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ORIGINAL PAPER

Growth response of *Abies spectabilis* to climate along an elevation gradient of the Manang valley in the central Himalayas

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Abstract The Himalayas are characterized by a broad gradient of bioclimatic zones along their elevation. However, less is known how forest growth responds to climatic change along elevation. In this study, four standard tree-ring width chronologies of Himalayan fir (*Abies spectabilis*) were developed, spanning 142–649 years along an elevation gradient of 3076–3900 m a.s.l. Principal component analysis classified the four chronologies into two groups; the ones at lower elevations (M1 and M2) and higher elevations (M3 and M4) show two distinct growth trends. Radial growth is limited by summer (June–August) precipitation at M3, and by precipitation during spring (March–May) and summer at M4. It is limited by spring temperatures and winter precipitation (December–February) at M1. Tree-ring width chronologies also significantly correlate with winter and spring Palmer Drought Severity Index (PDSI) at M1, and with summer PDSI at M3 and M4. Thus, Himalayan fir growth at high elevations is mainly limited by moisture stress rather than by low temperatures. Furthermore, the occurrence of missing rings coincides with dry periods, providing additional evidence for moisture limitation of Himalayan fir growth.

Keywords Climate signals · Tree-ring width · *Abies spectabilis* · Radial growth · Precipitation · Manang valley · Himalayas

Introduction

In recent decades, climate change has significantly affected the composition, structure, and dynamics of forest ecosystems (IPCC 2014; Allen et al. 2015). These effects are more pronounced on tree physiology and population dynamics in mountainous regions (Körner 2012). However, forest growth at high altitudes is often subjected to environmental gradients associated with elevation (LaMarche 1974; Hughes and Funkhouser 2003). As showed by different dendroclimatological studies, tree growth is limited by moisture at lower elevations (Fritts et al. 1965; Leel et al. 2007), and by temperatures at higher elevations (Savva et al. 2006; Fan et al. 2008). However, some studies have shown uniform growth response along elevation gradients (Liu et al. 2006; Liang et al. 2010; Wang et al. 2015). Therefore, a better understanding of tree growth response to climate along elevation gradients is highly important to assess the impacts of climate change on forest ecosystems.

The Himalayas are characterized by a broad gradient of bioclimatic zones and diverse forests along elevation gradients. It is one of the world's most vulnerable regions to

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global warming, with a warming rate higher than the global average (Shrestha et al. 2012). Warming-induced drought stress has caused a higher occurrence of missing annual rings of high-elevation forests in the central Himalayas (Liang et al. 2014), and declining recruitment at the world's highest juniper shrublines in recent decades on the Tibetan Plateau (Lu et al. 2019). Thus, ongoing warming is expected to further alter drought-sensitive forest ecosystems along elevations. To date, few studies have been conducted along the elevation gradients in the Himalayas (Kharal et al. 2017; Sohar et al. 2017).

In the central Himalayas, several studies have investigated tree growth response to climate in recent decades (Cook et al. 2003; Dawadi et al. 2013; Liang et al. 2014, 2019; Thapa et al. 2014; Panthi et al. 2017; Shrestha et al. 2017; Sigdel et al. 2018a). Based on published results, tree growth showed diverse responses to climatic change in the central Himalayas. Some studies have indicated that growth was primarily controlled by variations in temperature (Cook et al. 2003; Gaire et al. 2014; Thapa et al. 2014; Kharal et al. 2017), while other studies have shown that tree growth was significantly controlled by precipitation at higher elevations (Dawadi et al. 2013; Liang et al. 2014, 2019; Panthi et al. 2017). Meanwhile, both temperature and precipitation can have a significant influence on tree growth (Sano et al. 2005; Sohar et al. 2017). To better understand different growth responses to climate change in the central Himalayas, it is necessary to investigate growth responses along elevation gradients.

The objective of this study is to examine how Himalayan fir (*Abies spectabilis* (D. Don) Mirb.) growth responds to climate along an elevation gradient in the Manang valley of the central Himalayas (Nepal). Himalayan fir is an ecologically important species of sub-alpine forest ecosystems which form natural treelines in the central Himalayas (Sigdel et al. 2018b). Given that precipitation in the central Himalayas decreases with increasing elevations above 3000 m (Liang et al. 2014), it was hypothesized that moisture stress rather than low temperatures primarily control the growth of Himalayan fir at high elevations.

Materials and methods

Study area

The sampling sites are located along an elevation gradient of the Manang valley (83°40′–84°40′E and 28°20′–29°0′N). The elevation of the sampled Himalayan fir forest ranges from 3076 to 3900 m a.s.l. (Fig. 1).

Climate in the central Himalayas is influenced by two different weather circulation systems (Indian monsoons in the summer, and westerly jet streams in the winter), with a high inter-annual variability (Yao et al. 2012). The upper part of the Manang valley receives much less annual precipitation as it is surrounded by the Annapurna Mountain massif. Monthly mean maximum and minimum temperatures at Chame climate station (28°33′N, 84°14′E; 2680 m) are 11.3 °C and − 1.6 °C in winter, and 20.6 °C and 9.6 °C in summer (Fig. 2). Annual precipitation at Manangbhot climate station (28°40′N, 84°01′E; 3520 m) is about 400 mm (1977–2013) and ca. 65% of total annual precipitation occurs during the monsoon season. According to the climate data, annual maximum temperatures have been increasing significantly, and total annual precipitation has been significantly decreasing (Fig. 3).

Sample collection and dendrochronological analyses

Increment cores were extracted from a natural Himalayan fir stand using an increment borer. Core samples were collected along an elevation gradient from 3076 to 3900 m at every 250–300 m differences. The sites cover the lowest elevation limit and alpine timberline of Himalayan fir in the Manang valley. At each sampling site, 15–30 mature, healthy trees were selected and one to two cores were collected from each tree at breast height. A total of 33, 48, 30 and 25 increment cores were collected and used to develop chronologies from the sampling sites M1 (3076 m), M2 (3335 m), M3 (3666 m) and M4 (3900 m), respectively (Table 1).

Samples were stored in paper tubes and labeled. Preparation and processing were carried out following standard dendrochronological methods (Cook and Kairiukstis 2013). The dried cores were fixed in wooden slots and core surfaces smoothed with consecutively finer grades of sand papers until ring boundaries were clearly visible. Tree-ring widths were measured using a LINTAB measuring system at 0.01 mm precision (Rinntech, Heidelberg, Germany). The measurement and cross-dated series were further verified using the COFECHA software (Holmes 1983). Standardization of cross-dated tree-ring width data was performed using the computer program ARSTAN (Cook 1985). To remove any biological trends and maximize the strength of climatic signals of the chronology, all raw series were detrended and standardized by negative exponential curves or a 67-year cubic smoothing spline. Standard chronologies were used for all analyses.

Mean inter-series correlations (R_{BAR}) and expressed population signals (EPS) were calculated with a 50-year moving window with a 25-year overlap (Wigley et al. 1984). The common period (1930–2013) with an EPS ≥ 0.85 was used for further analysis except for the chronology at M1 (EPS = 0.78). A lower EPS value at M1

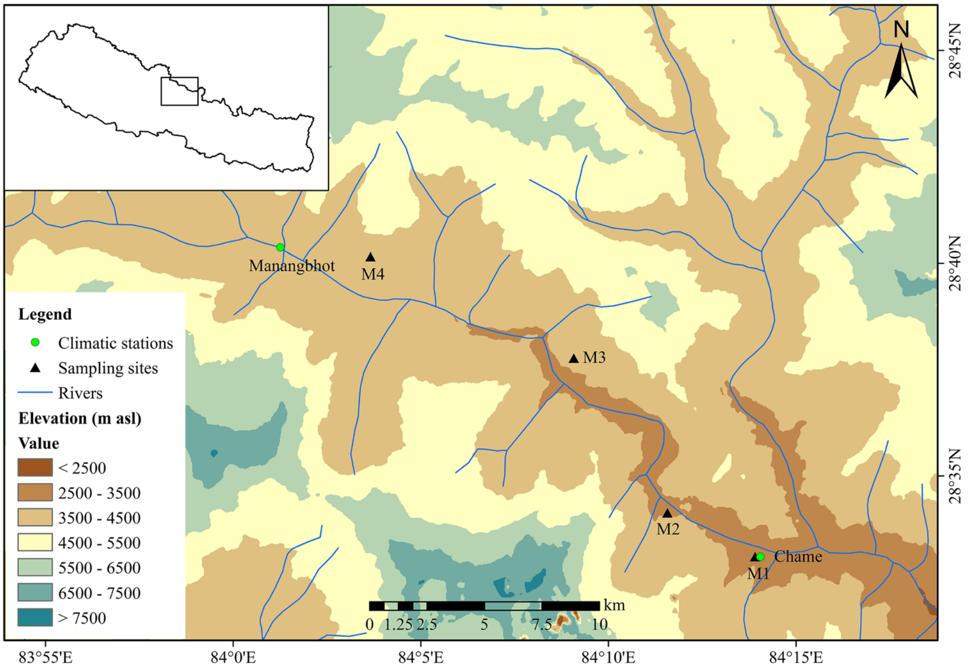


Fig. 1 Sampling sites of Himalayan fir and the local meteorological stations in the Manang valley, central Himalayas

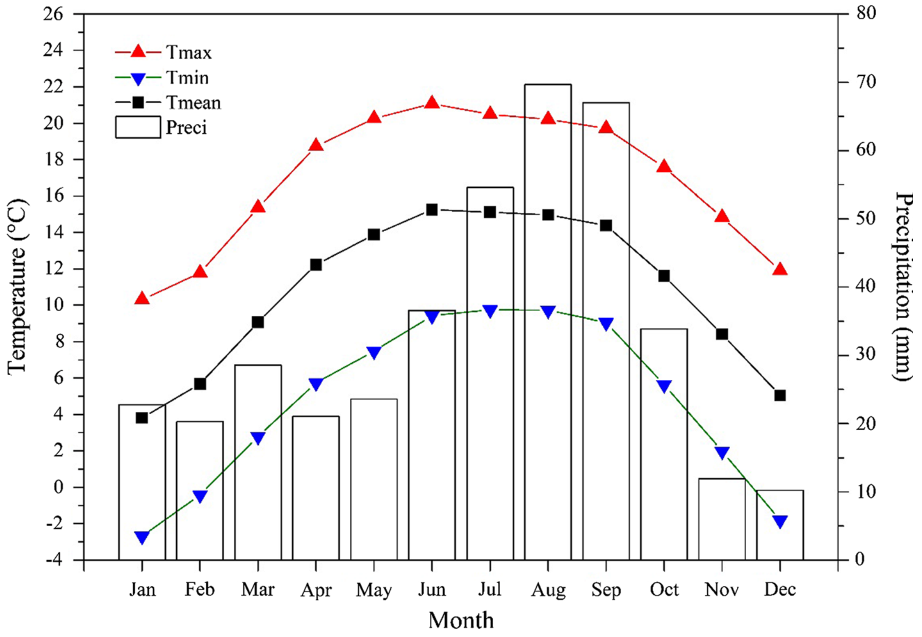


Fig. 2 Monthly maximum, minimum and mean temperatures (1977–2012) at Chame and precipitation (1977–2013) at Manangbhot

may be due to moderate climatic conditions or low sample depth.

Climate-growth relationships

Tree growth response to climate was investigated by calculating Pearson's correlation between the four standard chronologies and seasonal (winter 'DJF', spring 'MAM' and summer 'JJA'), as well as monthly climate data from 1979 to 2013 retrieved from high resolution (30 arc sec, ~ 1 km) satellite data CHELSA (Climatologies at High resolution for the Earth's Land Surface Areas) (Karger et al. 2017). Due to a lack of climatic data along sampling gradients, satellite data CHELSA was used to analyze climate-tree growth relationships. These climatic data showed high correlations with temperature records of Chame climate station (2680 m) from 1979 to 2012, and with precipitation records from 1979 to 2013 at Manangbhot climate station (3420 m). For monthly mean maximum and minimum temperatures, the correlation coefficient (r) ranged from 0.89 to 0.90 ($p < 0.001$). For precipitation data (r) ranged from 0.43 to 0.44 ($p < 0.001$).

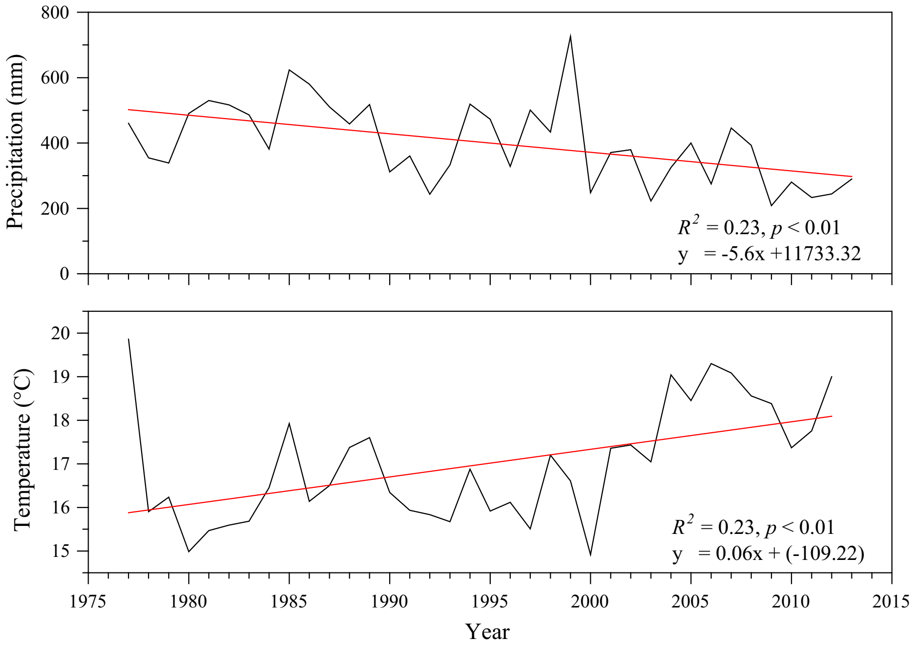


Fig. 3 Variations in annual precipitation (1977–2013) at Manangbhot and maximum temperatures (1977–2012) at Chame in the Manang valley

This demonstrates that the CHELSA climate data represents the climatic conditions of the four sampling sites.

Principal component analysis (PCA) was carried out using the four chronologies during the common period 1930–2013. PCA was calculated on the covariance matrix of the chronologies and only two principal components (PC1 and PC2) were retained as they had eigenvalues greater than one. Monthly and seasonal means of climatic variables were correlated with PC1 and PC2 to investigate the extent of common growth variations through time. Linear association between the two factors was calculated by employing partial correlation after excluding the third factor.

Results

Statistics of the chronologies

The longest chronology (649 years) was developed from the lowest elevation (M1) data, followed by a 402-year chronology from the mid-elevation (M2), a 229-year chronology from the higher-mid elevation (M3), and a 142-year chronology from the highest site (M4) (Table 1; Fig. 4). Of the total rings measured from the four sampling sites, locally missing rings accounted for 0.16%. During the past 200 years, locally missing rings were observed in 1820, 1821, 1848, 1849, 1864, 1866, 1867, 1898, 1918, 1968, 1971, 1978, 1979, 2000, 2002, 2003, 2004, 2010 and 2011. Frequency of locally missing rings increased with elevation, except for the M4 site where there were no missing rings.

Within the chronologies, R_{BAR} ranged from 0.15 to 0.61, and EPS crossed 0.85 from 1930 to 2013 at all sites except M1 (Table 1). Mean sensitivity (MS) ranged from 0.15 to 0.26. Principal component analysis showed that PC1 and PC2 explained 41.7% and 32.6% of variance, respectively (Fig. 5). All chronologies did not load positively on PC1. The higher elevation sites (M3 and M4) had positive loadings on PC1, while the lower elevation sites (M1 and M2) demonstrated positive loadings on PC2. (Fig. 5). Significant correlations have been observed between adjacent sites M1 and M2 ($r = 0.30$, $p < 0.01$), and M3 and M4 ($r = 0.66$, $p < 0.001$), while there were no significant correlations between the chronologies at lower and higher elevations (Table 2).

Climate-growth relationships

The growth of Himalayan fir varied in response to climatic change along the elevation gradient. Tree-ring width chronologies at M4 correlated positively with precipitation during spring ($r = 0.43$, $p < 0.05$), May ($r = 0.46$, $p < 0.01$), and summer ($r = 0.69$, $p < 0.001$) (Fig. 6). Tree growth at M3 also showed positive correlation with summer precipitation ($r = 0.59$, $p < 0.001$). On the other hand, tree growth at both M3 and M4 was weakly associated with temperature. Furthermore, growth of Himalayan fir at the M1 site was positively correlated with winter precipitation ($r = 0.52$, $p < 0.01$) and negatively with spring temperatures ($r = -0.54$, $p < 0.01$). In particular, the M1 chronology showed a negative correlation with April temperatures ($r = -0.55$, $p < 0.01$). Lastly, M2 chronologies were significantly positive correlated with

Table 1 Site characteristics and statistics of the four standard tree-ring chronologies

Sites	Elevation (m)	Lat (°N)	Long (°E)	Aspect	Trees/cores	Time span (AD)	Mean TRW	Missing rings (%)	SD	MS	First order autocorrelation	EPS ≥ 0.85 since	R_{BAR}
M1	3076	28.54	84.24	North	17/33	1365–2013	0.89	0.16	0.33	0.21	− 0.012	1645–1670, 1895–1970	0.15
M2	3335	28.55	84.23	North-west	23/48	1612–2013	0.93	0.18	0.26	0.2	0.002	1770	0.25
M3	3666	28.62	84.15	South-east	15/30	1785–2013	1.89	0.23	0.3	0.27	− 0.03	1840	0.61
M4	3900	28.67	84.01	West	14/25	1872–2013	1.72	0	0.24	0.16	− 0.024	1930	0.38

Lat latitude, *Long* longitude, *TRW* tree-ring width, *SD* standard deviation, *MS* mean sensitivity, *EPS* expressed population signal, R_{BAR} mean series inter-correlation

July temperatures ($r = 0.42$, $p < 0.05$) (Fig. 6). The first-order difference series for the chronologies and climatic data also supported this analysis (Fig. 6).

Tree growth showed positive significant correlation with Palmer Drought Severity Index (PDSI) during spring ($r = 0.38$, $p < 0.05$) and summer ($r = 0.58$, $p < 0.001$) at M3, and during summer at M4 ($r = 0.34$, $p < 0.05$). At M1, tree growth correlated positively with PDSI during winter ($r = 0.42$, $p < 0.05$) and spring ($r = 0.38$, $p < 0.05$) (Fig. 6).

Partial correlation analysis showed significant correlations between summer precipitation and M3 ($r = 0.59$, $p < 0.001$), and M4 chronologies ($r = 0.66$, $p < 0.001$) when controlling for the effect of summer temperatures. In addition, M4 chronology and spring precipitation correlated significantly ($r = 0.43$, $p < 0.05$) when reflecting the influence of spring temperatures. In addition, there was significant correlation between M1 chronology and winter precipitation ($r = 0.47$, $p < 0.01$), and spring temperatures ($r = -0.55$, $p < 0.001$) after excluding the effect of winter temperatures and spring precipitation.

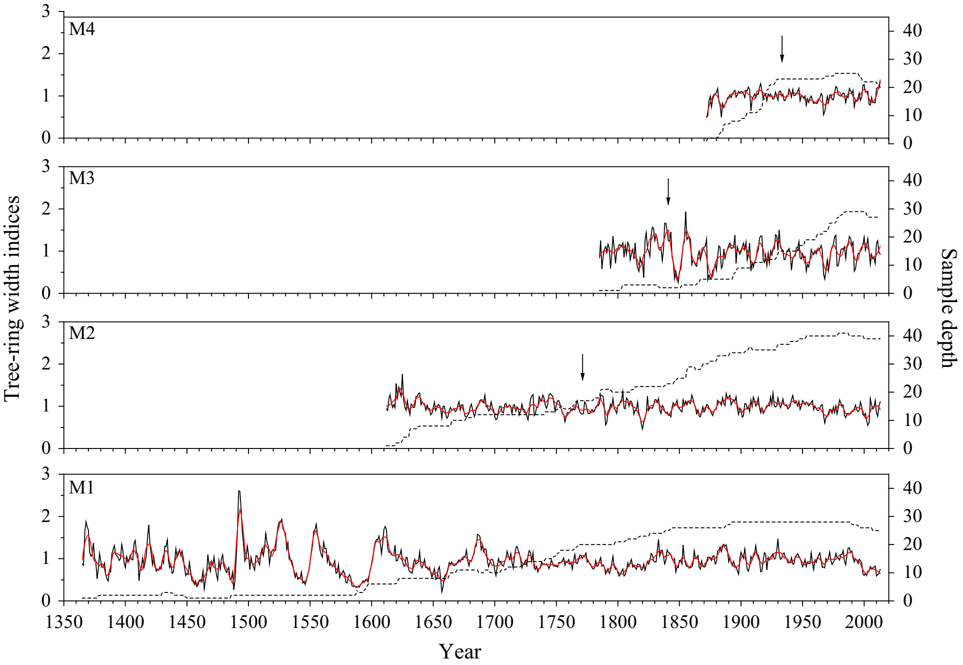
PC1 showed significant and positive correlation with summer precipitation ($r = 0.48$, $p < 0.01$), while weak correlation with summer temperature ($r = 0.179$, $p = 0.305$) (Fig. 7). It also had significant positive correlation with annual precipitation from July of the previous year to June of the current year ($r = 0.35$, $p < 0.05$). However, PC2 was significantly negative correlated with spring temperatures ($r = -0.52$, $p < 0.01$) (Fig. 7).

Discussion

Locally missing rings and drought

The occurrence of missing rings suggests that widespread drought influenced tree growth in the Manang valley. The missing rings synchronized with large-scale drought events in Nepal during 1967–1973 and 1999–2001 (Sigdel and Ikeda 2010). Most of the locally missing rings in our study area also correspond with dry periods (1848–1849, 1859–1876, 1887–1901, and 1964–1973) in the western Himalayas (Ram 2012). In addition, some of the missing-ring years coincided with those for Himalayan birch (*Betula utilis* D. Don) in 1968, 2000, 2003 and 2004 (Liang et al. 2014). Furthermore, the occurrence of narrow rings in the Himalayan fir chronologies also coincide with the drought periods (1807–1828, 1892–1898, 1915–1927) in the central Himalayas (Panthi et al. 2017), suggesting that frequency of missing rings may archive the signals of past drought events. However, the absence of missing rings at the uppermost sampling site might be due to the presence of young trees with good vigor. Hence, frequent locally

Fig. 4 Four standard tree-ring chronologies of Himalayan fir, sites M1, M2, M3, M4 with a 10-year moving average curve (red line), sample depth (black dash line shows the number of sampled trees or sample depth); vertical arrows indicate the start year from when expressed population signal ≥ 0.85



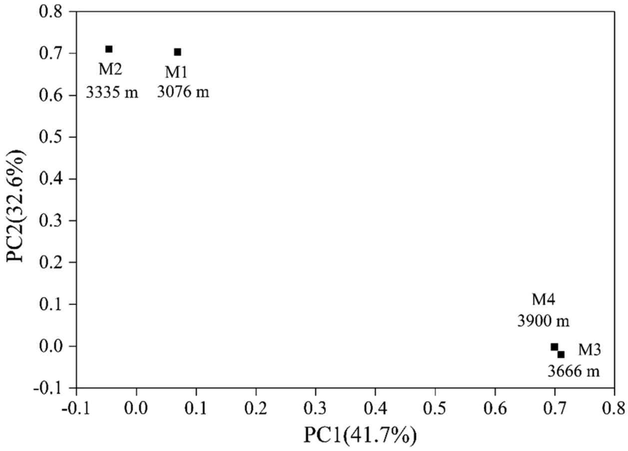


Fig. 5 Loadings of the first and second principal components (PC1 and PC2) calculated on the covariance matrix of the four standard tree-ring width chronologies (Fig. 4) and considering a common period (1930–2013 AD). Numbers indicate site elevation

Table 2 Correlation coefficients between all chronologies (1930–2013 AD)

Items	M1	M2	M3
M1			
M2	0.30**		
M3	0.10	− 0.11	
M4	− 0.02	0.04	0.66***

** and *** indicates $p < 0.01$ and $p < 0.001$ respectively

missing rings provide an additional insight about extreme climatic conditions and their effect on tree growth in the semi-arid regions of the central Himalayas.

Climate-growth relationships

Relationships between the radial growth of Himalayan fir and climate were not uniform along the elevation gradient. Variations in aspect, slope, and elevation of sites may influence tree growth (Lyu et al. 2017), hence obscuring climatic signals embedded in tree rings. In this study, the growth of Himalayan fir at high altitudes was mainly constrained by moisture stress rather than by growing season temperatures. Stronger precipitation signals at higher elevations further support the premise that precipitation decreases with increasing elevation in the central Himalayas (Liang et al. 2014). Moisture stress during pre-monsoon and monsoon seasons seems to limit Himalayan fir growth across the elevation gradient in our study area. Radial growth has a negative correlation with pre-monsoon temperatures and a positive correlation with PDSI at the M1 site, suggesting moisture stress on tree growth. The negative correlation between PC2 and spring temperatures further highlight the importance of moisture availability on tree growth. Such results have been reported for different tree species in the Himalayas and on the Tibetan Plateau (Yadav et al. 2004; Sano et al. 2005; Borgaonkar et al. 2011; Dawadi et al. 2013; Liang et al. 2014; Kharal et al. 2017; Panthi et al. 2017; Mou et al. 2019; Sigdel et al. 2018a). Although warming temperatures enhance xylem cell production, the thermal threshold is an important indicator of tree growth at the alpine treeline (Li et al. 2017; Liang and Camarero 2018). High spring temperatures can cause water deficits by enhancing evapotranspiration and hence delay the onset of xylogenesis or wood

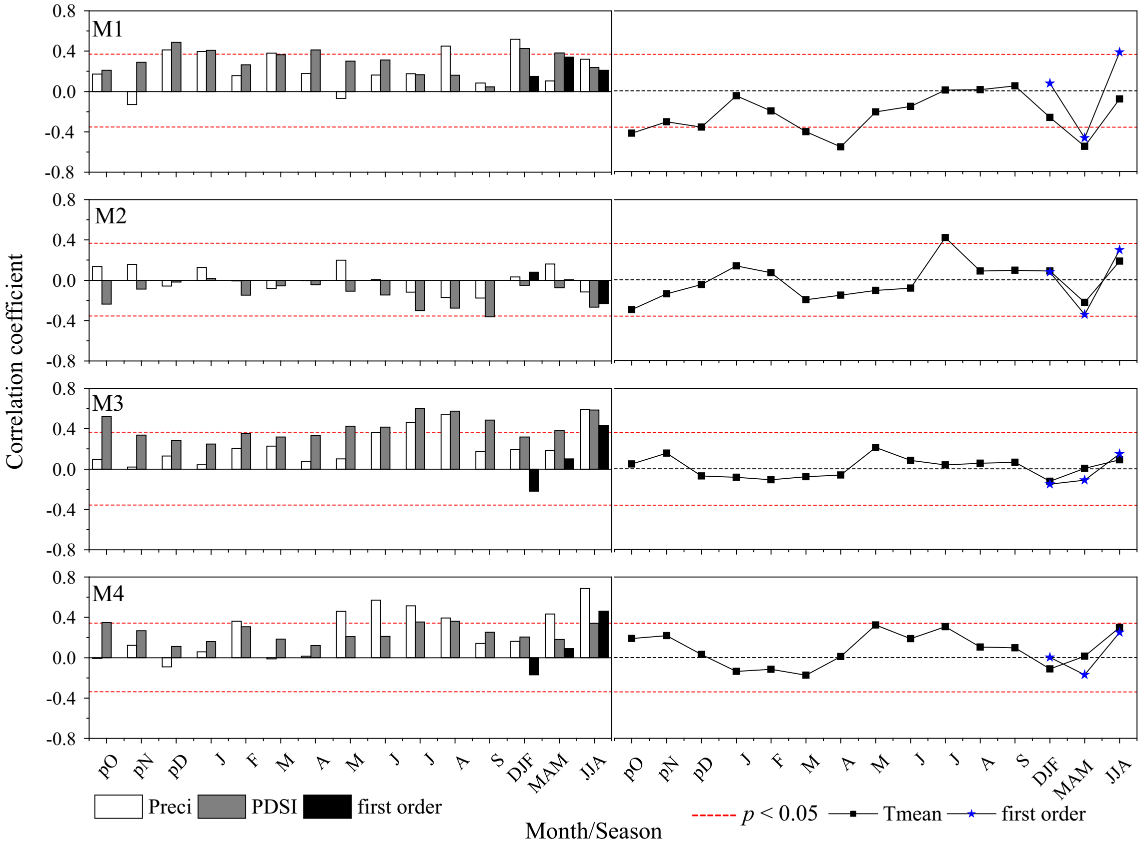


Fig. 6 Pearson correlation coefficients of ring-width indices and average monthly and seasonal temperatures, and total monthly and seasonal precipitation, including the previous year October (pO) to the present-year September (S), based on climate data from CHELSA. DJF: December to February; MAM: March to May; JJA: June to August, including seasonal first-order different series

formation (Ren et al. 2018). Increased temperatures coupled with lower precipitation in the early growing season can cause drought stress, stomata closure and reduced carbon assimilation (Wang et al. 2005). Likewise, significant positive correlations between tree growth at the M1 site and total winter precipitation might be related to the replenishing of soil moisture before the onset of xylogenesis. Further, tree growth at the M2 site was only significantly correlated with July temperatures. M1 and M2 chronologies are significantly correlated with each other (Table 2). However, it is difficult to understand why tree growth at the M2 site did not show signals of drought stress. Future studies should investigate the causes for different growth responses to climate at the M2 site. Likewise, site-specific climate data could better explain such climate-growth relationships.

Generally, temperature is a growth limiting factor for trees at higher elevations (Liu et al. 2005; Fan et al. 2008; Affolter et al. 2010; Bayramzadeh et al. 2018; Yu and Liu 2018). In the central Himalayas, spring precipitation is considered to be a driving factor for tree growth, in particular in high-elevation forests (Dawadi et al. 2013; Liang et al. 2014, 2019; Panthi et al. 2017; Tiwari et al. 2017), as well as in subtropical forests (Sigdel et al. 2018a). Not only tree growth, treeline upward shift across the central Himalayas was also primarily determined by spring precipitation (Sigdel et al. 2018b). However, this study shows that tree growth at high elevations is limited by precipitation during spring and summer seasons, possibly due to much drier climate conditions at higher elevations of the Manang valley compared with other research areas (Bhattarai et al. 2004). Positive correlations between tree growth and summer PDSI (Palmer Drought Severity Index) further suggests that moisture shortages limit tree growth. On the other hand, precipitation and surface water during summers are the major source of moisture for tree growth in arid locations (Littell et al. 2008), supporting our main findings. Similar cases of growth-climate relationships have been reported for the cold and arid regions of the northeastern Tibetan Plateau (Chen et al. 2011; Yang et al. 2013; Lyu et al. 2019).

Rising temperatures and decreasing precipitation could further accelerate drought stress in the future, especially in the highly sensitive, semi-arid trans-Himalayan region by increasing evapotranspiration and vapor pressure deficits (Wang et al. 2013; Ding et al. 2018). In addition,

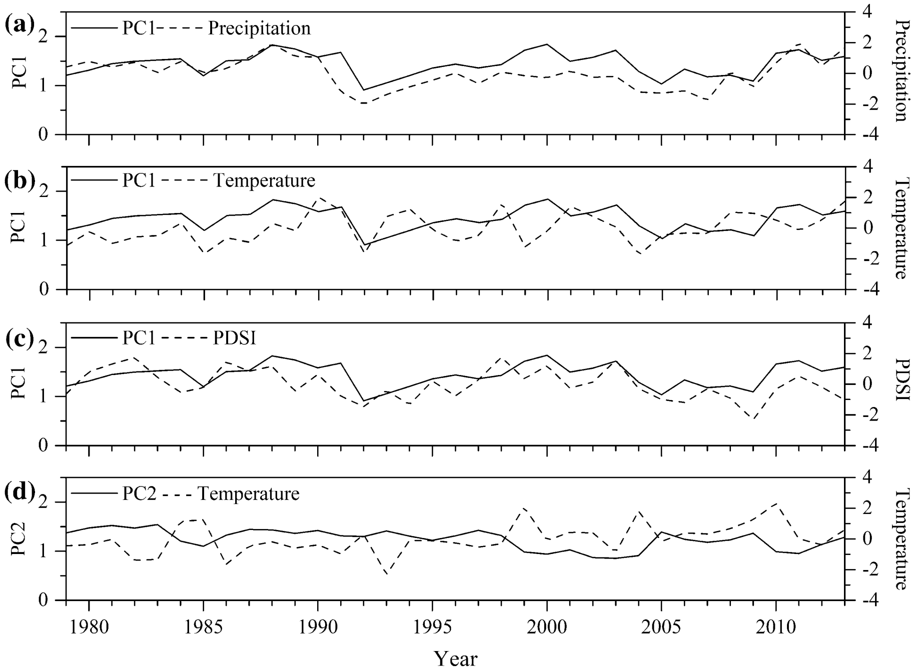


Fig. 7 Relationships between PC1 of four Himalayan fir chronologies and **a** summer precipitation (mm) **b** summer temperatures (°C) **c** summer PDSI, and **d** PC2 and spring temperatures from 1979 to 2013

competition between nearby trees for soil moisture may further exacerbate moisture stress for tree growth (Liang et al. 2016). Warming and drying climates have already caused growth decline, canopy dieback, and even mortality for drought-prone forests on the Tibetan Plateau and in the Himalayas (Liang et al. 2014, 2016; Fang et al. 2018).

Conclusions

The growth of Himalayan fir in the central Himalayas is primarily limited by moisture stress. Despite different climatic signals along the elevation gradient, moisture stress is a common force for growth variations. Under climate warming in recent decades, the growth of Himalayan fir in the Manang valley will undergo increasing moisture stress in the future. These findings contribute to a better understanding of the impacts of climate change on forest ecosystems in the central Himalayas.

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