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Increasing growth sensitivity of *Pinus wallichiana* to summer season maximum temperature – evidence from central Bhutan Himalaya

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Abstract: The impacts of global warming are pervasive across different forest biomes and are most pronounced in high mountain ecosystems such as the Himalayas. This study examines the growth response of Blue pine (*Pinus wallichiana*) to climate from Bumthang district in the central Bhutan Himalaya. Tree radial growth parameters (ring width index and basal area increment) were correlated with monthly and daily climate. Temporal changes in significant climate response were assessed using running correlations. Irrespective of tree growth parameters or temporal resolution of climatic variables, growth-climate response revealed maximum temperature during summer as the most significant climatic factor regulating the growth of *P. wallichiana* in central Bhutan. The strength and stability of the climate response improved when using daily climate, which is not restricted by non-biological calendar months. Around the turn of the 21st century, we observed a rapid rise in radial growth. Over the last ~30 years, blue pine from central Bhutan has benefited from warming summer season maximum temperatures. This study highlights the importance of considering daily climate variables for more accurate assessments of tree growth responses to climate. These findings have significant implications for understanding the impact of climate change on forests in the Himalayan region.

Keywords: tree-rings, eastern Himalaya, daily climate, climate change

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Introduction

The distribution of vegetation in the Himalayan regions is mainly attributed to climatic factors, and it is one of the most biologically diverse regions of the world (Salick et al., 2014). Bhutan, which lies in the eastern Himalayas, has been experiencing rapidly rising trends in temperature and precipitation both during summer and winter (Chhogyel & Kumar, 2018). The distribution range of major timber and fuelwood species in Bhutan is projected to decline substantially and shift to higher altitudes due to climate change (Choden et al., 2021). While most studies of species distribution assume linear relationships between tree species and climate, it is becoming increasingly clear that trees and, therefore, forests may respond dynamically to environmental changes (McDowell et al., 2020). Such variations in tree response can be evaluated more effectively from the level of individual trees to forest stands or even entire forest biomes by using tree rings (Speer, 2010).

The tree growth-climate response in dendrochronological studies is primarily carried out with monthly climate variables. This is partly because relatively long-term gridded climate datasets can be easily obtained at monthly time scales, even in places where station data are unavailable. Consequently, the usage of monthly climate is a common practice for identifying significant climatic variables. The restriction of climate variables to calendar months may dilute the climate signal embedded in tree rings since months are arbitrary limits and do not correspond with tree physiological processes. Recent improvements in methodology and availability of high-resolution daily climate records have aided in the analysis of tree growth-climate response to daily climate (Beck et al., 2013; Pritzkow et al., 2016; Jevšenak & Levanič, 2018; Nechita et al., 2019; Thomte et al., 2021; Magnússon et al., 2023). Studies using daily climate have demonstrated an enhanced relationship between climate and tree growth indices (Sun & Liu, 2016; Jevšenak, 2019; Thomte et al., 2022) and the potential for capturing the influence of short, extreme climate events on the growth of trees (O'Donnell et al., 2021; Trumper et al., 2022). Similar growth and daily climate response analyses have rarely been investigated in the Himalayan region, including Bhutan.

Dendroclimatic reconstructions are developed based on the assumption of a temporally stable response of trees to climate (Fritts, 1976). Consequently, if the climate response of trees is unstable, it would adversely impact the accuracy and reliability of the reconstructed climate. A global review by Wilmking et al. (2020) noted that around two-thirds of tree-ring studies did not evaluate for stationary of tree growth and climate relationships. Further, the authors found that more than half of the studies that tested the temporal stability reported a non-stationary temporal response of trees to climate. A non-stationary relationship between tree growth and climate may indicate a shift in the climatic variable limiting tree growth (D'Arrigo et al., 2008; Lebourgeois et al., 2012). Conversely, trees' temporally variable climate response may simply result from a dynamically evolving natural response between trees and their environment (McDowell et al., 2020; Wilmking et al., 2020). Analyzing the stability of tree growth climate responses over time may provide important clues to understanding and predicting the response of trees to climate change (Peltier & Ogle, 2020).

The basal area increment (BAI) or ring area is a two-dimensional variable considered a good measure of overall tree growth and productivity (Biondi, 1999; Biondi & Qeadan, 2008; Correa-Díaz et al., 2019). The conversion of ring width measurements to BAI removes the geometric restriction of decreasing (increasing) ring width (circumference) towards the bark. The BAI chronology may be an alternative to standard ring-width detrending methods used as (Sullivan et al., 2016; Mazza & Sarris, 2021). Some studies have demonstrated higher growth-climate correlations with BAI chronologies than detrended ring-width chronologies (Baral et al., 2019; Labrecque-Foy et al., 2023). A comparative analysis of the climate response of BAI and ring width chronologies may improve the reliability of potentially observed growth-climate relationships.

The abundance of forests and long-lived trees in the Bhutan Himalayas makes the region an important storehouse of paleoclimatic information. Sano et al. (2013) reconstructed 269-year summer monsoon precipitation using stable oxygen isotopes from tree rings of *Larix griffithii*. Multi-centennial temperature reconstructions have also been developed from the region using tree-ring width chronologies of *Picea spinulosa* (Krusic et al., 2015) and *Abies densa* (Khandu, Polthanee, & Ayutthaya, 2022b). Advancing tree lines have recently been reported in the northern extreme of Bhutan based on observations of regeneration and expansion rates of *Abies densa* (Khandu, Polthanee, & Ayutthaya, 2022a). The density fluctuations and scars observed in tree rings of multiple species were used to reconstruct flood history and estimate the streamflow of the Dhur River in north central Bhutan (Speer et al., 2019). The focal theme of most of these studies is for reconstructing past climate/ hydroclimate variability from tree-ring-derived proxies. Only a few studies have attempted to address aspects of tree growth variability due to changes in climate and other environmental parameters.

Blue pine (*Pinus wallichiana* A.B. Jackson) is considered one of the most suitable species for dendroclimatological studies in the Himalayan region due to its high sensitivity to climatic variables and wide geographical distribution (Gautam et al., 2021). It is a conifer native to the Himalayan region and is found at an altitude ranging from 1800–4000 m.a.s.l. (Dukpa et al., 2018; Wangchuk et al., 2018). *P. wallichiana* produces clear and dateable annual rings and has been extensively used in paleoclimatic studies across the entire range of the Himalayas (Shrestha et al., 2015;

Gaire et al., 2019; Shah et al., 2019; Bhandari & Speer, 2020; Gautam et al., 2022). Despite its prevalence in the forests of Bhutan, limited dendrochronological studies of *P. wallichiana* have been conducted in the region and are confined to a few localities (Tshering et al., 2023). One study focused on the relationship between three *Pinus* ring width chronologies (including *P. wallichiana*) from Bhutan, India, and Thailand with global surface temperatures (Buckley et al., 2005). In this study, spatial correlations with surface temperatures were distinct and weaker for Bhutan pines than those from India and Thailand. In the temperate conifer forest of western Bhutan, Wangchuk et al. (2018) examined the effect of topography and climate on the radial growth of *P. wallichiana*. Correlation analysis indicated radial growth was negatively correlated with altitude (slope and aspect) in the trees from the northern (southern) aspect (Wangchuk et al., 2018). They also described a higher climate sensitivity in trees from the southern aspect compared to the northern aspect. A recent study by Choden et al. (2021) modeled the future distribution of *P. wallichiana* in Bhutan, which projected a range contraction by as much as 78% towards the end of the 21st century. Considering the potentially drastic decline in species distribution, the effect of climate change on the growth and productivity of *P. wallichiana* in Bhutan remains poorly understood.

This study addresses the dynamic relationship between climate variability and tree growth in Bhutan, focusing on *P. wallichiana* in central Bhutan. Specifically, our objectives include the development of tree-ring chronologies based on detrended ring width and BAI, analyzing tree growth trends, and assessing the impact of climate variability using daily climate variables. This research aims to enhance our understanding of how *P. wallichiana* responds to changing climatic conditions and contribute valuable insights for forest management and conservation strategies in the Himalayan region.

Materials and methods

Study area

The sampling was conducted in the Ugyen Wangchuk Institute for Forestry Research and Training (UWIFoRT) forest research preserve (27°31’–27°33’N and 90°41’–90°44’E) situated in the Bumthang district of Bhutan, Central Bhutan Himalaya (Fig. 1). The samples were collected during the

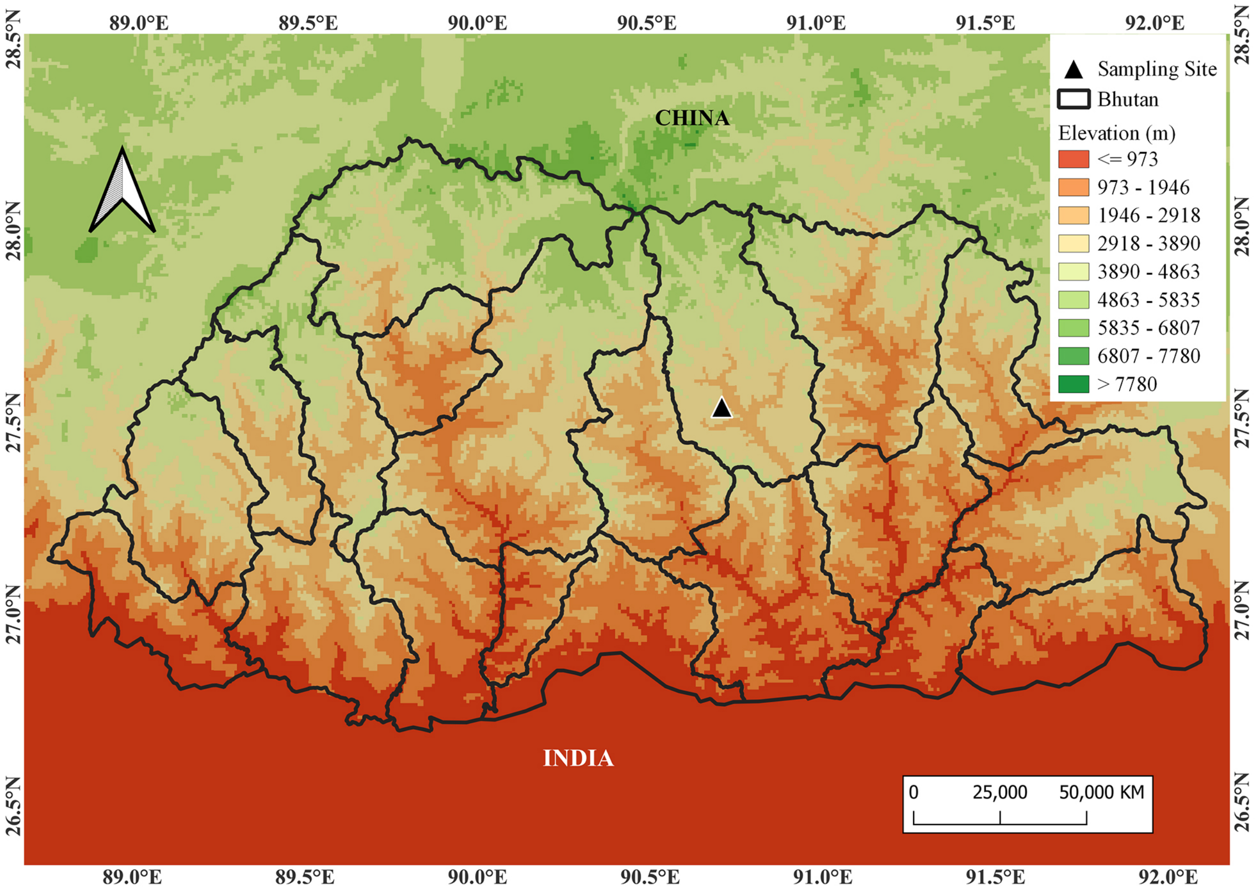

Fig. 1. Geographical location of the study area showing tree-ring sampling site and elevation

first week of September, 2021. The research preserve area lies at an elevation ranging from 2831 m.a.s.l to 4021 m.a.s.l., covering an area of 1098 ha. The region receives an annual rainfall of 1404 mm with summer temperatures as high as 23° C while the temperature during winter months may fall to –6° C (Pearl et al., 2015; Dhendup et al., 2019). The vegetation comprises mainly mixed conifer species such as *P. wallichiana*, *Picea spinulosa*, *Tsuga dumosa*, *Rhododendron* spp., and bamboo.

Sample collection, processing and chronology development

The sampling areas were confined at an elevation of 2800 to 3000 m.a.s.l. The dominant and co-dominant *P. wallichiana* trees having straight boles with large crowns and gnarled branches were sampled. In total, 30 trees (60 cores) were sampled at breast height using Swedish increment borers following the standard procedures of dendrochronology (Fritts, 1976; Smith & Lewis, 2006). For each tree, two 5 mm increment cores were obtained from opposite sides of the tree. The diameter at breast height (dbh) was also measured and recorded for all sampled trees.

The core samples were brought to the laboratory and mounted on a wood block using water-soluble glue. These samples were dried at room temperature and later sanded using progressively finer sandpapers. Each sanded sample was placed under a high-resolution scanner, and its images were captured for measurement. Individual ring widths were measured and visually cross-dated to the calendar year of their formation using the CooRecorder software (Fig. S1) to the nearest 0.01 mm (Maxwell & Larsson, 2021). The cross-dating accuracy was ascertained using COFECHA software (Holmes, 1983). Problematic tree cores that could not be corrected or were decayed, twisted, or damaged were discarded. Our experiments with different curve-fitting options indicated that the age-dependent splines (Melvin et al., 2007) produce the optimal growth curve for each ring width series. A ring width index (RWI) chronology was developed using the signal-free method (Melvin & Briffa, 2008) in the RCS signal-free tree-ring standardization computer program version RCSsigfree_2019 (Cook et al., 2017) and the variance was stabilized (Osborn et al., 1997). To assess the quality and reliability of the detrended chronology, we calculated the chronology statistics such as mean sensitivity (MS), standard deviation (SD), serial autocorrelation (AC), inter-series correlation (Rbar), signal-to-noise ratio (SNR), running mean, sub-sample signal strength (SSS), expressed population signal (EPS) and variance explained by the first principal component (PC1). We also developed the basal area increment (BAI) chronology to estimate tree growth trends and a comparative analysis with RWI chronology. Since most tree core samples missed the pith, the BAI chronology was computed with the "outside-in-method" using ring width data and dbh (LeBlanc, 1993; Biondi, 1999). The BAI was calculated using the *dplR* package (Bunn, 2008) in R programming software (R Core Team, 2022).

Climate and tree growth relationship

The RWI and BAI chronologies developed from the *P. wallichiana* tree cores were further processed to derive the influence of climate on tree radial growth. The closest station data for the study site is located at Chamkhar where the records are available only from 1996 CE onwards. As the available station data is too short to ascertain meaningful correlations, we used gridded climate data available for a more extended and uninterrupted period (1951–2020 CE). The climate variables for the sampling site were extracted from the nearest 1° × 1° grid (90°30' E, 27° 30' N) of the Indian Meteorological Department (IMD) gridded climate dataset, which includes daily climate records of maximum and minimum temperatures, and precipitation (Rajeevan et al., 2008; Srivastava et al., 2009). Pearson's correlation was used to examine the effect of daily and monthly climatic variables on the radial growth of *P. wallichiana*. The correlation analysis was performed between tree growth parameters (RWI and BAI) with monthly climate for a 14-month dendroclimatic window beginning from September of the previous year to October of the current year. Likewise, the same period was used to compute growth-climate correlations with daily climate. The months from the previous year were included to account for the influence of the previous year's climate on the amount of growth and carbon fixed by the trees (Grissino-Mayer & Butler, 1993). We also performed an additional correlation analysis between growth parameters and climatic variables from the Chamkhar station for a comparative assessment of the growth-climate response between the station and gridded climate data. All correlation analyses were performed using the R package *dendroTools* (Jevšenak & Levanič, 2018; Jevšenak, 2020) in the R programming environment (R Core Team, 2022).

Results and discussion

The tree rings of *P. wallichiana* show clear ring boundaries with a gradual transition from earlywood to latewood. Excluding only two problematic cores from the original collection, we cross-dated 58 core samples from 30 trees. The final ring width chronology

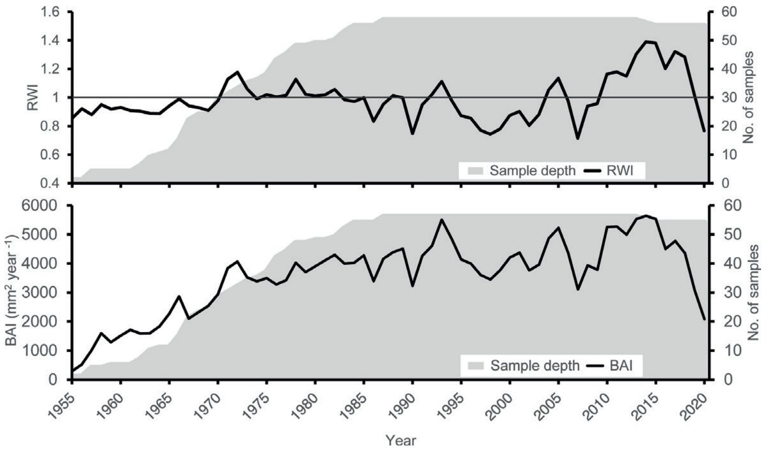

Fig. 2. Tree-ring chronologies of ring width index (RWI) and basal area increment (BAI)

spans 58 years (1955–2022 CE) with a median age of 51 years (Fig. 2). The samples show a high mean inter-series correlation (0.546), suggesting a strong common stand-wide signal. This is also reflected in the between trees Rbar (0.346), within tree Rbar (0.498), and all series Rbar (0.349). The chronology statistics indicate moderate values of MS (0.118), SD (0.119), reliable EPS (0.954), and relatively high SNR (25.709) and variance explained in PC1 (30.2%). The presence of autocorrelation, as indicated by positive AC1 (0.143), suggests the influence of growth from the previous year on the current year's growth. The BAI chronology depicted a consistent positive growth trend during the initial period until the late 1960s (Fig. 2). A distinct peak in growth is evident around the period 2010–2015, which is followed by an abrupt decline in the last few years.

The correlation analysis was carried out for the period 1970–2020 CE in both RWI and BAI chronologies. We truncated the initial period of the chronology to 1970 in the analysis to remove the early portion of the BAI chronology exhibiting a strong positive growth trend (Fig. 2). Additionally, the SSS value of 0.978 in the RWI chronology for the year 1970 well exceeds the 0.85 criteria (Wigley et al., 1984). This further ensures that the less reliable earlier portion of the chronology with low sample replication is excluded from the analysis. The climate response of RWI was most significant (positive) with mid to late summer maximum temperatures and early summer

Table 1. Optimal correlation coefficients (significant at $p < 0.05$) obtained for RWI and BAI chronologies with monthly and daily climate variables. The months from the previous year are prefixed by an asterisk symbol (*). (Abbreviations: RWI – Ring width index; BAI – Basal area increment; DOY – Day of the year; WL – Window length of optimal climate response; NS – Not significant)

Parameter	Resolution	r-value	Onset DOY	End DOY	WL
		Maximum Temperature			
RWI	Daily	0.458	187 (Jul 07)	284 (Oct 11)	97
	Monthly	0.416	182 (Jul 01)	273 (Sep 30)	92
BAI	Daily	0.433	190 (Jul 10)	216 (Aug 04)	26
	Monthly	0.330	182 (Jul 01)	212 (Jul 31)	31
		Minimum Temperature			
RWI	Daily	−0.386	299 (*Oct 27)	329 (*Nov 25)	30
	Monthly	−0.336	305 (*Nov 01)	334 (*Nov 30)	30
BAI	Daily	−0.316	302 (*Oct 30)	327 (*Nov 23)	25
	Monthly	NS			
		Mean Temperature			
RWI	Daily	0.337	190 (Jul 10)	215 (Aug 03)	25
	Monthly	0.278	182 (Jul 01)	212 (Jul 31)	31
BAI	Daily	0.347	191 (Jul 11)	215 (Aug 03)	24
	Monthly	0.281	32 (Feb 01)	212 (Jul 31)	181
		Precipitation			
RWI	Daily	−0.363	156 (Jun 05)	248 (Sep 05)	93
	Monthly	−0.348	152 (Jun 01)	273 (Sep 30)	122
BAI	Daily	−0.317	141 (May 21)	171 (Jun 20)	31
	Monthly	−0.325	152 (Jun 01)	181 (Jun 30)	30

mean temperature (Fig. 3. S2; Table 1). Conversely, correlations between RWI and the previous November minimum temperature and summer season precipitation were significant and negative. A positive response to temperature variables (mean and maximum) was obtained for BAI with a shorter earlier significant period during the early summer (Fig. 3, Fig. S2, Table 1). The correlation between BAI and minimum temperature was negative and significant, with only a daily minimum temperature in November. The negative influence of precipitation on BAI was observed for a comparatively shorter period than RWI and, most significantly, during the early summer months. The growth-climate response computed using daily climate was broadly consistent with those observed using monthly climate. Further, RWI and BAI exhibited similar climate response patterns peaking during the summer. The climate response of both tree growth parameters derived from the IMD gridded data also compared favorably with those obtained using monthly climate records from the Chamkhar meteorological station (Fig. S2).

We developed RWI and BAI chronologies based on the tree-ring width of *P. wallichiana* from central

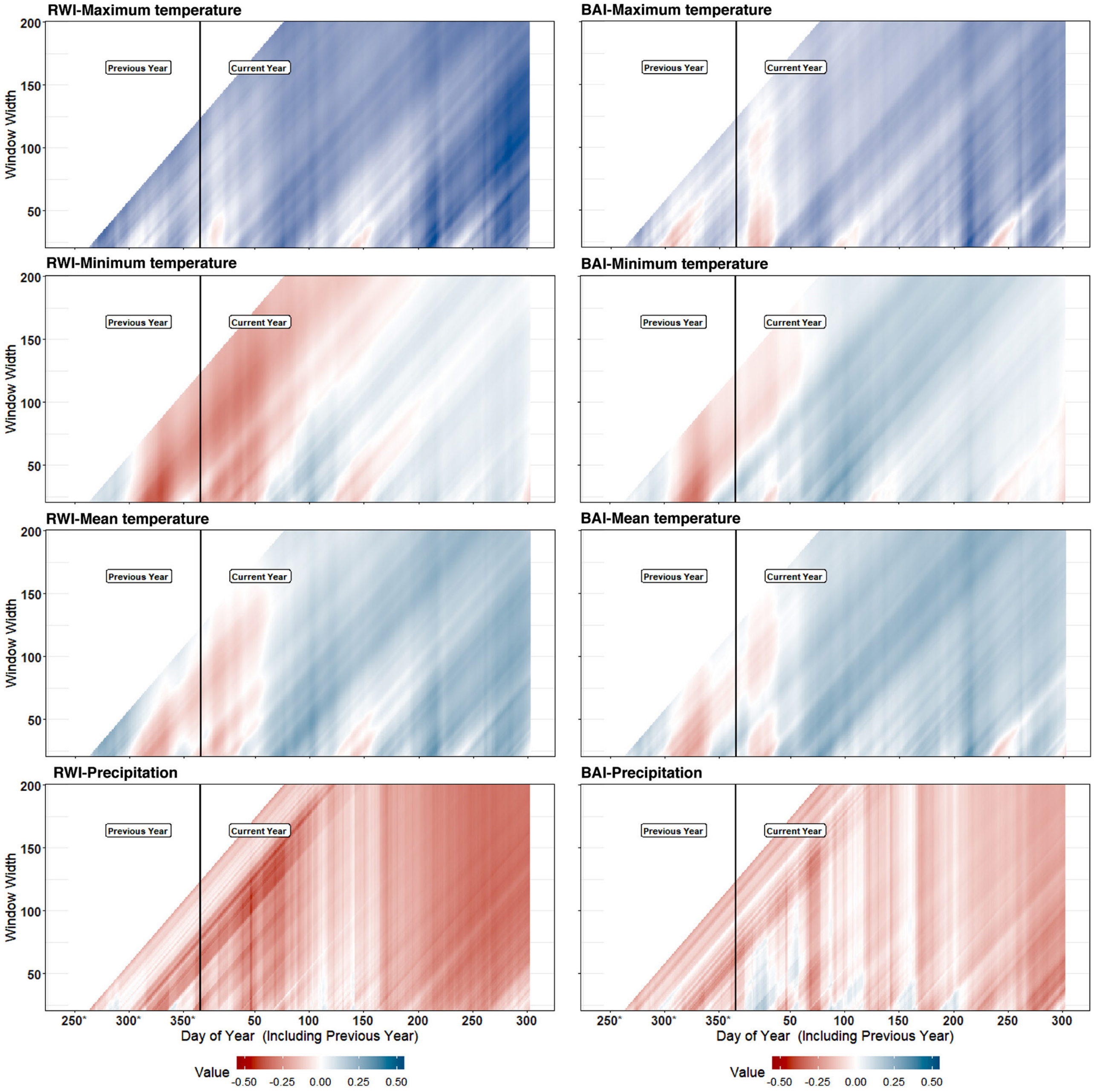

Fig. 3. Correlation coefficients of ring width index (RWI) and basal area increment (BAI) chronology with daily temperature variables (maximum, minimum, and mean temperature) and precipitation for the period 1970–2020. The dendroclimatic window is considered for a 425-day (14-month) period beginning from the day of the year 244 (Sep 1) of the previous year to the day of year 304 (Oct 31) of the current year

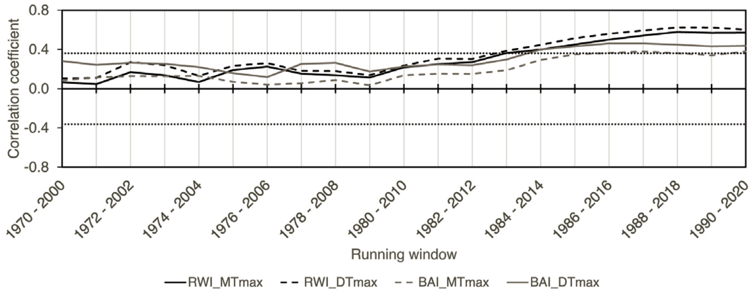

Fig. 4. Running 31-year correlations between RWI with Jul–Sep monthly maximum temperature (RWI_MTmax) and Jul 7–Oct 11 daily maximum temperature (RWI_DTmax); BAI with Jun-Jul monthly maximum temperature (BAI_MTmax) and Jul 10–Aug 4 daily maximum temperature (BAI_DTmax). The running correlation coefficients for only the most significant season of growth-climate response are plotted. The dotted lines indicate significance level ($p < 0.05$)

Bhutan. Analysis of the climate response of RWI and BAI chronology reflected a pronounced positive influence of summer maximum temperature on the radial growth of *P. wallichiana*. The growth-climate correlations showed comparatively higher correlations with daily climate and an essentially shorter optimal window of significant response with daily precision (Table 1). The advantage of identifying a precise window of significant climate response with daily climate has helped improve tree-ring reconstructions of past climate (Dolgova et al., 2022). Previous studies using daily data have also reported a similarly enhanced climate response between tree growth indices and daily climate (Sun & Liu, 2016; Jevšenak, 2019), even with much shorter tree-ring chronologies (Thomte et al., 2022). The stability of the temperature response also improved substantially in the case of BAI chronology when using daily data (Fig. 4). Analysis of the impact of warming on radial growth using daily climate has been demonstrated to be a more effective method for assessing the relationship between temperature and the growth of larch trees in Eurasia (Li et al., 2023). Our results broadly align with the positive growth response to growing season temperatures commonly found in energy-limited boreal forests worldwide (Babst et al., 2019). This summer, temperature sensitivity is also consistently observed in the radial growth of *P. wallichiana* from different parts of Bhutan (Wangchuk et al., 2018; Bhandari & Speer, 2020). Similar temperature sensitivity has also been noted for *P. spinulosa* from central Bhutan (Krusic et al., 2015) and *A. densa* from North Bhutan (Khandu, Polthanee, & Ayutthaya, 2022a; b). A warm summer provides optimal conditions for photosynthesis and xylem production, particularly in temperature-limited environments. Radial growth of *P. wallchiana* from the Western Himalayas have also reported an equally positive relationship with temperature, although the primary temperature response occurs during winter (Yadava et al., 2017; Shah et al., 2019).

Conversely, in moisture-stressed sites, the growth response of *P. wallichiana* may be negative (positive) with temperature (precipitation), such as in central Nepal (Gaire et al., 2018; Gautam et al., 2021),

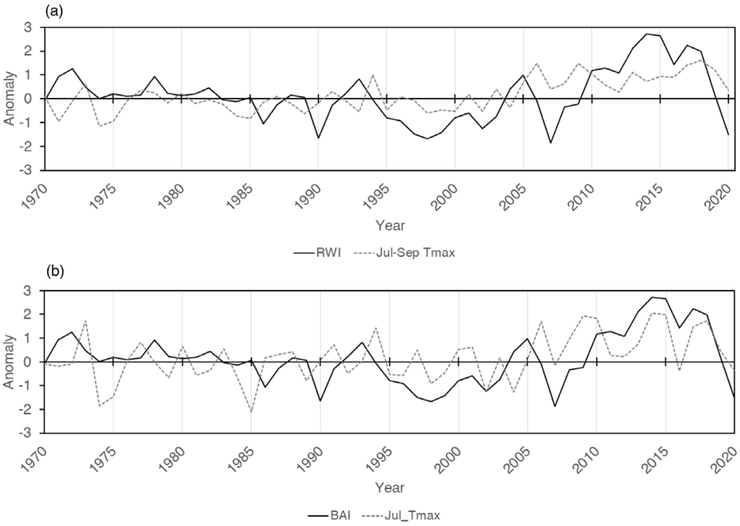

Fig. 5. Anomalies (Z-score) of (a) RWI plotted against Jul–Sep monthly maximum temperature and (b) BAI plotted against Jul monthly maximum temperature for the analyzed period of both tree growth parameters (1970–2020)

North Pakistan (Bhandari et al., 2020). The negative relationship between radial growth and summer season precipitation suggests that the moisture supply is sufficient for overall tree growth in our study site. The summer monsoon season is often characterized by enhanced cloudiness associated with frequent precipitation. Consequently, a decline in insolation and low temperatures may limit photosynthetic activity, reducing growth (Takahashi et al., 2005). Studies of xylogenesis indicated a strong coupling between photoperiodicity and sub-annual variations in xylem size increase and temperature with woody biomass production (Cuny et al., 2015).

Since the mid-1980s, variations in summer maximum temperatures reasonably tracked fluctuations in tree growth (Fig. 5). An abrupt decline in growth has occured during the last few years. It appears to be unrelated to climatic changes. This may result from natural processes such as stand maturation or periodic growth suppression due to canopy closure and competition for light and nutrients. The possibility of anthropogenic disturbances at the site may be ruled out since we found no evidence of recent human activity, such as resin tapping, logging, or livestock grazing. The trees were also essentially free of injuries, and there was no known record of fire or insect outbreaks in the past. In general, the conspicuous intensification of warming over the last few decades may promote the rapid growth of *P. wallichiana*. A study using temperature-sensitive trees distributed across the northern hemisphere also revealed a distinct positive effect of temperature on radial growth associated with rapid warming during the late 20th century (Liu et al., 2022). During the last three decades, increasing growth rates have been noted in temperature-sensitive trees from high-altitude forests worldwide (Treml & Veblen, 2017; Cao et al., 2018; Devi et al., 2020). Such temperature-induced growth intensification has been projected to reduce the negative impact of climate change-related forest disturbances (Li et al., 2023). Conversely, under declining moisture supply, the positive effect of temperature on radial growth in our site may be inhibited and replaced by water limitation, as observed elsewhere (Babst et al., 2019; Mirabel et al., 2023). Analysis of gridded temperature datasets with temperature data from climate stations in Bhutan depicts a rising trend (Hoy et al., 2016). The departures in mean annual temperatures remained consistently positive since 1997, with an 11-year running mean demonstrating an increasingly warming trend beginning around the mid-1970s (Hoy et al., 2016). According to the National Centre for Hydrology and Meteorology (NCHM), the annual precipitation in Bhutan is decreasing with high seasonality characterized by drying winters and increasingly wet summers (Department of Environment and Climate Change, 2023). Future climate projections point to a warmer and wetter Bhutan (Department of Environment and Climate Change, 2023). Based on current trends in temperature, the warming-induced radial growth enhancement of *P. wallichiana* may continue, provided the intensity and distribution of future precipitation do not exhibit extreme deviations. The potential influence of non-climatic disturbances to growth related to forest stand dynamics also exists, which may impact future tree growth.

Conclusion

The radial growth of *P. wallichiana* in central Bhutan, represented by RWI and BAI, exhibited enhanced growth in the recent decade, coherent with a contemporaneous rise in mean annual temperature. Analyses of climate-growth relationships suggest that this growth is driven by maximum temperature during the summer season. The highest growth-climate sensitivity was obtained with calculations derived from the more flexible daily climate variables. Temporally, the growth response to summer maximum temperature attained statistical significance from the mid-1980s, closely associated with recent warming trends. While our results are promising, they are based on a single-site chronology and must be replicated in other potential temperature-sensitive sites. Moreover, growth-climate responses are often dynamic, and the beneficial effects of temperature may become detrimental under water limitations. The sharp decline in tree growth during the last few years also suggests the possible influence of non-climatic disturbances on growth dynamics. Further studies, including older trees, are also needed to identify how trees of different age classes respond to the changing environment and potentially for temperature reconstruction. An expansive network of tree-ring chronologies covering the entire distribution of *P. wallichiana* needs to be developed for a more comprehensive picture of the impact of climate change.

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References

Babst F, Bouriaud O, Poulter B, Trouet V, Girardin MP & Frank DC (2019) Twentieth century redistribution in climatic drivers of global tree growth. Science Advances 5: 1–10. doi:10.1126/sciadv.aat4313.

Baral S, Gaire NP, Aryal S, Pandey M, Rayamajhi S & Vacik H (2019) Growth ring measurements of *Shorea robusta* reveal responses to climatic variation. Forests 10: 1–18. doi:10.3390/f10060466.

Beck W, Sanders TGM & Pofahl U (2013) CLIMTREG: Detecting temporal changes in climate-growth reactions – A computer program using intra-annual daily and yearly moving time intervals of variable width. Dendrochronologia 31: 232–241. doi:10.1016/j.dendro.2013.02.003.

Bhandari S & Speer JH (2020) Growth-climate relationship of *Pinus wallichiana* in three different parts of the Himalayas. Banko Janakari 30: 12–20. doi:10.3126/banko.v30i1.29177.

Bhandari S, Speer JH, Khan A & Ahmed M (2020) Drought signal in the tree rings of three conifer species from Northern Pakistan. Dendrochronologia 63: 125742. doi:10.1016/j.dendro.2020.125742.

Biondi F (1999) Comparing tree-ring chronologies and repeated timber inventories as forest monitoring tools. Ecological Applications 9: 216–227. doi:10.1890/1051-0761(1999)009[0216:CTRCAR]2.0.CO;2.

Biondi F & Qeadan F (2008) A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. Tree-Ring Research 64: 81–96. doi:10.3959/2008-6.1

Buckley BM, Cook BI, Bhattacharyya A, Dukpa D & Chaudhary V (2005) Global surface temperature signals in pine ring-width chronologies from southern monsoon Asia. Geophysical Research Letters 32: 1–4. doi:10.1029/2005GL023745

Bunn AG (2008) A dendrochronology program library in R (dplR). Dendrochronologia 26: 115–124. doi:10.1016/j.dendro.2008.01.002.

Cao J, Zhao B, Gao L, Li J, Li Z & Zhao X (2018) Increasing temperature sensitivity caused by climate warming, evidence from Northeastern China. Dendrochronologia 51: 101–111. doi:10.1016/j.dendro.2018.06.007

Cook ER, Krusic PJ, Peters K & Melvin T (2017) Program Signal Free (RCSsigFree_2019), RCS Signal Free tree–ring standardization program. Tree–Ring Laboratory of Lamont–Doherty Earth Observatory.

Chhogyel N & Kumar L (2018) Climate change and potential impacts on agriculture in Bhutan: a discussion of pertinent issues. Agriculture & Food Security 7: 79. doi:10.1186/s40066-018-0229-6.

Choden K, Nitschke CR, Stewart SB & Keenan RJ (2021) The potential impacts of climate change on the distribution of key tree species and Cordyceps in Bhutan: Implications for ecological functions and rural livelihoods. Ecological Modelling 455: 109650. doi:10.1016/j.ecolmodel.2021.109650.

Correa-Díaz A, Silva LCR, Horwath WR, Gómez-Guerrero A, Vargas-Hernández J, Villanueva-Díaz J, Velázquez-Martínez A & Suárez-Espinoza J (2019) Linking remote sensing and dendrochronology to quantify climate-induced shifts in high-elevation forests over space and time. Journal of Geophysical Research: Biogeosciences 124: 166–183. doi:10.1029/2018JG004687.

Cuny HE, Rathgeber CBK, Frank D, Fonti P, Makinen H, Prislan P, Rossi S, Del Castillo EM, Campelo F, Vavrčík H, Camarero JJ, Bryukhanova M V, Jyske T, Gricar J, Gryc V, De Luis M, Vieira J, Cufar K, Kirdyanov AV, Oberhuber W, Treml V, Huang JG, Li X, Swidrak I, Deslauriers A, Liang E, Nojd P, Gruber A, Nabais C, Morin H, Krause C, King G & Fournier M (2015) Woody biomass production lags stem-girth increase by over one month in coniferous forests. Nature Plants 1: 1–6. doi:10.1029/2018JG004687.

D'Arrigo R, Wilson R, Liepert B & Cherubini P (2008) On the "Divergence Problem" in Northern Forests: A review of the tree-ring evidence and possible causes. Global and Planetary Change 60: 289–305. doi:10.1016/j.gloplacha.2007.03.004.

Department of Environment and Climate Change (2023) National Adaptation Plan (NAP) of the Kingdom of Bhutan. Department of Environment and Climate Change, Ministry of Energy and Natural Resources, Royal Government of Bhutan, Thimphu, Bhutan.

Devi NM, Kukarskih VV, Galimova AA, Mazepa VS & Grigoriev AA (2020) Climate change evidence in tree growth and stand productivity at the upper treeline ecotone in the Polar Ural Mountains. Forest Ecosystems 7: 7. doi:10.1186/s40663-020-0216-9.

Dhendup T, Thinley K & Tenzin U (2019) Mammal diversity in a montane forest in central Bhutan. Journal of Threatened Taxa 11: 14757–14763. doi:10.11609/jott.5058.11.13.14757-14763.

Dolgova EA, Solomina ON, Matskovsky VV, Cherenkova EA & Semenyak NS (2022) Climate signal strength in tree-ring width of spruce growing in the Solovetsky Islands (Russia). Dendrochronologia 76: 126012. doi:10.1016/j.dendro.2022.126012.

Dukpa D, Cook ER, Krusic PJ, Rai PB, Darabant A & Tshering U (2018) Applied dendroecology informs the sustainable management of Blue Pine forests in Bhutan. Dendrochronologia 49: 89–93. doi:10.1016/j.dendro.2018.03.003.

Fritts HC (1976) Tree rings and climate. Academic Press, New York.

Gaire NP, Dhakal YR, Shah SK, Fan ZX, Bräuning A, Thapa UK, Bhandari S, Aryal S & Bhuju DR (2019) Drought (scPDSI) reconstruction of trans-Himalayan region of central Himalaya using *Pinus wallichiana* tree-rings. Palaeogeography, Palaeoclimatology, Palaeoecology 514: 251–264. doi:10.1016/j.dendro.2022.126012.

Gautam D, Gaire NP, Subedi M, Sharma RP, Tripathi S, Sigdel R, Basnet S, Miya MS, Chhetri PK & Tong X (2022) Moisture, not temperature, in the pre-monsoon influences *Pinus wallichiana* growth along the altitudinal and aspect gradients in the lower Himalayas of Central Nepal. Forests 13: 1771. doi:10.3390/f13111771.

Gautam D, Karki J, Gaire NP, Roth BE, Bhattarai S, Thapa S, Sharma RP, Li J, Tong X & Liu QJ (2021) Intra-and interannual climate variability drives the radial growth of *Pinus wallichiana* in the Nepalese Himalayas. Plant Ecology and Diversity 13: 391–400. doi:10.1080/17550874.2021.1890258.

Grissino-Mayer HD & Butler DR (1993) Effects of climate on growth of shortleaf Pine (*Pinus echinata* Mill.) in Northern Georgia: A Dendroclimatic Study. Southeastern Geographer 33: 65–81. doi:10.1353/sgo.1993.0003.

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43: 69–78.

Hoy A, Katel O, Thapa P, Dendup N & Matschullat J (2016) Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: an implementation strategy. Regional Environmental Change 16: 1401–1415. doi:10.1007/s10113-015-0868-0.

Jevšenak J (2019) Daily climate data reveal stronger climate-growth relationships for an extended European tree-ring network. Quaternary Science Reviews 221: 105868. doi:10.1016/j.quascirev.2019.105868.

Jevšenak J (2020) New features in the dendroTools R package: Bootstrapped and partial correlation coefficients for monthly and daily climate data. Dendrochronologia 63: 125753. doi:10.1016/j.dendro.2020.125753.

Jevšenak J & Levanič T (2018) dendroTools: R package for studying linear and nonlinear responses between tree-rings and daily environmental data. Dendrochronologia 48: 32–39. doi:10.1016/j.dendro.2018.01.005.

Khandu Y, Polthanee A & Ayutthaya SIN (2022a) Ecological dynamics and regeneration expansion of treeline ecotones in response to climate change in Northern Bhutan Himalayas. Forests 13: 1–22. doi:10.3390/f13071062.

Khandu Y, Polthanee A & Ayutthaya SIN (2022b) Dendroclimatic reconstruction of mean annual temperatures over treeline regions of Northern Bhutan Himalayas. Forests 13: 1794. doi:10.3390/f13111794.

Krusic PJ, Cook ER, Dukpa D, Putnam AE, Rupper S & Schaefer J (2015) Six hundred thirty-eight years of summer temperature variability over the Bhutanese Himalaya. Geophysical Research Letters 42: 2988–2994. doi:10.1002/2015GL063566.

Labrecque-Foy JP, Angers-Blondin S, Ropars P, Simard M & Boudreau S (2023) The use of basal area increment to preserve the multi-decadal climatic signal in shrub growth ring chronologies: A case study of *Betula glandulosa* in a rapidly warming environment. Atmosphere 14: 319. doi:10.3390/atmos14020319.

LeBlanc DC (1993) Temporal and spatial variation of oak growth–climate relationships along a pollution gradient in the midwestern United States. Canadian Journal of Forest Research 23: 772–782. doi:10.1139/x93-102.

Lebourgeois F, Mérian P, Courdier F, Ladier J & Dreyfus P (2012) Instability of climate signal in tree-ring width in Mediterranean mountains: a multi-species analysis. Trees 26: 715–729. doi:10.1007/s00468-011-0638-7.

Li W, Manzanedo RD, Jiang Y, Ma W, Du E, Zhao S, Rademacher T, Dong M, Xu H, Kang X, Wang J, Wu F, Cui X & Pederson N (2023) Reassessment of growth-climate relations indicates the potential for decline across Eurasian boreal larch forests. Nature Communications 14: 3358. doi:10.1038/s41467-023-39057-5.

Magnússon R, Sass-Klaassen U, Limpens J, Karsanaev SV, Ras S, van Huissteden K, Blok D & Heijmans MMPD (2023) Spatiotemporal variability in precipitation-growth association of *Betula nana* in the Siberian lowland tundra. Journal of Ecology 111: 1882–1904. doi:10.1111/1365-2745.14165.

Maxwell RS & Larsson LA (2021) Measuring tree-ring widths using the CooRecorder software application. Dendrochronologia 67: 125841. doi:10.1016/j.dendro.2021.125841.

Mazza G & Sarris D (2021) Identifying the full spectrum of climatic signals controlling a tree species' growth and adaptation to climate change. Ecological Indicators 130: 108109. doi:10.1016/j.ecolind.2021.108109.

McDowell NG, Allen CD, Anderson-Teixeira K, Aukema BH, Bond-Lamberty B, Chini L, Clark JS, Dietze M, Grossiord C, Hanbury-Brown A, Hurtt GC, Jackson RB, Johnson DJ, Kueppers L, Lichstein JW, Ogle K, Poulter B, Pugh TAM, Seidl R, Turner MG, Uriarte M, Walker AP & Xu C (2020)

Pervasive shifts in forest dynamics in a changing world. Science 368. doi:10.1126/science.aaz9463.

Melvin TM & Briffa KR (2008) A "signal-free" approach to dendroclimatic standardisation. Dendrochronologia 26: 71–86. doi:10.1016/j.dendro.2007.12.001.

Melvin TM, Briffa KR, Nicolussi K & Grabner M (2007) Time-varying-response smoothing. Dendrochronologia 25: 65–69. doi:10.1016/j.dendro.2007.01.004.

Mirabel A, Girardin MP, Metsaranta J, Way D & Reich PB (2023) Increasing atmospheric dryness reduces boreal forest tree growth. Nature Communications 14: 1–12. doi:10.1038/s41467-023-42466-1.

Nechita C, Čufar K, Macovei I, Popa I & Badea ON (2019) Testing three climate datasets for dendroclimatological studies of oaks in the South Carpathians. Science of the Total Environment 694: 133730. doi:10.1016/j.scitotenv.2019.133730.

O'Donnell AJ, Renton M, Allen KJ & Grierson PF (2021) The role of extreme rain events in driving tree growth across a continental-scale climatic range in Australia. Ecography 44: 1086–1097. doi:10.1111/ecog.05671.

Osborn T, Biffa K & Jones P (1997) Adjusting variance for sample-size in tree-ring chronologies and other regional-mean timeseries. Dendrochronologia 15: 89–99.

Pearl H, Bonney N, Whitehead J, Simpson IH, Singye R & Gross CL (2015) Plant species richness, structure and life form respond to an altitudinal gradient in central. Journal of Bhutan Ecological Society 2: 66–90.

Peltier DMP & Ogle K (2020) Tree growth sensitivity to climate is temporally variable (ed. by M Uriarte) Ecology Letters 23: 1561–1572. doi:10.1111/ele.13575.

Pritzkow C, Wazny T, Heußner KU, Słowiński M, Bieber A, Liñán ID, Helle G & Heinrich I (2016) Minimum winter temperature reconstruction from average earlywood vessel area of European oak (*Quercus robur*) in N-Poland. Palaeogeography, Palaeoclimatology, Palaeoecology 449: 520–530. doi:10.1016/j.palaeo.2016.02.046.

R Core Team (2022) R: A language and environment for statistical computing.

Rajeevan M, Bhate J & Jaswal AK (2008) Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. Geophysical Research Letters 35: 1–6. doi:10.1029/2008GL035143.

Salick J, Ghimire SK, Fang Z, Dema S & Konchar KM (2014) Himalayan alpine vegetation, climate change and mitigation. Journal of Ethnobiology 34: 276. doi:10.2993/0278-0771-34.3.276.

Sano M, Tshering P, Komori J, Fujita K, Xu C & Nakatsuka T (2013) May-September precipitation in the Bhutan Himalaya since 1743 as reconstructed from tree ring cellulose $\delta^{18}O$. Journal of Geophysical Research Atmospheres 118: 8399–8410. doi:10.1002/jgrd.50664.

Shah SK, Pandey U, Mehrotra N, Wiles GC & Chandra R (2019) A winter temperature reconstruction for the Lidder Valley, Kashmir, Northwest Himalaya based on tree-rings of *Pinus wallichiana*. Climate Dynamics 53: 4059–4075. doi:10.1007/s00382-019-04773-6.

Shrestha KB, Hofgaard A & Vandvik V (2015) Tree-growth response to climatic variability in two climatically contrasting treeline ecotone areas, central Himalaya, Nepal. Canadian Journal of Forest Research 45: 1643–1653. doi:10.1139/cjfr-2015-0089.

Smith D & Lewis D (2006) Dendrochronology: Encyclopedia of quaternary science, pp. 459–465. doi:10.1016/B0-44-452747-8/00063-6.

Speer JH (2010) Fundamentals of tree-ring research. The University of Arizona Press, Tucson, AZ.

Speer JH, Shah SK, Truettner C, Pacheco A, Bekker MF, Dukpa D, Cook ER & Tenzin K (2019) Flood history and river flow variability recorded in tree rings on the Dhur River, Bhutan. Dendrochronologia 56: 125605. doi:10.1016/j.dendro.2019.125605.

Srivastava AK, Rajeevan M & Kshirsagar SR (2009) Development of a high resolution daily gridded temperature data set (1969-2005) for the Indian region. Atmospheric Science Letters 10: 249–254.

Sullivan PF, Pattison RR, Brownlee AH, Cahoon SMP & Hollingsworth TN (2016) Effect of tree-ring detrending method on apparent growth trends of black and white spruce in interior Alaska. Environmental Research Letters 11: 114007. doi:10.1088/1748-9326/11/11/114007.

Sun C & Liu Y (2016) Climate response of tree radial growth at different timescales in the qinling mountains. PLoS ONE 11: 1–14. doi:10.1371/journal.pone.0160938.

Takahashi K, Tokumitsu Y & Yasue K (2005) Climatic factors affecting the tree-ring width of *Betula ermanii* at the timberline on Mount Norikura, central Japan. Ecological Research 20: 445–451. doi:10.1007/s11284-005-0060-y.

Thomte L, Shah SK, Mehrotra N, Bhagabati AK & Saikia A (2021) Response between tree–rings of *Pinus kesiya* and daily climate–A study from Manipur, Northeast India. Journal of Palaeosciences 69: 27–34. doi:10.54991/jop.2020.28.

Thomte L, Shah SK, Mehrotra N, Bhagabati AK & Saikia A (2022) Influence of climate on multiple tree-ring parameters of *Pinus kesiya* from Manipur, Northeast India. Dendrochronologia 71: 125906. doi:10.1016/j.dendro.2021.125906.

Treml V & Veblen TT (2017) Does tree growth sensitivity to warming trends vary according to treeline form? Journal of Biogeography 44: 1469–1480. doi:10.1111/jbi.12996.

Trumper ML, Griffin D, Montpellier EE & Kipfmueller KF (2022) *Pinus resinosa* tree-ring latewood response to daily-scale precipitation variability at Lake Itasca, Minnesota. Frontiers in Water 3: 801265. doi:10.3389/frwa.2021.801265.

Tshering C, Tenzin K & Nguyen TV (2023) A review of the current state and future prospects of dendrochronological research in Bhutan. Tree-Ring Research 79: 41–49. doi:10.3959/2022-6.

Wangchuk S, Prasomsin P, Tenzin K, Duangsathaporn K, Omule Y & Dukpa D (2018) Effect of topography and climate on the radial growth of Blue Pine (*Pinus wallichiana*) in the temperate conifer forests of Chapcha in Western Bhutan. Journal of Tropical Forest Research 2: 16–35.

Wigley TML, Briffa KR & Jones PD (1984) On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. Journal of Climate & Applied Meteorology 23: 201–213. doi:10.1175/15200450(1984)023<0201:OTAVOC>2.0.CO;2.

Wilmking M, van der Maaten-Theunissen M, van der Maaten E, Scharnweber T, Buras A, Biermann C, Gurskaya M, Hallinger M, Lange J, Shetti R, Smiljanic M & Trouillier M (2020) Global assessment of relationships between climate and tree growth. Global Change Biology 26: 3212–3220. doi:10.1111/gcb.15057.

Yadava AK, Sharma YK, Dubey B, Singh J, Singh V, Bhutiyani MR, Yadav RR & Misra KG (2017) Altitudinal treeline dynamics of Himalayan pine in western Himalaya, India. Quaternary International 444: 44–52. doi:10.1016/j.quaint.2016.07.032.