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Common tree growth anomalies over the northeastern Tibetan Plateau during the last six centuries: implications for regional moisture change

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Abstract

The world's hydrological cycle is believed to intensify with global warming, yet current climate models have only a limited ability to assess moisture responses at regional scales. Tree-ring records are a valuable source of information for understanding long-term, regional-scale moisture changes, particularly for large regions such as the Tibetan Plateau (TP), where the observational data are short and sparse. Here, we present a new ring-width chronology developed from Qilian Juniper (*Sabina przewalskii*) wood at two sites on the northeastern TP. This chronology, combined with others from the same region, demonstrates that tree growth anomalies are linked to regional late spring to early summer moisture availability. Although late monsoon season precipitation in the study area decreased during recent decades, tree growth continued to increase due to persistent moisture availability in the early monsoon season. Comparison with global sea surface temperatures (SSTs) indicates that early (late) monsoon season precipitation is closely related to tropical Pacific (Indian Ocean) SSTs, suggesting a possible seasonal shift in the dominant moisture source area for monsoonal precipitation over the northeastern TP. It is further shown that there is a very high degree of coherency regarding low-frequency tree growth anomalies over the northeastern TP during the last six centuries. The most prominent drought epoch occurred during ca. 1450–1500, which may have been caused by a significant decrease in the thermal gradient between the Eurasian continent and the tropical oceans. A persistent tree growth increase since the 1880s is coincident with global warming, suggesting an intensified early monsoon season moisture regime in the study area.

Keywords: Asian monsoon, climate change, dendrochronology, moisture change, Tibetan Plateau, tree growth anomalies

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Introduction

Global average surface temperature increased $\sim 0.6\,^{\circ}$C during the 20th century and is projected to rise 1.8–4.0 °C in the 21st century (IPCC, 2007). Associated with this warming is an intensified hydrological cycle, with more rainfall likely in the tropics and mid-to-high latitudes and a substantial reduction in the subtropics (Douville *et al.*, 2002; Held & Soden, 2006; IPCC, 2007). However, precipitation is highly variable both spatially and temporally, and its long-term observations are lacking over many regions. Current climate models have only a limited ability to assess precipitation changes at regional scales (Douville *et al.*, 2002, 2006; Dai, 2006). Considering the critical importance of moisture availability to human populations and ecosystems, efforts must be made to understand regional moisture

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variability, as well as its relevant natural and/or anthropogenic forcings, particularly those concerned with global warming.

The Tibetan Plateau (TP) is a unique geological feature, with an average elevation above 4000 m a.s.l. Tectonic uplift of the TP played a key role in the evolution of the Asian monsoon system over millions of years (An *et al*., 2001; Guo *et al*., 2002), and its current extent and topography strongly influence modern monsoon dynamics (Fu & Fletcher, 1985; Webster *et al*., 1998; Meehl, 1994; Bansod *et al*., 2003). Climate conditions (e.g. temperature, snow cover) over the TP are closely related to the variability of monsoon strength and thus to water resource availability over most of the Asian continent (Barnett *et al*., 1988; Sirocko *et al*., 1993; Douville & Royer, 1996; Kripalani *et al*., 2003; Gou *et al*., 2007a). Understanding of spatial and temporal climate variations over the TP is thus vital to improve our knowledge of Asian monsoon dynamics and for development of strategies for large-scale water resource management.

Unfortunately, our knowledge on climate variability over the TP is still limited, largely due to the paucity of instrumental records over both time and space. Meteorological stations over the TP are sparse, and most were not established until the 1950s. Such short and sparse climate data limit our ability to examine current climate regimes with a long-term perspective, including identification of any trends or periodicities. High-resolution proxy records for the TP, such as tree rings, ice cores, lake sediments, are invaluable for extending the limited instrumental records back in time. Tree rings are of particular value in that they provide exactly dated, annually resolved information about past climate conditions (Fritts, 1976; Cook & Kairiukstis, 1990).

Although tree rings have been used to reconstruct past climate over the TP (e.g. Zhang *et al*., 2003b; Bräuning & Mantwill, 2004; Sheppard *et al*., 2004; Shao *et al*., 2005; Gou *et al*., 2007a, b; Huang & Zhang, 2007), the density of the network is still low, and the sampling sites are highly clustered on the southeastern and northeastern TP. More sampling sites over the TP are thus in need in order to achieve reliable information about large-scale climate changes. In this paper, we present a new tree-ring chronology developed from two sites of Qilian Juniper (*Sabina przewalskii*) on the eastern part of the northeastern TP and discuss in detail tree growth anomalies that are closely related to regional late spring to early summer (i.e. May–June) moisture conditions. Using tree rings and local meteorological records, we clarify the influence of tropical SSTs on regional moisture variability. By comparing with other tree-ring chronologies developed from the same region, we find that there is a high degree of coherency regarding tree growth and late spring to early summer moisture conditions over this area of TP. The identified common tree growth anomalies are used to infer prominent drought epochs over the northeastern TP during the last six centuries and a persistent trend toward wetter conditions during the 20th century.

Materials and methods

Tree-ring data

Our study sites are located in the headwater area of the Yellow River on the northeastern TP (Fig. 1). Qilian Juniper (*S. przewalskii*) is the regionally dominant tree species, which is typically found growing at 3400–3800 m a.s.l. Our two sampling sites are close to each other (Table 1), and both are at the lower forest border, where tree growth is generally sensitive to moisture availability (Fritts, 1976). Increment cores were taken from living trees of Qilian Juniper at both sites. All sampled trees appeared healthy and relatively isolated, representing optimal conditions for maximizing climate signals contained in the growth rings.

Samples were mounted in slotted wooden boards, air dried, and then polished with progressively fine sandpaper. To assign the exact calendar year to each growth ring, tree-ring sequences were carefully cross-dated by visually comparing their growth patterns. Ring widths were subsequently measured to 0.001 mm precision using a Velmex measuring system (Velmex Inc., Bloomfield, NY, USA). The COFECHA program (Holmes, 1983) was further employed to check the quality of visual

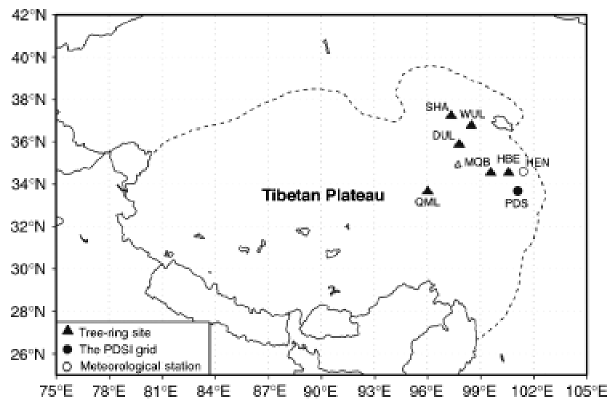

Fig. 1 Map showing the locations of tree-ring sampling sites, the meteorological station (HEN), and the nearest PDSI grid point (PDS) developed by Dai *et al*. (2004). The tree-ring sites are as follows: HBE (the two sites of this study, for details see Table 1), MQB (a tree site of Gou *et al*., 2007a), QML (the two sites of Qin *et al*., 2003), DUL (the sites of Zhang *et al*., 2003b; Sheppard *et al*., 2004), WUL (the site of Huang & Zhang, 2007), and SHA (the seven sites of Shao *et al*., 2005). The dashed line outlines the boundary of the TP (defined by elevations over 3000 m a.s.l.).

Table 1 Statistics of the two tree-ring sampling sites, the nearest meteorological station, and the PDSI grid point developed by Dai *et al.* (2004)

Data type	Site code	Location (latitude, longitude)	Elevation (m)	Number (core/tree)	Time span (AD)
Tree-ring	DEZ	34°45′N, 100°49′E	3495	47/22	1287–2004
	GOU	34°44′N, 100°48′E	3370	41/21	1346–2004
Meteorological data	HEN	34°44′N, 101°36′E	3500	–	1960–2001
PDSI	PDS	33°45′N, 101°15′E	–	–	1953–2005

cross-dating. The final chronology is based on 88 cores from 43 trees, with 47 (41) cores of 22 (21) trees from the DEZ (GOU), respectively (Table 1).

In order to remove biological trends associated with tree growth (Fritts, 1976) while preserving variations that are likely related to climate, all the raw measurements were conservatively detrended using the ARSTAN program (Cook, 1985) by fitting negative exponential curves or linear regression curves of any slope. Tree-ring indices were calculated as the ratio of raw measurements to the fitted curve values. If averaged separately, correlation between the two chronologies during 1346–2004 is 0.73 ($P<0.001$), and the first principal component explains 90.31% of their total variance. Hence, all tree-ring index series were merged to develop one robust mean chronology that reflects a regional-scale climate signal. In order to reduce the potential influence of changing sample size, the chronology variance was stabilized using the method described in Osborn *et al.* (1997). Subsample signal strength (SSS; Wigley *et al.*, 1984) with a threshold value of 0.85 was employed to evaluate the most reliable period of the chronology. Finally, the significance of the linear trends of the chronology during 1880–2004 and 1960–2004 was evaluated using the Mann–Kendall trend test (Mann, 1945; Kendall, 1975).

Climate data

Monthly temperature and precipitation records were obtained from the nearest meteorological station (HEN; Fig. 1). The HEN station is situated in Henan town, Qinghai province. Although being the 'nearest' meteorological station, the HEN is still quite far away from our sampling sites, which will to some extent influence the signal strength of the correlations between tree rings and meteorological data. However, unlike many other stations in this region that are situated in valleys, the HEN station is on a flat plateau. Thus, data from this station are more likely to indicate large-scale climate processes. Elevation of the HEN station (3500 m) is also similar to that of our sampling sites (3370–3495 m; Table 1), allowing a more direct calibration of tree rings and meteorological data. Similarly, the significance of trends of monthly precipitation at this station was evaluated by the Mann–Kendall trend test.

We used the monthly Palmer Drought Severity Index (PDSI; Palmer, 1965) dataset in order to investigate the relationship between tree rings and regional moisture availability on the northeastern TP. The PDSI functions as a metric of meteorological drought and is suitable for describing soil moisture and streamflow changes. We used the updated monthly PDSI dataset developed by Dai *et al.* (2004; version 3, updated in November 2006), which was designed for global coverage based on a $2.5^\circ \times 2.5^\circ$ gridding system and has a maximum time span from 1870 to 2005. The grid point used in the current study is located at 33.75°N, 101.25°E, which is the nearest one to our sampling sites (Fig. 1). Because the earliest instrumental records in this grid do not begin until 1953, we truncated the PDSI data before this time in order to only use the most reliable data (1953–2005).

Two other climate datasets were used in this study. To demonstrate that both the tree-ring chronology and the HEN precipitation records reflect large-scale rainfall variability, we correlated the data with the regional monthly gridded precipitation dataset developed by the Global Precipitation Climatology Centre (GPCC; Fuchs *et al.*, 2007). To conduct spatial analysis of local precipitation and tree-ring data with global SSTs, we employed the extended reconstructed SST dataset (ERSST.v2) developed by Smith & Reynolds (2004). The above analyses were performed using the KNMI Climate Explorer (available at http://www.knmi.nl).

Results and discussion

Characteristics of regional climate

The HEN meteorological data for 1960–2001 show a mean annual temperature of 2.6 °C, with monthly mean temperature over 5.0 °C in May–September (Fig. 2a). January (−11.8 °C) and July (10.4 °C) are the coldest and warmest months, respectively. The mean annual precipitation is 583.5 mm, 83.7% of which falls in

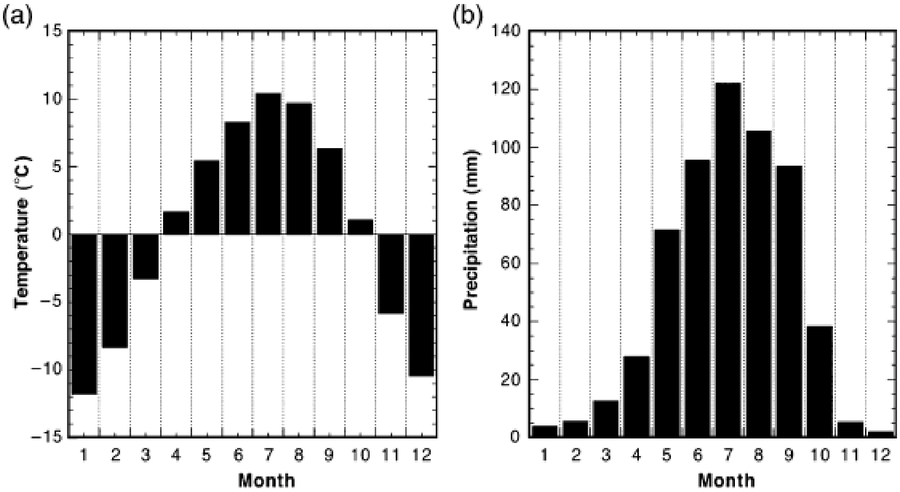

Fig. 2 (a) Monthly mean temperature and (b) monthly total precipitation records at the HEN meteorological station as averaged during 1960–2001.

May–September (Fig. 2b). July is the month with the most rainfall (122.1 mm). Thus, the seasonality of temperature with precipitation at this location reflects a typical monsoonal climate (Wang, 2006).

Monthly precipitation in the summer monsoon rainy season (i.e. May–September) was examined, and the significance of trends was evaluated using the Mann–Kendall trend test. As shown in Fig. 3a, precipitation in May and June increased during 1960–2001, albeit these trends are not statistically significant. Precipitation from July to September decreased, with July statistically insignificant and August and September significant at the 0.01 and 0.05 levels, respectively (Fig. 3b). Annual precipitation also decreased significantly (at the 0.01 level) during the same time period (Fig. 3c). As discussed later, the difference in temporal changes of monsoonal rainfall from May to September may indicate a seasonal shift in the dominant moisture source area for monsoonal precipitation over the northeastern TP.

Climate–tree growth relationships

The mean value of all ring-width measurements is 0.51 mm, indicating that radial growth rates of Qilian Juniper on the northeastern TP are fairly low. The developed chronology spans from 1287 to 2004, in total 718 years (Fig. 4a and b). Based on the arbitrary SSS cutoff value of 0.85, the chronology (hereafter named HBE) is considered most reliable when sample size exceeds seven cores, corresponding to the period from 1351 to 2004. The mean segment length of the chronology is 360 years, indicating its ability to resolve interannual to interdecadal, as well as centennial-scale tree

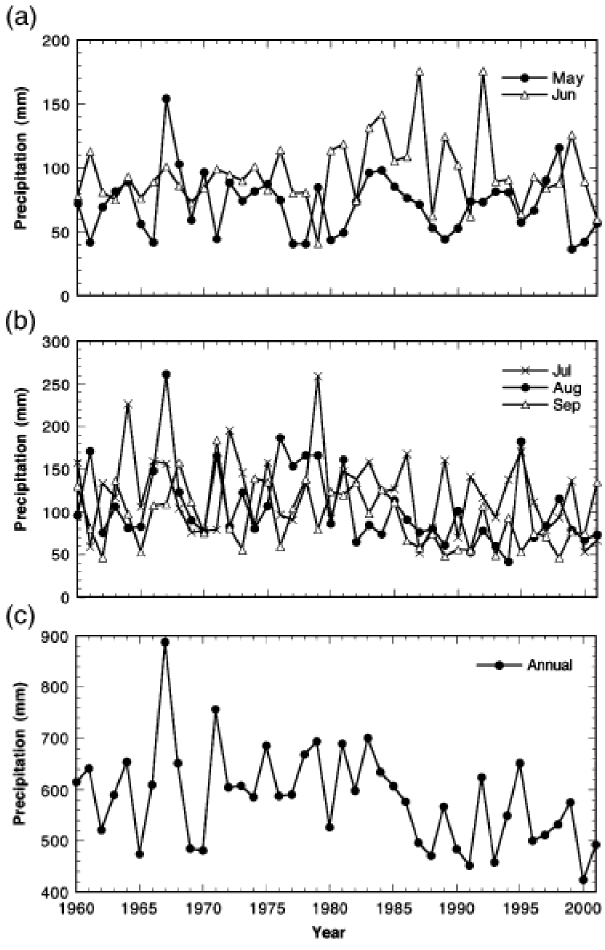

Fig. 3 Temporal changes of (a) May and June; (b) July, August, and September; (c) annual precipitation during 1960–2001 at the HEN station.

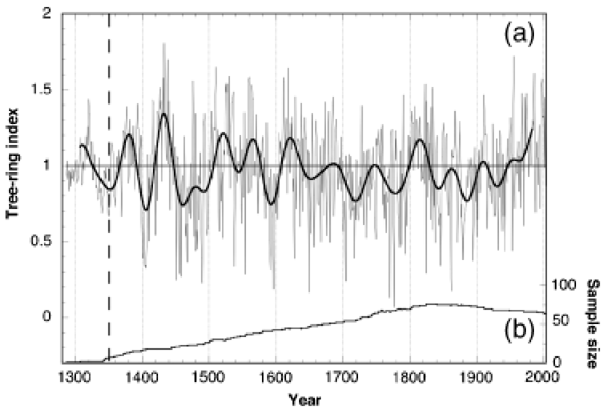

Fig. 4 (a) Standard ring-width chronology (solid line) developed from two sites of Qilian Juniper on the northeastern TP. The most reliable period of the chronology covers 1351–2004. The bold line indicates a 40-year low-pass filter; (b) the corresponding sample size.

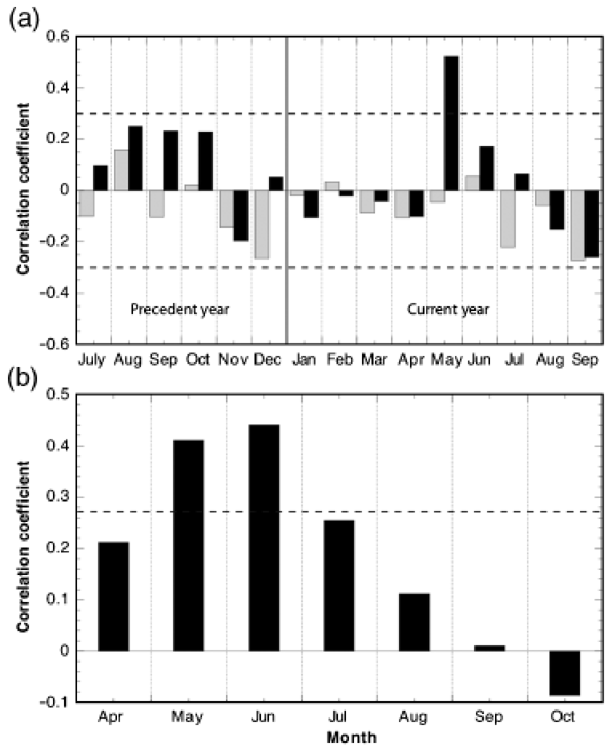

Fig. 5 Correlations of tree rings with (a) monthly precipitation (solid bars) and temperature records (light bars) for last July to current September during 1960–2001, and with (b) the monthly PDSI data for current growth season during 1953–2004. The dashed lines indicate the corresponding 95% confidence level.

growth variations that are likely related to climate change (Cook *et al.*, 1995). The all-series RBAR [i.e. the mean correlation coefficient among all tree-ring series (Briffa, 1995)] is 0.352. The running RBAR ranges from 0.329 around 1915 to 0.787 around 1365. The expressed population signal (EPS) exceeds 0.936 over 1351–2004, well above the generally accepted cutoff value of 0.85 (Wigley *et al.*, 1984). Based on these evaluations, we consider that the signal strength of the HBE is fairly stable through time, and the chronology is valid for dendroclimatic studies described in the following text.

Climate–tree growth relationships were assessed for the common period of tree rings and climate data. The common period between tree rings and temperature and precipitation records is 1960–2001, and their monthly correlations were calculated from previous July to September of the current growth year. Likewise, the common period between tree rings and the PDSI is 1953–2004, and their monthly correlations were calculated for the warm season (i.e. April–October). As shown in Fig. 5a, precipitation in the previous August –October and current May–June seasons was positively correlated with tree growth, although only May ($r = 0.523$) was statistically significant (at the 0.05 level). Temperature in prior November–December and current July–September was negatively correlated with tree growth, although none of these correlations were statistically significant. As shown in Fig. 5b, statistically significant correlations with the PDSI (at the 0.05 level) were found in May ($r = 0.41$) and June ($r = 0.44$). The correlations were not significant in other warm season months, and they were particularly weak in August–October.

In order to identify whether the above relationship between tree growth and regional moisture availability exists over a large scale, we correlated the HBE chronology with regional GPCC gridded precipitation data for the early (May–June) and late (July–September) monsoon season, respectively. As shown in Fig. 6a, the chronology is significantly and positively correlated with May–June precipitation over large areas of northeastern TP, while it has no significant correlation with regional July–September precipitation (Fig. 6b).

The observed pattern of moisture–tree growth relationships during the summer monsoon season on the northeastern TP is also present on longer time scales. As shown in Fig. 6c, tree growth increased during 1960–2004, albeit its trend is not statistically significant. Correspondingly, regional May–June precipitation also increased (statistically insignificant) during the same period. The long-term covariability between tree growth and monsoonal precipitation justifies the above moisture–tree growth relationships revealed by correlation analysis. Considering the dominant effect of moisture availability on tree growth in May–June, it is not surprising that although the late monsoon season as well as annual precipitation decreased significantly during 1960–2001, tree growth is less affected.

The results described earlier highlight the critical importance of May–June moisture availability to tree

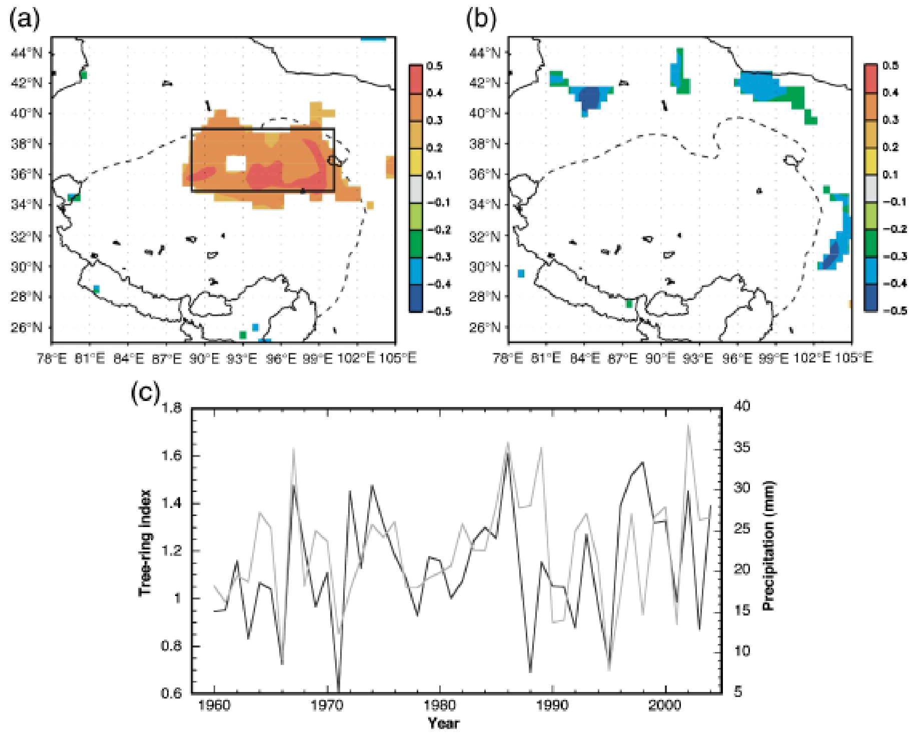

Fig. 6 Correlation patterns of tree rings with regional GPCC (a) May–June precipitation and (b) July–September precipitation for the period of 1960–2004. Note that insignificant correlations (i.e. $P < 10\%$) were masked out. (c) Temporal changes of tree-ring series (solid line) and regional May–June precipitation (gray line) during 1960–2004. The regional May–June precipitation data were extracted from a region as denoted in Fig. 6a.

growth. The arrival of summer monsoon rainfall in May provides the main source of water for tree growth, thus playing a dominant role in enhancing early wood formation. The early wood generally accounts for over 80% of total annual ring width of Qilian Juniper, dominating the total annual ring width. Regarding the relationship between tree growth and May–June moisture availability, our finding herein is in good agreement with dendroclimatic studies of this species at other moisture-sensitive sites on the northeastern TP (Qin *et al*., 2003; Zhang *et al*., 2003b; Sheppard *et al*., 2004; Shao *et al*., 2005; Huang & Zhang, 2007; locations of these sites are shown in Fig. 1). This observed coherency of moisture–tree growth relationship on a regional scale suggests that late spring to early summer moisture is probably the most critical climate factor limiting tree growth on the northeastern TP.

Temperature in May–June has little impact on tree growth at our study sites (Fig. 5a). This finding differs from other tree-ring studies on the northeastern TP, which generally revealed that temperature in the early growth season has significant negative effects on the tree growth (Qin *et al*., 2003; Zhang *et al*., 2003b; Sheppard *et al*., 2004; Shao *et al*., 2005). As pointed out earlier, the long distance between our sampling sites and the meteorological station may to some extent affect the correlation analysis results. Meanwhile, we also noticed the level of annual precipitation in our study area is over 550 mm, while it is less than 200 mm in these cited studies. We speculate that due to high precipitation at our study sites, the influence of high temperatures on soil moisture through evapotranspiration is minor, while at other sites, its influence is much more significant due to the shortage of soil water. Interestingly, Gou *et al*. (2006, 2007b) suggest that at some sites on the northeastern TP, tree growth is most sensitive to maximum summer half-year temperature or minimum winter half-year temperature. Therefore, the influence of temperature on tree growth over the northeastern TP is quite variable, and relationships are likely to depend on site elevation, amount of local rainfall, and microsite conditions.

While early monsoon season moisture is shown to be crucial to tree growth, our study indicates that late monsoon season moisture has rather weak effects on tree growth (Fig. 5b). Similarly, weak and generally insignificant correlations between tree rings and July–September precipitation are present in other dendroclimatic studies on the northeastern TP (Qin *et al*., 2003; Zhang *et al*., 2003b; Sheppard *et al*., 2004; Shao *et al*., 2005; Huang & Zhang, 2007), suggesting that trees in this region are generally not sensitive to late monsoon season moisture. Meanwhile, our study also indicates that late monsoon season rainfall of the prior year may have influence on current year's tree growth (Fig. 5a), consistent with the findings of Sheppard *et al.* (2004) and Shao *et al.* (2005). Therefore, these results together suggest that late monsoon season rainfall may have a limited influence on the current-year tree growth, but may influence tree growth in the following year.

The different trends of early and late monsoon season rainfall in the study area inspired us to examine the associated changes of global SSTs, because the latter is directly related to the variability of monsoon strength (Meehl, 1987; Fasullo & Webster, 2002; Meehl & Arblaster, 2003; Wang, 2006). Before performing the analysis, we determined that precipitation records at HEN are capable of representing regional large-scale rainfall processes. To this end, the monsoon season precipitation records at HEN were correlated with concurrent regional GPCC gridded precipitation data. As shown in Fig. 7, the monsoon season precipitation at HEN is significantly and positively correlated with concurrent precipitation over large areas of northeastern TP, validating its ability to represent regional, large-scale rainfall processes. Meanwhile, HEN precipitation also shows significant negative correlations with concurrent precipitation over large areas of the southern TP. The above correlation pattern defines a dipole mode, suggesting contrasting trends of monsoonal precipitation over these two regions of the TP.

Because monsoon season precipitation records at HEN are capable of representing regional large-scale rainfall processes, we used them to indicate the changes of monsoonal precipitation over the northeastern TP, and calculated their correlations with global SSTs for the common period of 1960–2001. As shown in Fig. 8a, in

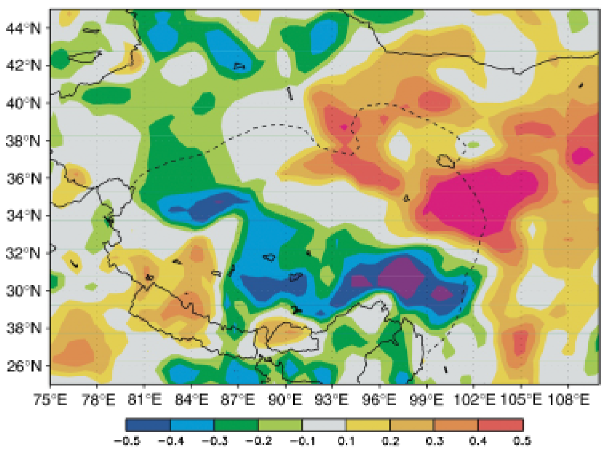

Fig. 7 Correlation pattern of May–September precipitation at HEN station with regional GPCC May–September precipitation for the period of 1960–2001.

May–June when summer monsoon initiates and its strength is relatively weak (Fig. 2b), the HEN precipitation is only weakly correlated with SSTs over the tropical oceans, except the tropical Pacific. Particularly, the negative correlations with SSTs over the western tropical Pacific are the most significant.

It is generally believed that the onset of the Asian summer monsoon and its subsequent strength depend largely on the thermal contrast between the Eurasian continent and the tropical oceans. In particular, the warming of the TP in May–June acts as an elevated heat source that initiates the summer monsoon (Li & Yanai, 1996; Wu & Zhang, 1998). For the early monsoon season, our results suggest that precipitation over the northeastern TP is closely linked to the tropical Pacific SST anomalies. This finding is broadly consistent with previous studies that demonstrated that climate conditions over the TP in spring are strongly related to the tropical Pacific ocean–atmosphere dynamics, such as the changes of El Niño-Southern Oscillation (ENSO) and/or trade winds (Fasullo & Webster, 2002; Shaman & Tziperman, 2005; Zhao & Moore, 2006; Zhao *et al.*, 2007).

Correlations of tree rings with global May–June SSTs during 1960–2001 show a similar, albeit much weaker, correlation pattern than that of May–June precipitation (Fig. 8b). This result further justifies the above moisture–tree growth relationship revealed by correlation analysis, confirming that tree growth on the northeastern TP is closely related to early monsoon season rainfall.

In July–September when monsoon strength is much stronger (Fig. 2b), the HEN precipitation correlates strongly and negatively with SSTs over most of the tropical oceans, in particular the Indian Ocean (Fig. 8c). This correlation pattern suggests that the Indian Ocean is the main contributor to late monsoon season precipitation over the northeastern TP. Although the tropical Pacific still strongly influences the late season monsoon, its strength is relatively weaker than that of Indian Ocean. Furthermore, it has been suggested that tropical Pacific forcing is a primary cause for enhanced monsoon precipitation variability via the large-scale east–west (Walker) circulation (Meehl & Arblaster, 2003). Therefore, the difference in correlation patterns between the early and late monsoon season, along with the different temporal trends of monsoonal rainfall from May to September, together suggest that there is a seasonal shift in the dominant moisture source area for monsoonal precipitation over the northeastern TP.

Long-term changes of regional tree growth anomalies

The above climate–tree growth relationship analysis demonstrates that climate signals contained in our chronology are significant. However, signal strengths

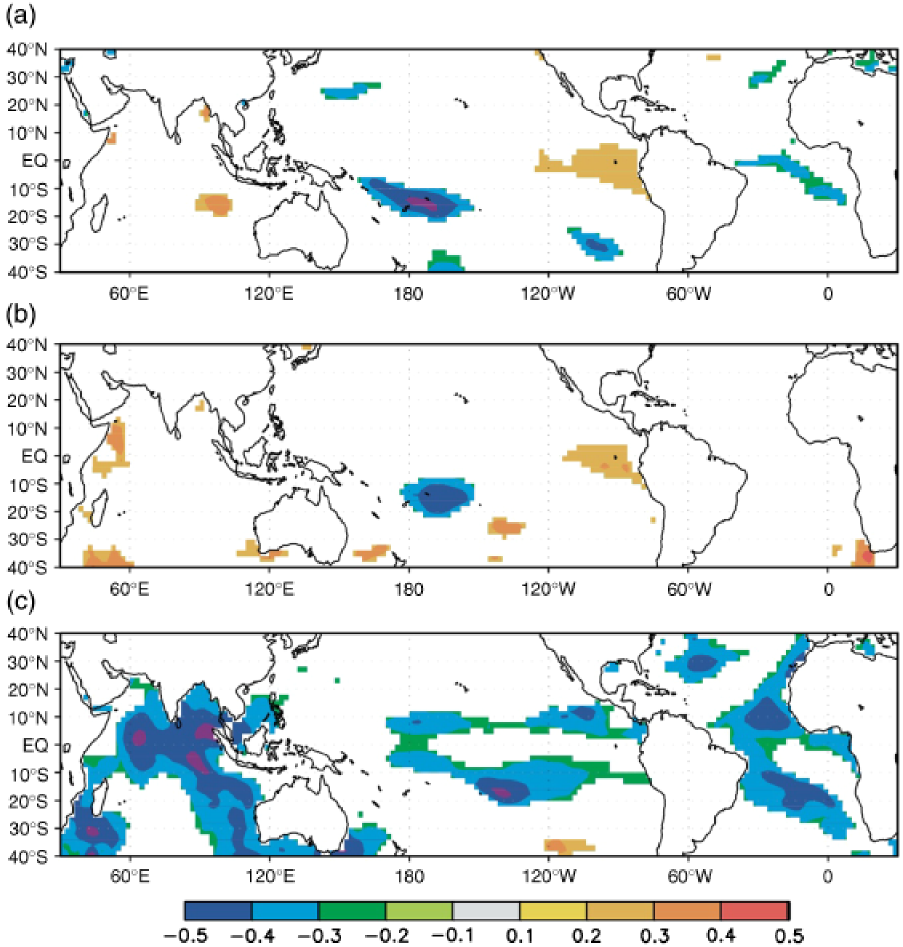

Fig. 8 Correlation patterns of (a) May–June precipitation at HEN station with concurrent global SSTs; (b) tree rings with May–June global SSTs; and (c) July–September precipitation at HEN station with concurrent global SSTs. All the correlations were calculated for the period of 1960–2001 and insignificant correlations (i.e. $P<10\%$) were masked out.

of the correlations between tree rings and climate factors are yet not strong enough for conducting reconstructions. The relatively low correlation results are likely caused by the long distance between the meteorological station and the sampling sites and/or by the short meteorological data. At any rate, the chronology is clearly capable of indicating long-term changes of regional moisture conditions on the northeastern TP.

Over the period of 1351–2004, our new chronology presents direct evidence that long-term tree growth anomalies are closely related to regional late spring to early summer moisture availability over the northeastern TP (Fig. 4a). With respect to decadal to multidecadal variations, below-average tree growth occurred around the 1400s, 1450–1490s, 1590s, 1700–1720s, 1760–1790s, and 1880–1890s, with persistent, above-average tree growth observed from around the 1360–1390s, 1410–1440s, 1500–1530s, 1550–1560s, 1600–1630s, 1800–1830s, and after the 1950s. Another noteworthy feature of the chronology is a persistent positive trend in tree growth since the 1880s (statistically significant at the 0.01 level).

In order to identify whether the HBE chronology represents features that are coherent over large areas of the northeastern TP, we compared our chronology with others developed from the same region, focusing on three chronologies (i.e. MQB, DUL, and WUL) that have been shown to be very sensitive to late spring to early summer moisture conditions (Sheppard *et al*., 2004; Gou *et al*., 2007a; Huang & Zhang, 2007). As shown in Fig. 1, MQB is from the eastern part of the northeastern TP, relatively close to our sampling sites. DUL and WUL are from the northern part of the northeastern TP, and both demonstrate very strong coherence with other moisture-sensitive chronologies for the same area (Zhang *et al*., 2003b; Shao *et al*., 2005; Zhang & Qiu, 2007). The four chronologies were all smoothed with a 40-year low-pass filter in order to highlight the common low-frequency variations. The smoothed chronologies are found to be strongly coherent with regards to low-frequency trends in tree growth and inferred late spring to early summer moisture conditions over the northeastern TP (Fig. 9a). A major divergence between tree growth and moisture conditions occurred in the early 19th century, when the two chronologies from the eastern (northern) part of the northeastern TP demonstrate prominent above (below) average tree growth, respectively. The cause of this major divergence is not known.

The most severe and long-lasting below-average growth anomaly occurred during ca. 1450–1500 (Fig. 9a), suggesting a prominent drought over the northeastern TP during this period. Around this time, the salinity of Qinghai Lake in the northeastern TP increased, and this higher level persisted for several decades (Zhang *et al.*, 2003a). Also at this time, a multi-decadal tree growth reduction was found on the southeastern TP (Bräuning, 2006), and there was a minimum in lamina thickness during the last millennium at Shihua Cave near Beijing during ca. 1450–1580 (Qin *et al.*, 1999). A moisture index derived from Chinese historical documents indicated a persistent drought over most of the eastern China during this period as well (Gong & Hameed, 1991; Qian *et al.*, 2003;

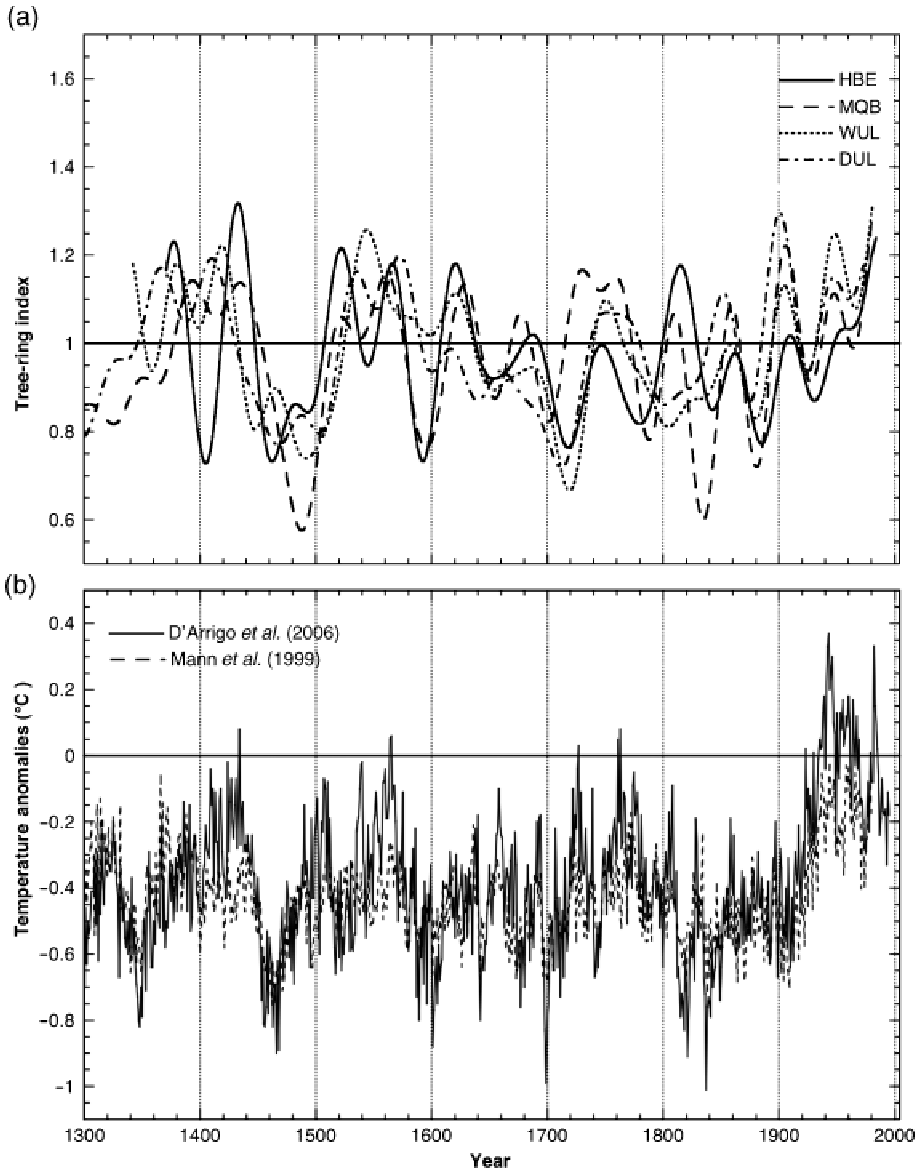

Fig. 9 (a) Forty-year low-pass filter of the four tree-ring chronologies developed from the northeastern TP. See Fig. 1 for site codes and locations. (b) Northern Hemisphere temperature (with regard to 1856–1978 mean) as reconstructed by Mann *et al.* (1999) and D'Arrigo *et al.* (2006a).

Zheng *et al.*, 2006). These results from a number of different proxies, together suggest that there was a substantial drought epoch during ca. 1450–1500 that occurred over a large geographic region, and that it was related to the Asian monsoon climate. As shown in Fig. 9b, this drought epoch corresponds/coincides with one of the most persistent and severely cold periods within the Northern Hemisphere during the last six centuries (Mann *et al.*, 1999; D'Arrigo *et al.*, 2006a). This finding suggests that the prominent monsoon failure of ca. 1450–1500 may have been caused by a significant decrease in the thermal contrast between the Eurasian continent and the tropical oceans.

Many other prominent dry epochs over the northeastern TP are revealed by common tree growth anomalies during the last six centuries, such as those around the 1590–1600s, 1640s, 1690–1710s, 1780–1790s, and 1880s (Fig. 9a). The occurrence of these dry epochs has been well validated by multiple proxy records (e.g. historical documents, ice cores, lake sediments) over the northeastern TP and its surrounding areas (see related discussions in Zhang *et al.*, 2003a; Sheppard *et al.*, 2004; Shao *et al.*, 2005; Gou *et al.*, 2007a; Huang & Zhang, 2007). Likewise, these prominent dry epochs broadly correspond to severe cold periods reconstructed for the Northern Hemisphere (Fig. 9b), suggesting that changes in monsoon strength over the northeastern TP during the last six centuries have been closely related to the variations of Northern Hemisphere surface temperature.

With regard to common long-term changes of tree growth anomalies during the last six centuries, the most striking feature is a persistent trend of tree growth increase since the 1880s (Fig. 9a). This common growth increase implies that late spring to early summer moisture conditions in our study area have become more persistent and wetter due to global warming (Fig. 9b). Intensified moisture regimes have been reported in many other monsoon-affected regions (Anderson *et al.*, 2002; Zhang *et al.*, 2003a; Bräuning & Mantwill, 2004; Li *et al.*, 2006; Treydte *et al.*, 2006), suggesting a strengthening Asian monsoon system during the 20th century. These findings are consistent with the notion that, due to global warming, the thermal gradient between the Eurasian continent and the tropical oceans may have increased during the last century, as suggested by a number of modeling and other studies (Meehl & Washington, 1993; Meehl & Arblaster, 2003; Dairaku & Emori, 2006; D'Arrigo *et al.*, 2006b; Sutton *et al.*, 2007).

Conclusions

As an effort to improve the spatial coverage of tree-ring sites across the TP, we developed a new ring-width chronology by merging tree-ring data from two sites of Qilian Juniper (*S. przewalskii*) on the northeastern TP. Because of the limitation of meteorological data, no tree-ring-based drought reconstruction was conducted in the current study. However, the chronology still presents direct evidence of tree growth anomalies during 1351–2004, and provides a long-term context to evaluate regional moisture variability. Tree growth at our sites is most sensitive to regional late spring to early summer moisture, while it is less sensitive to late monsoon season moisture and growth season temperature. Comparison of our chronology with others developed for the northeastern TP indicates a large-scale coherency regarding tree growth and moisture–tree growth relationships.

Although late monsoon season precipitation in the study area decreased during recent decades, tree growth continued to increase due to an increase in moisture in the early monsoon season. Correlation of local precipitation with global SSTs suggests that early monsoon season precipitation over the northeastern TP is closely related to the tropical Pacific dynamics, while the late monsoon season precipitation is more strongly linked to the Indian Ocean. The difference in correlation patterns suggests a possible seasonal shift in the dominant moisture source area for monsoonal precipitation over the northeastern TP.

Our study demonstrates a strong coherency in low-frequency tree growth anomalies over the northeastern TP. Regional moisture variations during the last six centuries revealed by common tree growth anomalies over this region are well verified by other proxy records. The most prominent drought epoch over the northeastern TP occurred during ca. 1450–1500, which was observed over a large geographic region known to be impacted by the Asian monsoon. This monsoon failure corresponded to one of the coldest periods of Northern Hemisphere temperature during the last six centuries, suggesting that it may have been caused by a significant decrease in the thermal gradient between the Eurasian continent and the tropical oceans. During the past century of overall global warming, a persistent tree growth increase has occurred since the 1880s, suggesting an intensified early monsoon season moisture regime in our study area. Taken together, our analysis illustrates that regional moisture conditions and tree growth anomalies over the northeastern TP are closely related to the Asian monsoon dynamics, and that global warming appears to have significantly impacted these moisture processes.

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