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ORIGINAL PAPER

Has an extending growing season any effect on the radial growth of Smith fir at the timberline on the southeastern Tibetan Plateau?

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Abstract The growing season of high-elevation forests will presumably lengthen in response to warming. However, little is known about long-term effects of an extended growing season, particularly on the Tibetan Plateau. Based on a strong correlation between the daily mean temperatures at an automatic weather station at timberline (4,390 m a.s.l.) in the Sygera Mts., recorded since 2007, and at the meteorological station at Nyingchi (3,000 m a.s.l.), recorded since 1960, we modeled the variation in daily mean temperature at the timberline back to 1960. The onset and end of the growing season at the timberline were determined by the first and the last day within a year when the mean daily air temperature equals or exceeds, respectively falls below, +5 °C for at least 5 days. From 1960 to 2010, the estimated length of the growing season at the timberline has significantly extended by 21.2 days, resulting mainly from a significant delay of its end (by 14.6 days) rather than from an earlier onset (by 6.6 days). Nevertheless, the variation of the length of the growing season did not exhibit any significant effect on the radial growth of Smith fir at the timberlines. Thus, tree-ring width is still a reliable proxy for summer temperature.

Keywords Tree ring · Timberline · Growing season · *Abies georgei* var. *smithii* · Climate change · Southeastern Tibetan Plateau

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Introduction

The position of the natural timberline reaches its highest northern hemispheric elevation on the southeastern Tibetan Plateau, making it potentially sensitive to climate change (Miehe et al. 2007; Liang et al. 2012). As repeatedly reported, trees at high elevations are "recording" the recent warming on the southeastern (Bräuning and Mantwill 2004; Liang et al. 2009, 2011b; Yang et al. 2010; Zhu et al. 2011; Lv and Zhang 2012) and northeastern Tibetan Plateau (Liu et al. 2005, 2006a, b; Gou et al. 2008; Zhu et al. 2008). In response to this warming, the growing season length may have extended at timberlines. However, little is known whether such an extension has any effect on tree growth at high elevations. If so, summer temperature signals from timberline tree rings may be disrupted by the extended growing season, and hence could not be reconstructed straightforwardly.

Changes in the length of the growing season are of particular importance for both high-elevation and high-latitude

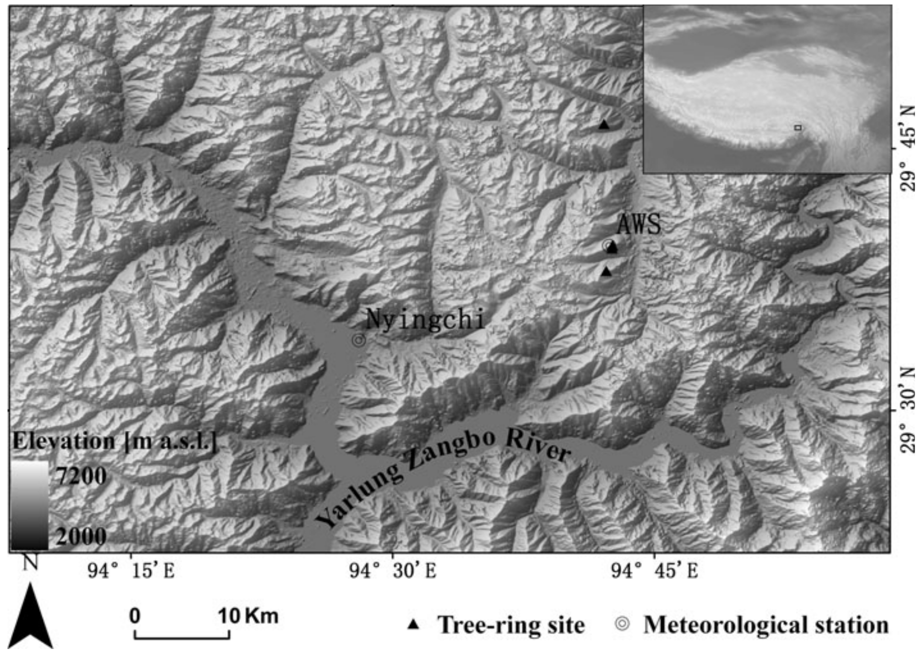


Fig. 1 Map showing the location of the meteorological station at Nyingchi on the river valley bottom and of the automatic weather station (AWS) at the upper timberline in the Sygera Mts., southeastern Tibetan Plateau, and location of the study area within the Tibetan Plateau (*inset*)

ecosystems where the growing season is very short (Vaganov et al. 1999; Wieser et al. 2009). Lengthening of the growing season, caused by an earlier onset, is considered to enhance the forest productivity (Keeling et al. 1996; White et al. 1999; Kimball et al. 2004). On the other hand, an increased snowfall may delay the onset of the growing season (Vaganov et al. 1999; Høgda et al. 2007). Due to difficulties by poor access and bad weather conditions throughout much of the year, long-term meteorological data and phenological observations at timberlines are scarce for the Tibetan Plateau (Liu et al. 2011; Liu and Luo 2011; Wang et al. 2012b). Alternatively, Liu et al. (2006a, b) evaluated the effect of variable growing season lengths on tree growth up in the mountains, based on the climatic data recorded at meteorological stations in low-elevation river valleys. At the end of 2006, an automatic weather station was set up at the timberline in the Sygera Mts. (Liu et al. 2011). Its daily temperature record highly correlates with that from the meteorological station at Nyingchi on the valley bottom (Liang et al. 2011a).

The objectives of this study, therefore, are (1) to estimate the variations of daily mean air temperature at the timberline in the Sygera Mts. using the record from the meteorological station at Nyingchi from 1960 to 2010, and (2) to apply this model for assessing the variations of onset, end and length of the growing season and testing their effect on the growth of Smith fir high up on the mountains. We challenged the hypothesis that an extended growing season was responsible for an increased forest growth at high elevations, as reported at high latitudes (Keeling et al. 1996; Myneni et al. 1997; White et al. 1999; Kimball et al. 2004).

Materials and methods

Study area and meteorological data

The study area, characterized by a humid climate, is located between 4,280 and 4,400 m a.s.l. in the Sygera Mts. (29°10′–30°15′N, 93°12′–95°35′E) on the southeastern Tibetan Plateau. The South Asian monsoon reaches up there through the valley of the Yarlung Zangbo River, resulting in ample summer rainfall.

The closest meteorological station at Nyingchi (Linzhi) (29°34′ N, 94°28′ E, 3,000 m a.s.l) is located in a river valley on the western side of the Sygera Mts. (Fig. 1). Based on the records from 1960 to 2010, the average sum of annual precipitation is 674.4 mm, of which 71 % fall from June to September. July (mean temperature of 15.9 °C) and January (0.6 °C) are the warmest and the coldest month, respectively.

The automatic weather station (AWS) (Campbell CR1000) at the upper timberline (29°39.420′ N, 94°42.427′ E, 4,390 m a.s.l.) of the Sygera Mts. is in operation since November 2006 (Liu et al. 2011) (Fig. 1). The annual mean air temperature varied from 0 to 0.8 °C since 2007, and July (7.9 ± 0.5 °C) was the warmest month. Mean annual precipitation was 871.3 mm (Liu et al. 2011). This AWS has a linear distance of around 30 km to the closest meteorological station at Nyingchi on the valley bottom.

Modeling air temperature at the timberline

A linear regression function, using the daily mean air temperatures at Nyingchi (as independent variable) and at the AWS (as dependent variable), both from 2007 to 2010, was developed to reconstruct the daily mean air temperature for the timberline. The trustability of our transfer model was evaluated by splitting the entire period of 1,461 days into two sub-periods for separate calibration and verification. Pearson's correlation coefficient (r) and the reduction of error (RE) were applied to test the model.

Definition of the growing season

Three methods are mainly applied to determine the length of the growing season (GSL): phenology, normalized difference vegetation indices (NDVI) from satellite remote sensing data, and surface air temperature (Myneni et al. 1997; Chmielewski and Rötzer 2001; Walther and Linderholm 2006; Čufar et al. 2012). But for the upper timberline of the Tibetan Plateau, there are basically no long-term phenological observations (Wang et al. 2012b). Moreover, due to a low spatial resolution of the NDVI dataset, it is difficult to detect long-term phenological changes along the evergreen coniferous timberlines. Alternatively, the growing season can be defined using the daily mean air temperature, at which growth can theoretically take place (Liu et al. 2006a, b; Walther and Linderholm 2006). At high elevations or latitudes, air temperature above a certain threshold is among the main factors to initiate tree growth (Holtmeier 2003; Körner 2003). A daily mean air temperature of 5 °C is widely employed to determine the growing season, in particular for mid and high latitudes (Jones and Briffa 1995; Walther and Linderholm 2006). As shown by Shen et al. (2012) for temperate China, the growing season at present starts by 8.4 days earlier and ends by 5.7 days later, resulting in a 14.1 day extension, as compared to 1960.

Here, we determined the onset (GSO) and the end (GSE) of the growing season by the first and last day of the year (in terms of Julian days) when the mean daily air temperature equals or exceeds, respectively falls below, +5 °C for at least 5 days.

The effects of GSO, GSE, and GSL on the radial growth of Smith fir

Smith fir (*Abies georgei* var. *smithii*), growing along an elevation gradient from 3,300 to 4,400 m a.s.l., is a dominant tree species in the Sygera Mts. We selected a regional tree-ring width "standard" chronology (RC) assembled from four Smith fir timberline sites (Liang et al. 2009) as dependent variable. As independent variables, we took the annual values of the GSO, GSE, GSL as well as of the summer (Jun–Aug) temperature from 1960 to 2010. Then, we compared the dependent variable with each of the independent variables by means of Pearson's correlation.

Furthermore, a path analysis was used to examine direct and indirect effects of the GSO, GSE, GSL, and summer (Jun–Aug) temperature on the radial growth of Smith fir (RC) from 1960 to 2006.

Results

Daily mean air temperature at the timberline

The linear regression function developed from the 4 years of available daily mean air temperature data from the timberline weather station and from Nyingchi at the valley bottom was $T_{\mathrm{Timberline}} = -8.851 + 0.960 \times T_{\mathrm{Nyingchi}}$. Despite this short period for calibration, a high agreement of $r^2 = 0.91$ ($p < 0.001$) between the observed and the simulated daily mean air temperature at the upper timberline was evident from 2007 to 2010 (Fig. 2). Such high correlation partly resulted from the annual periodicity in the data. But according to Liang et al. (2011a), a strong linkage did exist even after removing the influences of these cycles. Based on the model from 2007 to 2009, the simulated and the measured daily mean temperatures at the timberline in 2010 are highly correlated ($r = 0.97$, RE $= 0.93$). Alternately, the model based on the data from 2008 to 2010 is able to well-predict the variations of the daily mean temperature in 2007 ($r = 0.96$, RE $= 0.92$). All in all, the model showed a confident skill for prediction.

Trends of precipitation and temperature at timberline

Precipitation from February to May slightly increased (not significant) at Nyingchi from 1960 to 2010 (Fig. 3a), suggesting some more early-spring snowfall at the timberline. Monthly mean air temperature from May to June

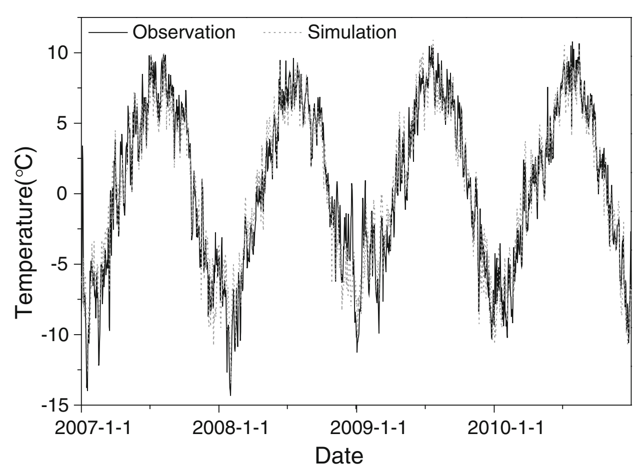


Fig. 2 Comparison between observed and simulated daily mean air temperatures at the timberline of the Sygera Mts. from 2007 to 2010

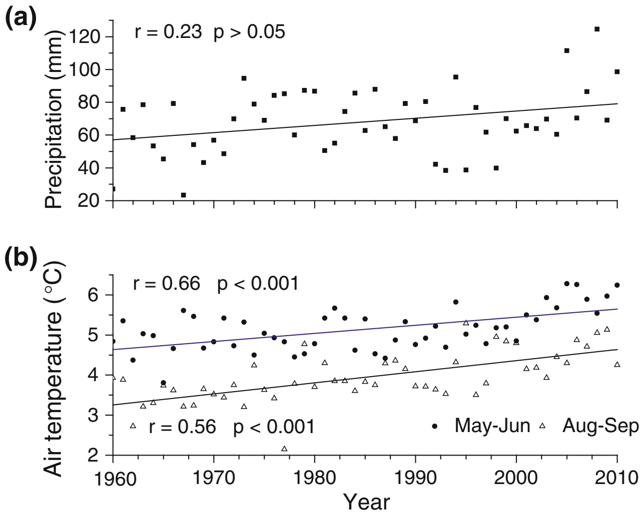


Fig. 3 Trends from 1960 to 2006 in **a** the sum of recorded precipitation from Feb to May at the meteorological station at Nyingchi, and **b** the mean air temperature from May to Jun and Aug to Sep at the timberline

and from August to September significantly increased by 1.4 and 1.0 °C, respectively, from 1960 to 2010 at the timberline (Fig. 3b).

Trends of the GSO, GSE, and GSL at timberline

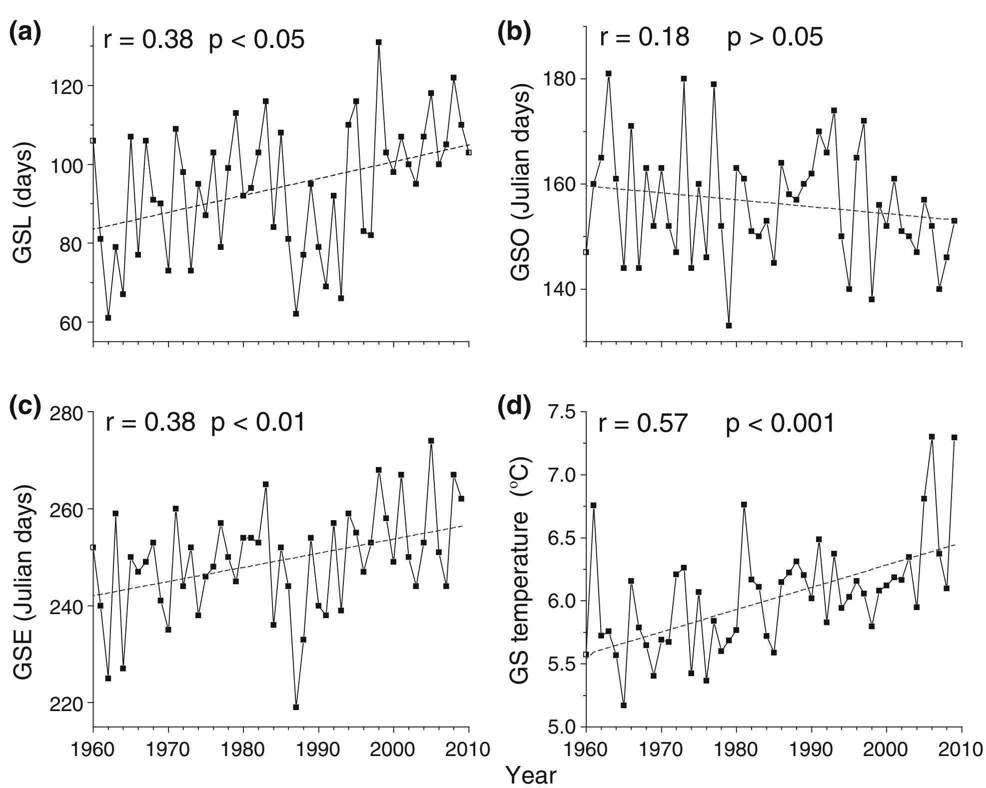
From 1960 to 2010, the GSL significantly increased by 21.2 days (Fig. 4a). Whereas the GSO was advanced by 6.6 days (not significant) (Fig. 4b), the GSE was significantly delayed by 14.6 days (Fig. 4c). The average air temperature during the growing season at the timberline was 6.0 °C and has significantly increased by 0.9 °C (Fig. 4d). On average over the last 50 years, the GSL amounted to 94 days, the GS (growing season) started in early June and ended in early September.

The GSO is negatively correlated with the mean air temperature from May to June ($r = -0.59$, $p < 0.001$), whereas the GSE is positively correlated with the mean air temperature from August to September ($r = +0.55$, $p < 0.001$). The GSL is positively correlated with the mean air temperature from June to August ($r = 0.39$, $p < 0.01$).

The effects of GSO, GSE, and GSL on the radial growth of Smith fir

Summer temperature ($r = 0.57$, $p < 0.001$) and the GSE ($r = 0.34$, $p < 0.01$) were both positively correlated, whereas the GSO and GSL were not at all correlated with the regional tree-ring width chronology (RC). According to the path analysis, summer temperature ($r = 0.55$, $p < 0.001$) exhibited the highest direct effect on RC, whereas the direct effects of the GSO and GSE were negligible. Due to a strong collinearity between GSE and GSL, the same holds true for the GSL. Thus, among the independent variables, only summer temperature showed a significant and direct effect on the radial growth of timberline Smith fir.

Fig. 4 Trends of the growing season from 1960 to 2010; **a** growing season length (GSL); **b** growing season onset (GSO); **c** growing season end (GSE); **d** air temperature during the growing season (GS)



Discussion

Trends of the growing season

In our study area, the conspicuous extension of the growing season during the past 50 years is more attributed to a significant delay of its end than to an advance of its onset. This is consistent with other reports for China (Chen et al. 2005; Liu et al. 2006a, b; Jiang et al. 2011) and for North America (Chmielewski and Rötzer 2001; Tucker et al. 2001; Zhu et al. 2012).

The slight but non-significant advancement of the onset of the growing season at the timberline may result from an opposing interaction between increasing snowfall and rising temperature. An early onset is most likely due to a higher late winter/spring temperature (Chmielewski and Rötzer 2001; Karlsen et al. 2007; Seo et al. 2008) and a reduced amount of snow cover (Groisman et al. 1994; Körner and Paulsen 2004). A delayed onset of the growing season, in contrast, may in some mountain areas and in continental northern regions result from an increased amount of snowfall (Kozlov and Berlina 2002; Shutova et al. 2006; Høgda et al. 2007).

Effects of GSO, GSE, and GSL on the radial growth of Smith fir

The obvious variations in GSO, GSE, and GSL did not significantly affect the radial growth of Smith fir. This disagrees with studies at high latitudes where a recent extension of the GSL is considered to be responsible for an increased forest growth (Keeling et al. 1996; Myneni et al. 1997; White et al. 1999; Kimball et al. 2004). In our case, the GSE has delayed significantly and is now ending in early September. Large-scale observations at high elevations and latitudes assure that the cambium activity ends already in mid-August, even though temperature is still favorable for growth (Rossi et al. 2008). It is also the same case for Smith fir in the Sygera Mts. (Li et al. 2012). As suggested by Piao et al. (2009), autumn warming does not favor the net carbon uptake in northern temperate and boreal forests. Thus, it is reasonable that an extended GSL, resulting mainly from a delayed GSE, would not leave a clear fingerprint in the growth of timberline trees in the Sygera Mts.

According to the path analysis, mean summer temperature (Jun–Aug) is the only significant limiting factor for the radial growth of timberline Smith fir. This is in line with other studies in southeastern Tibet (Bräuning and Mantwill 2004; Liang et al. 2009, 2010; Zhu et al. 2011; Wang et al. 2012a). As we expected, tree-ring width at timberlines is still a reliable proxy for summer temperature and hence suited for a straightforward reconstruction of temperature on the southeastern Tibetan Plateau. In despite of our ongoing efforts (Liu et al. 2011; Li et al. 2012; Wang et al. 2012b), long-term monitoring of microclimate and phenology of Smith fir at the timberline in the Sygera Mts. is essential to gain clear evidence about the impacts of the observed warming trend on tree phenology and growth.

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