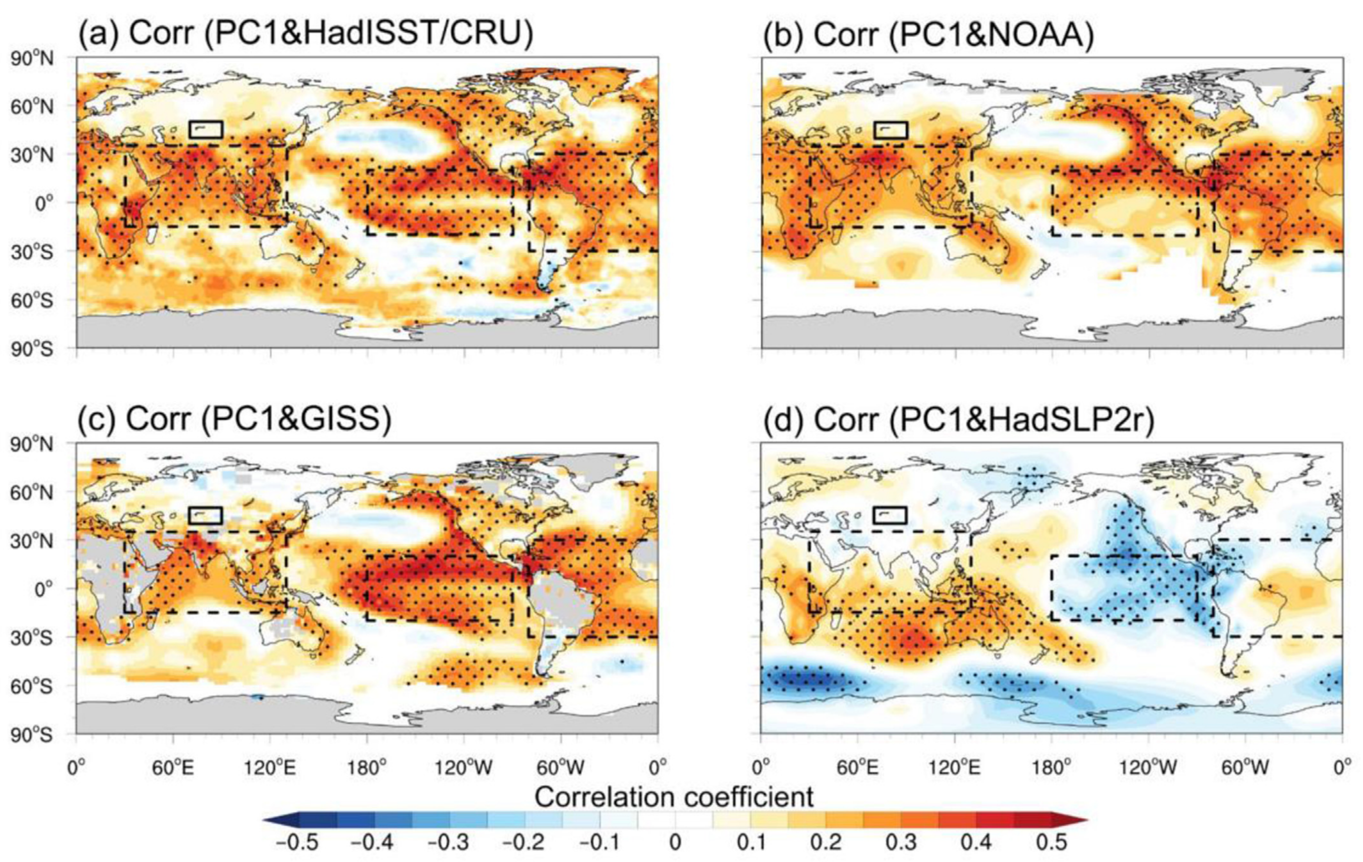

Fig. 6. (a) Spatial correlation patterns between PC1 and sea surface temperature from HadISST1/land temperature from CRU TS4.07 since the 20th century. Dotted areas indicate above the 95% significance level. **(b, c)** are the same as (a) but from NOAA and GISS. **(d)** is the same as (a) but for SLP from HadISLP2r.

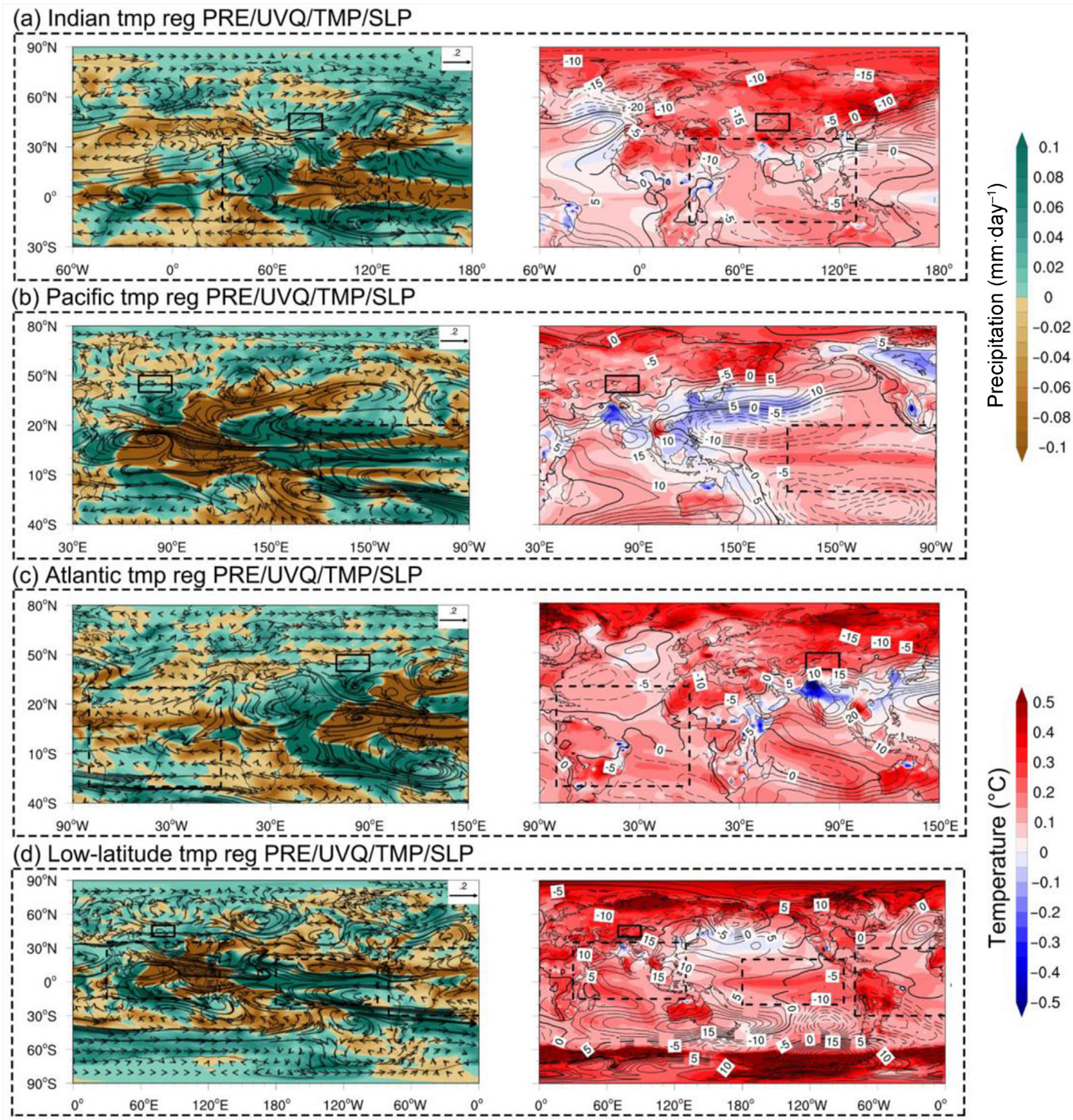

Fig. 7. Precipitation (left shading, unit: mm·day^{-1}), water vapor flux at 500 hPa (left vector, unit: kg·m^{-2}·s^{-1}), surface temperature (right shading, unit: °C), and SLP (right contour, unit: Pa) regressed by the normalized surface temperature regressions since the 20th century in the CESM-LME, including **(a)** the circum-low-latitude Indian Ocean (15°S–35°N, 30°E−130°E), **(b)** the circum-low-latitude central-east Pacific Ocean (20°S–20°N, 90°W–180°), **(c)** the circum-low-latitude Atlantic Ocean (30°S–30°N, 0°–80°W), and **(d)** the entire low-latitude regions (30°S–30°N). The surface temperature of each individual ocean is isolated from the influences of the other two oceans through multiple linear regression to highlight the unique signal, while the low-latitude surface temperature represents the overall signal.

vital during the early growing season when it supports tree growth by increasing soil moisture availability (Chen et al., 2016c, 2016d; Gradel et al., 2017; Opala et al., 2017). This facilitates water uptake by tree roots and offsets losses from intense evapotranspiration, thereby promoting cellular production essential for the development of the tree's formative layers (Fritts, 1976; Ziaco and Liang, 2018). Strong evapotranspiration caused by the high temperatures in early summer has a negative impact on the radial growth of trees, via stomatal closure and water loss (Williams et al., 2013; Lian et al., 2021). By contrast, a warmer pre-winter can enhance cellular activity and increase meltwater from snow and ice, which mitigates the negative effect of low temperatures and also improves the growth conditions for the subsequent year (Salzer et al., 2009; Zhao et al., 2023) (Figs. 3, 4b and 4c). Overall, appropriate warming and humidification are beneficial in the Central Asian alpine forests. In addition, these forests are key factors in maintaining the water cycle and ecosystems of Central Asia, which are essential for inland water

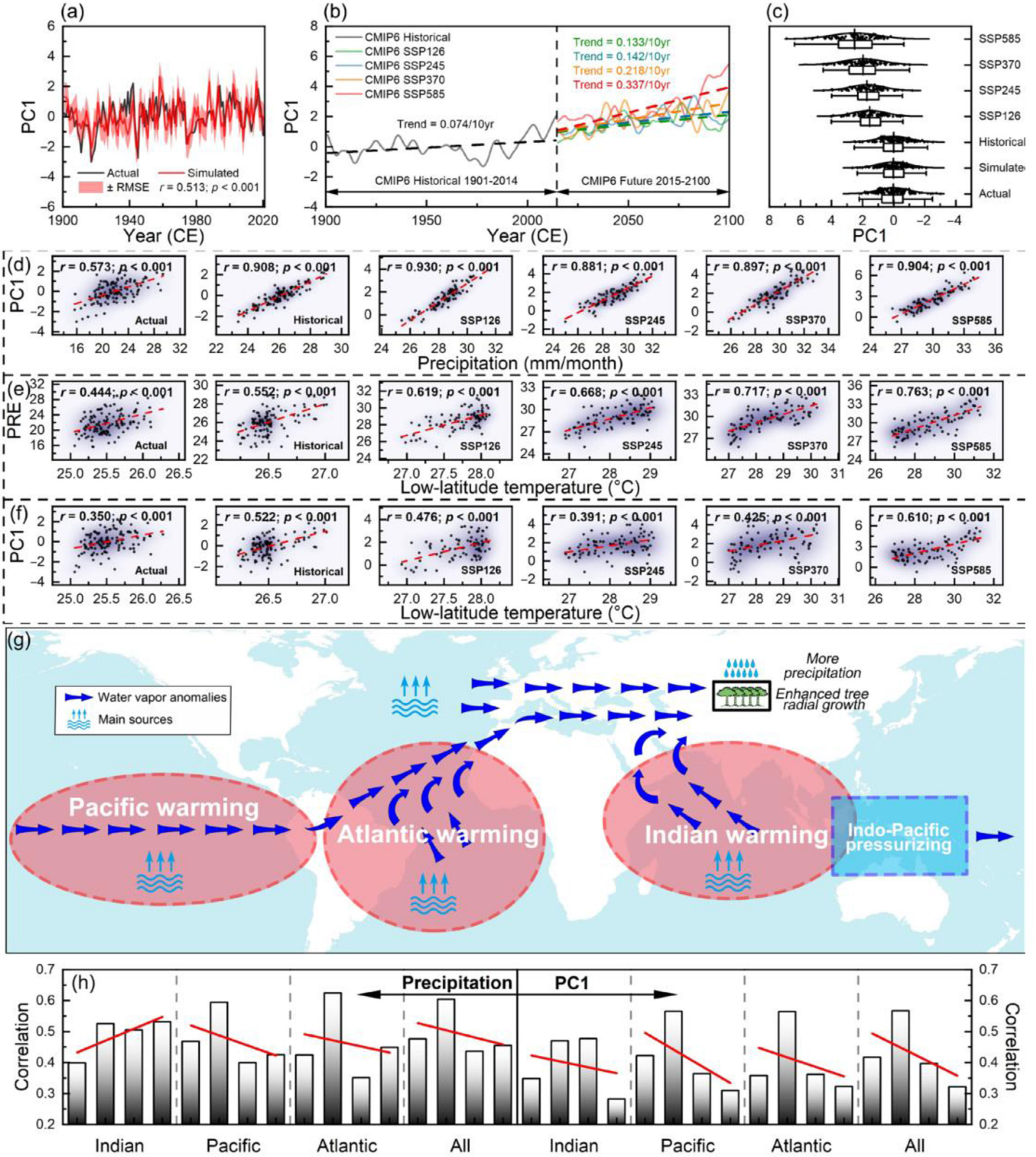

Fig. 8. **(a)** Comparison of actual and simulated PC1 from VS-Lite model based on CRU TS4.07 data (40°N–50°N, 70°E−90°E). The shaded area denotes ± root mean square error (RMSE) range. **(b)** Simulated tree radial growth after 9-year low-pass filter smoothing for historical (black line) and future scenarios (SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5) (green, blue, orange, and red lines) in CMIP6 based on VS-Lite model. The simulated original values are scaled to the actual PC1, making the two directly comparable. The dashed lines represent linear fits, the same as below. **(c)** Distributions of tree radial growth for actual, simulated, and CMIP6. **(d)** Scatter density plots indicate the association between precipitation and tree radial growth. From left to right, the actual, CMIP6 historical, and future periods are shown. A darker purple shade represents a more concentrated kernel density. **(e, f)** are the same as **(d)** but indicate the associations between low-latitude temperature with precipitation and low-latitude temperature with tree radial growth, respectively. **(g)** Schematic diagram of hydroclimatic responses and tree radial growth due to low-latitude warming. **(h)** First-order differential correlations of temperatures with precipitation and PC1 for the circum-low-latitude Indian Ocean, circum-low-latitude Pacific Ocean, circum-low-latitude Pacific Ocean, and the entire low-latitude regions. Each sub-zone includes, from left to right, SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5. The solid red lines are the fitted lines.

conservation and natural sustainability (Davi et al., 2006; Chen et al., 2021b; Bakhtiyorov et al., 2023; Shi et al., 2024) (Figs. 3, 4d and 4f).

The intensity and duration of extreme hydroclimatic events often have complex effects on tree growth and forest health (Allen et al., 2020; Zhang et al., 2022b; Zhao et al., 2023). In Central Asia, a region characterized by chronic water scarcity due to its location in the arid interior of Eurasia, moisture availability is a critical factor for tree growth (Liu et al., 2022; Wise and Dannenberg, 2022). Extreme wet events above thresholds that negatively impact tree radial growth in this region are rare. Rather, prolonged wet conditions can enhance moisture availability, supporting sustained growth (Rodríguez-González et al., 2010; Gee et al., 2014) (Figs. 5a and c, and S3a). In contrast, the impacts of extreme droughts on tree growth are more pronounced in these vulnerable alpine forests, and there are significant linear relationships observed between drought intensity and reduced growth (Figs. 5b and d, and S3b). During droughts, reduced water availability inhibits photosynthesis and slows tree growth, leading to stunted growth and potential mortality under severe conditions (Ripullone et al., 2009; Allen et al., 2015; Zhang et al., 2022c). Recovery processes vary depending on the severity of the drought. Trees exposed to mild and moderate droughts can exhibit compensatory growth, potentially by deepening their root systems to access deeper water reserves (Ovenden et al., 2021). Upon the return of favorable environmental conditions, trees utilize stored reserves to accelerate growth and recover to pre-drought growth rates, driven by their genetic potential (Balducci et al., 2016; Pan et al., 2022). However, severe droughts can overwhelm the tree's capacity for recovery, leading to irreversible damage and a failure to return to pre-drought growth levels (Dannenberg et al., 2019; van Kampen et al., 2022; Zhao et al., 2023) (Fig. 5d). The ability of trees to recover from drought stress is closely linked to the moisture thresholds that determine their growth potential post-event. These thresholds are crucial for understanding resilience to drought events. Although extreme wet events, including those triggered by floods, can also result in tree mortality (Tzeng et al., 2018; de Resende et al., 2019), the primary risk for Central Asian alpine forests remains drought events. Drought thresholds, when surpassed, can lead to substantial reductions in tree growth and, in extreme cases, death, underscoring the need for adaptive forest management strategies that account for these thresholds and the vulnerability of these ecosystems to extreme hydroclimatic events.

4.2. Contributions and mechanisms of low-latitude warming

It is noteworthy that there is a positive association between the tree radial growth in the Central Asian alpine forests and much of the global warming, especially at low latitudes (Figs. 6 and S4). To determine the specific effects of temperature variations across different low-latitude oceans on atmospheric circulation, we used multiple linear regression techniques that adjust for inter-regional differences, isolating warming trends and the specific variabilities for each circum-oceanic region. Temperatures averaged across all the low-latitude regions were examined for common signals. Several studies have observed a robust link between atmospheric circulation patterns due to large-scale surface temperature changes and hydroclimatic shifts (Chen and Huang, 2012; Huang et al., 2015; Zhao and Zhang, 2016; Guan et al., 2019; Chen et al., 2020, 2021b; Jiang et al., 2021; Bakhtiyorov et al., 2023; Jiang and Zhou, 2023). Our findings based on the CESM-LME further support this link, showing that large-scale atmospheric circulations driven by temperature changes centered on low-latitude oceans are critical for regulating the hydroclimatic variability and tree growth dynamics in Central Asian alpine forests (Fig. 7).

Warm phases in the circum-low-latitude Indian Ocean enhance southwesterly water vapor transport across regions such as the Somali Peninsula, the Arabian Sea, the Arabian Peninsula, and the Iranian Plateau, causing increased precipitation in Central Asia and thereby promoting tree growth in alpine forests (Huang et al., 2015; Zhao and Zhang, 2016; Guan et al., 2019; Chen et al., 2021b) (Fig. 7a). Similarly, warm conditions in the tropical east-central Pacific Ocean often leads to higher SLP over the Indo-Pacific warm pool, driving moisture-laden southwesterly winds towards Central Asia along the northwestern boundary of the high SLP zone (Chen and Huang, 2012; Chen et al., 2020; Bakhtiyorov et al., 2023; Jiang and Zhou, 2023) (Fig. 7b). Additionally, a weakened Pacific Walker Circulation during warm phases promotes increased water vapor retention in the eastern Pacific, which enables moisture accumulation and latent heat release across the Pacific-Atlantic region, further enhancing the precipitation in Central Asia (Weng et al., 2007; Wu et al., 2021). The warm phases of the circum-low-latitude Atlantic Ocean trigger diagonal pressure wave trains that propagate eastward in the northern hemisphere, creating favorable conditions for ascending atmospheric motion in Central Asia and enhancing westerly wind-driven moisture transport from the North Atlantic and Northern Europe, thus inducing precipitation (Chen et al., 2010, 2023b; Ma et al., 2020; Jiang et al., 2021) (Fig. 7c). When the entire low-latitude region transitions from a cold to a warm phase, the intensified water vapor supply and circulation dynamics centered around these three oceans lead to increased precipitation in the areas of Central Asian alpine forests, promoting increased tree radial growth (Fig. 7d). There is no doubt that global warming provides certain favorable conditions for forest ecosystems, which suggests that policymakers need to pay attention not only to regional changes but also to large-scale climate anomalies.

4.3. Implications for future environmental management and limitations

Future climate projections based on CMIP6 indicate that warming and humidification in the Central Asian alpine forests will still be ongoing (Fig. S5). In this context, the tree radial growth based on the VS-Lite model also showed increasing trends (0.133, 0.142, 0.218, and 0.337 per decade under the SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5 scenarios) (Fig. 8b). Notably, the expanded variability in future projections suggests increased risks of extreme climatic impacts (Fig. 8c). The positive feedback of continued low-latitude warming on increased precipitation in Central Asia is still present, which is one of the reasons why the tree radial growth in alpine forests is still enhanced (Figs. 8d–g and S7–S11). Nevertheless, this positive feedback is not without its limitations, as current idealized and simplified models fail to accurately capture the complex feedback mechanisms between tree growth and climate. On one hand, if precipitation does not keep pace with rising temperatures, the positive effects of warming on tree growth may be reversed. As temperatures continue to increase, the risk of more severe droughts intensifies, particularly in regions where water availability is already constrained (Zheng et al., 2022). On the other hand, as climate change progresses, trees may exhibit nonlinear growth responses to extreme climatic events, with growth potentially being strongly limited by thresholds not accounted for in current linear model assumptions (Camarero et al., 2022). For example, prolonged droughts or heatwaves could lead to sudden and severe declines in tree growth or even mortality, which the current model framework may fail to predict accurately. Additionally, we are concerned that the first-order differential relationships between low-latitude temperatures and precipitation or tree growth in Central Asian alpine forests are weakening along with increasing emission concentrations, which is noteworthy and alarming (Figs. 8h and S7–S11). In conclusion, while projections based on CMIP6 and the VS-Lite model provide valuable preliminary insights, these results should be interpreted with caution. It is crucial for environmental managers to monitor the potential for negative tipping points to mitigate the risk of widespread forest ecological collapse and its cascading effects.

The limitations of the VS-Lite model for projecting tree radial growth are not negligible. Specifically, the model does not account for the hysteresis of climatic effects, particularly the lagged influence of previous precipitation on current growth (Zeng et al., 2019). Moreover, concerns have been raised regarding the model's reliance on temperature as the sole driver for estimating evapotranspiration. This simplification may become less accurate under future warming scenarios, potentially leading to inaccuracies in the model's soil moisture calculations (Smerdon et al., 2015; Matskovsky et al., 2021; Wang et al., 2024). The model's current method of estimating evapotranspiration does not fully capture the complex interactions between various climatic variables, which can be critical under changing climate conditions. Therefore, the VS-Lite model's simplified evapotranspiration estimations might underestimate the impacts of drought in future projections, as it does not consider factors such as changes in humidity, wind speed, and solar radiation. Additionally, the VS-Lite model does not integrate several critical environmental factors that may significantly influence future tree growth dynamics, such as winter snowpack, atmospheric CO_2 concentrations, tree mortality rates, and potential physiological responses to changing environmental conditions (Qin et al., 2016; Zeng et al., 2019; Matskovsky et al., 2021). These factors could play substantial roles in determining the growth patterns of trees, especially in regions experiencing rapid climatic shifts.

While enhancing the model's complexity by incorporating these factors could provide more detailed and potentially more accurate insights, it would also necessitate more extensive data and increase computational demands. Therefore, the relative simplicity of the VS-Lite model remains one of its strengths, particularly in situations where data availability is limited. Nevertheless, to improve the model's accuracy and applicability under complex climate change scenarios, future model developments should consider integrating a broader range of climatic and environmental variables. Our preliminary findings suggest a positive response of tree growth to global warming in Central Asian alpine forests, driven by increased precipitation associated with low-latitude warming. However, to better reflect the complex physiological processes within trees, further validation under the unique climatic conditions of Central Asia is essential. This validation should be coupled with the development of more sophisticated growth models that can account for the nuances of tree physiology and environmental interactions. Additionally, policymakers should pay close attention to the risks posed by recurrent droughts to forest ecosystems and prioritize the protection of inland water resources, as well as the rational management of water resources and agricultural production in riparian regions.

5. Conclusions

Climate change significantly affects forest ecosystems, particularly in sensitive regions like Central Asian alpine forests in Eurasia's center. Given the region's susceptibility to climatic fluctuations and the importance of water conservation, understanding overall tree growth dynamics is crucial for projecting ecological and hydrological evolutions and averting adverse impacts. Based on 128 published and newly acquired tree-ring chronologies, we observe that, benefiting from a warmer and wetter climate, tree radial growth is enhancing in the alpine forests of Central Asia, implying a greener center of Eurasia. Regional water cycles dominated by precipitation play a significant role in tree growth, with high temperatures causing intense evaporation as a primary limitation, while warmer conditions during the dormant season favor growth. Additionally, maintaining these forests is vital for conserving water sources in inland rivers and stabilizing ecosystems. While the overall trend was positive, and tree growth showed remarkable resilience, our analysis of extreme hydroclimatic events suggests that the damaging risks of severe drought cannot be ignored. Trees managed to maintain growth rates even during periods of drought and extreme weather, indicating an inherent adaptive capacity. However, whether this resilience will stay sustainable under continued climate stress remains uncertain.

Our study highlighted the significant role of low-latitude warming, particularly around the Indian, Pacific, and Atlantic Oceans, in enhancing the greening of Eurasia's center. This warming promotes favorable atmospheric circulation patterns that increase precipitation in Central Asia, ultimately promoting tree radial growth in alpine forests. This positive feedback mechanism highlights the complex and interconnected nature of global climatic systems, where changes in one part of the world can have far-reaching effects on ecosystems in distant regions. In particular, low-latitude warming, which is more precise in the broader global warming discussions, has emerged as a key driver of alpine forest growth patterns in Central Asia. The models project continued increases in tree radial growth rates under future warming scenarios, with significant growth projected under future warming scenarios. However, the projections also reveal a heightened risk of greater climatic variability and more frequent extreme weather events. Additionally, as more severe global warming scenarios emerge, positive feedback mechanisms are weakened, and the relationship between low-latitude warming and increased precipitation shows decoupling signs, which raises concerns for forest growth dynamics. In conclusion, our research provides valuable insights into the dynamic relationship between climate change and tree growth in Central Asian alpine forests, offering a unique perspective on how low-latitude warming influences growth patterns in a high-altitude, water-scarce region. While current climatic conditions favor tree growth, the potential for increased variability and extreme events poses significant risks. Enhanced modeling approaches and continuous climatic monitoring are essential for better understanding and mitigating future impacts. Policymakers must prioritize sustainable water resource management and protective measures to ensure the resilience of these critical forest ecosystems under changing climatic conditions.

Data archiving statement

The tree-ring width data can be found in the International Tree Ring Database (ITRDB) (https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring). The instrumental hydroclimatic data can be obtained from the Koninklijk Netherlands Meteorologisch Instituut (KNMI) (https://climexp.knmi.nl/). The CESM-LME Database is provided by the Earth system grid (https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_LME.html). All data from CMIP6 simulations used in our analyses are freely available from the Earth System Grid Federation (ESGF) (https://esgf-node.llnl.gov/search/cmip6/). The code to perform these analyses is available from the corresponding authors upon request.

CRediT authorship contribution statement

Shijie Wang: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Feng Chen:** Writing – review & editing, Visualization, Validation, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Youping Chen:** Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Data curation. **Max C.A. Torbenson:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis. **Jan Esper:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis. **Xiaoen Zhao:** Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Mao Hu:** Writing – original draft, Visualization, Methodology, Formal analysis. **Heli Zhang:** Supervision, Resources, Data curation. **Weipeng Yue:** Validation, Methodology. **Honghua Cao:** Visualization, Methodology.

Data availability

Data will be made available on request.

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Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fecs.2025.100330.

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