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Annual precipitation since 515 BC reconstructed from living and fossil juniper growth of northeastern Qinghai Province, China

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Abstract Annual precipitation for the last 2,500 years was reconstructed for northeastern Qinghai from living and archaeological juniper trees. A dominant feature of the precipitation of this area is a high degree of variability in mean rainfall at annual, decadal, and centennial scales, with many wet and dry periods that are corroborated by other paleoclimatic indicators. Reconstructed values of annual precipitation vary mostly from 100 to 300 mm and thus are no different from the modern instrumental record in Dulan. However, relatively dry years with below-average precipitation occurred more frequently in the past than in the present. Periods of relatively dry years occurred during 74–25 BC, AD 51–375, 426–500, 526–575, 626–700, 1100–1225, 1251–1325, 1451–1525, 1651–1750 and 1801–1825. Periods with a relatively wet climate occurred during AD 376–425, 576–625, 951–1050, 1351–1375, 1551–1600 and the present. This variability is probably related to latitudinal positions of winter frontal storms. Another key feature of precipitation in this area is an apparently direct relationship between interannual variability in rainfall with temperature, whereby increased warming in the future might lead to increased flooding and droughts. Such increased climatic variability might then impact human societies of the area, much as the climate has done for the past 2,500 years.

1 Introduction

Reconstructing climate is useful for understanding past climatic changes, for evaluating present conditions in the long-term context of the past, and for projecting future climate scenarios (Bradley 1985; Briffa and Osborn 1999). Geographical regions of particular interest in the study of global climate change are those where processes may reflect global-scale atmospheric conditions and circulation systems; China is one such region where the climate reflects that of Asia and even of Europe (Gao and Li 1980). For example, temperature trends from 1880 to 1980 for eastern China match well the temperature trends averaged over the Northern Hemisphere land areas (Bradley et al. 1987). In particular, the Qinghai–Tibetan Plateau interacts with subcontinental to hemispheric climate processes (Lin and Wu 1987; Gao et al. 1981; Lau and Li 1984; He et al. 1987). Indeed, the Qinghai–Tibetan Plateau profoundly influences the climate of China and much of eastern Asia because of its enormous size and height into the troposphere (Zou 1987). Therefore, paleoclimatic study of the Qinghai–Tibetan Plateau is especially fruitful for understanding the climate on subhemispheric scales.

A difficulty in analyzing relationships between the climate of the Qinghai–Tibetan Plateau and large-scale climate patterns is the lack of long meteorological records in western China: there are no continuous meteorological records from China west of 100°E before

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1950. To extend climate investigations back beyond 1950, natural and/or documentary archives of climate must be used. High-resolution climate archives of the late Holocene are especially critical because recent climate variation is highly relevant to human society (Thompson et al. 1993).

Tree-ring records are important sources of paleoclimatic information on annual to centennial scales, (e.g., Fritts 1976; Cook and Kairiukstis 1990; Schweingruber 1996) and are integrated worldwide into research on global change (Bradley 1989). There has been much dendroclimatic research done in China (e.g., Zheng et al. 1982; Wu et al. 1987; Wu and Zhan 1991; Wu 1992; Hughes et al. 1994; Bräuning 1994, 1999, 2001, 2003), but the density of tree-ring research in Qinghai Province is still low and reconstructions of hydrometeorological parameters are notably rare (e.g., Yuan 2003; Zhang et al. 2003).

Accordingly, the objectives of this research were (1) to reconstruct the climate of northeastern Qinghai from living trees for the purpose of linking the climate there to the regional variation in climate and with the hemispheric-scale atmospheric circulation, and (2) to extend the living-tree reconstruction further back to 500 BC using archaeological specimens excavated from tombs of the Tubo kingdom in Dulan County, northeastern Qinghai Province (Wagner et al. 2002). With the combined climate reconstruction, human–climate interactions through multimillennia can be analyzed to better understand the cultural responses to the climatic variability of the area.

2 Methods

2.1 Field and archeological sites

The living-tree sampling sites are located in the montane forest steppe belt above 3,000 m elevation (Zhao 1986) of northeastern Qinghai (Fig. 1). Natural vegetation is sparse, with rare forest stands of widely spaced juniper (*Sabina przewalskii* Kom.) growing on steep, south-facing slopes (Richardson 1990). Stands near the towns of Shenge (37.0°N, 98.5°E, 3,800 m elevation) and Dulan (36.0°N, 98.0°E, 3,800 m elevation) were selected for study (Fig. 1). From a cursory pedological survey, it was observed that the soils are generally shallow (< 0.5 m deep), light brown to yellow in color, silty-loamy in texture with weak granular structure, and poor in organic matter.

According to meteorological records from Dulan (36°17.46′N, 98°4.44′E, 3,200 m elevation, continuous data extending from 1955 to 1993), this area is cold and semiarid (Lin and Wu 1981). The mean annual temperature is + 3°C with a January average of −10°C and a July average of + 15°C (Fig. 2a), and the mean annual precipitation is 188 mm, 78% of which falls from May through September (Fig. 2b). Coefficients of variation of monthly rainfall are very high for winter, averaging 95% for November through February, but lower for summer, averaging 65% for May through September.

The sites with archaeological wood are located in mountain valleys south of Dulan (Fig. 1). Between 1982 and 1999, large tombs that are thought to be remains from the time of the Tubo (Tufan) kingdom were surveyed, registered, and partly excavated. As these tombs had been disturbed, a clear cultural context is difficult to assign, and the accompanying writings have not been interpreted yet. Undisturbed textile fragments show distinct technical features and decorative patterns of Chinese as well as central or western Asian origin (Xu and Zhao 1996). Though no age determination of the tomb construction has yet been reported based on radiocarbon or dendrochronological dating of the juniper wood, the textiles provide some chronological information by which the tombs have been dated

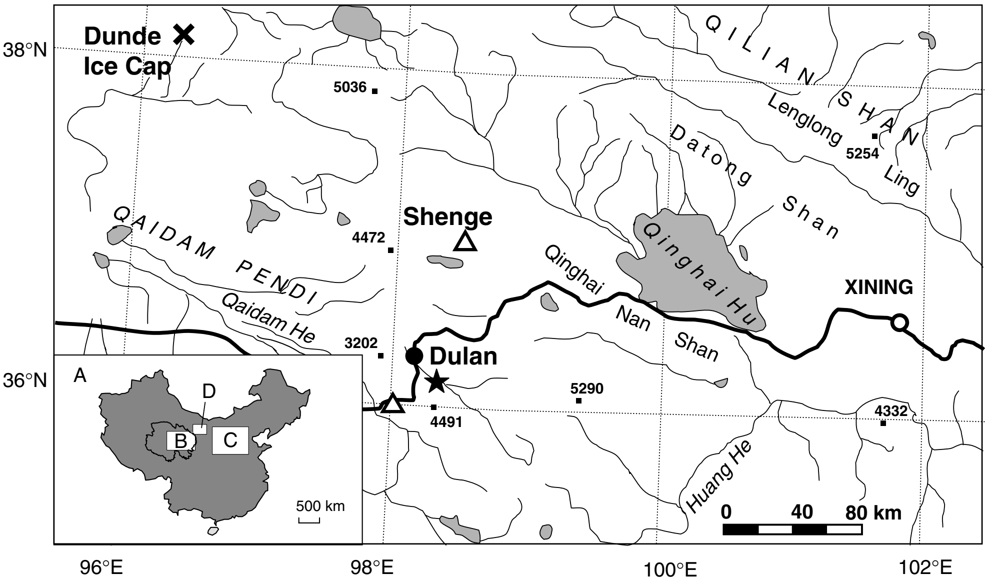
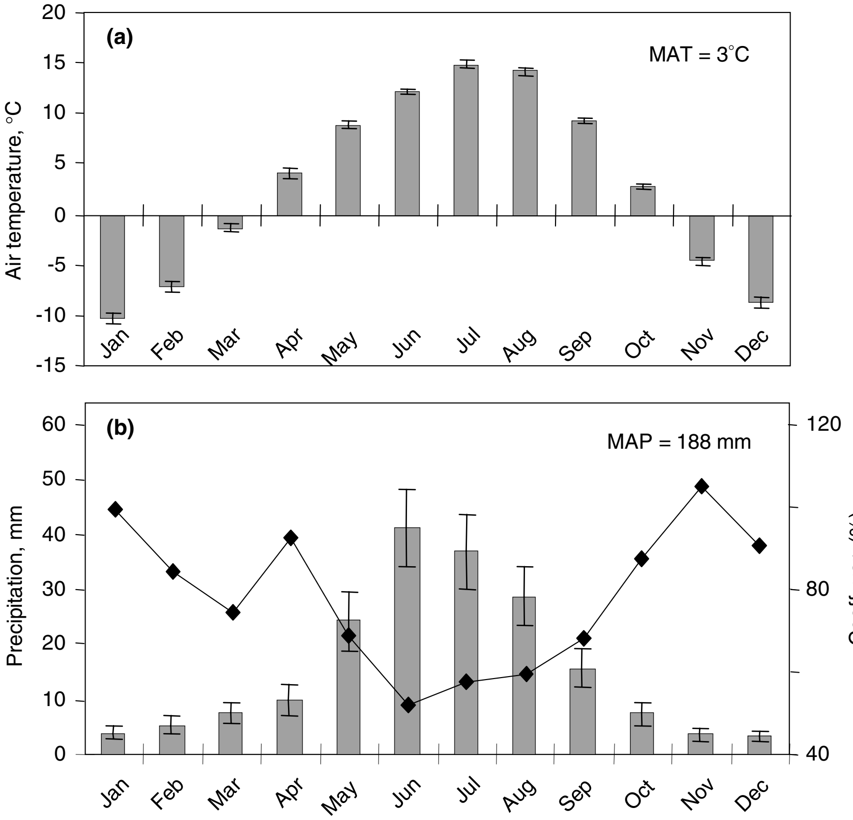


Fig. 1 Map of People's Republic of China (*A*) with the boundary of Qinghai Province. The *white rectangular region B* indicates an enlargement of northeastern Qinghai, where *triangles* indicate living tree-ring sites, the *star* indicates the site with archaeological wood, the *closed circle* indicates the meteorological station at Dulan, and the *cross* indicates the Dunde ice cap (Thompson et al. 1989). The *white rectangular region C* is area *I* of moisture indices of Gong and Hameed (1991), and the region *D* indicates an area of Shiyang River catchment (after Chen et al. 1999, with modifications)

Fig. 2 Monthly **a** temperature and **b** precipitation climographs for Dulan, Qinghai Province. *Error bars* show the 95% confidence interval around each monthly mean. The *line* for precipitation indicates the coefficient of variation for each month



roughly to the period from the fourth to the ninth century AD.

Juniper wood was used in various ways within the tombs, including in parts of above-ground pyramid constructions, alternating with mud bricks (Xu 2002), as the main construction material for subterranean tomb chambers (block house type), or as layers of un-worked trunks covering the chambers. The huge quantity of tomb wood contrasts with the barren, dry steppe vegetation surrounding the burial ground at present.

2.2 Sampling

In 1993, 50–60 living trees per site were increment cored. Selected trees were old but did not have outward signs of disturbance (e.g., abrasion scarring, cut branches). From each tree, two increment cores were collected along opposing radii that were approximately parallel to the slope contour.

In 1999, numerous juniper trunks and wooden coffins from the tombs in the Reshui Valley, 20 km southeast of Dulan (Fig. 1), were sampled in the field as well as in the storeroom of the Archeological Institute in Xining. The maximum diameter of the excavated trunks reached 45 cm. Sampled trunks were well-preserved, but not every sample had the bark with the outermost ring. Altogether, 82 wood samples were collected, including cross sections and increment cores. Cross sections were collected from 21 trunks and six coffins, and increment cores were collected from trunks inside the tomb chambers. All the samples were packed in plastic for transporting to the laboratory.

2.3 Data measurement and analysis

The living-tree increment cores were air dried and glued into grooved sticks with the transverse surface facing up (Phipps 1985). Cores were sanded with successively finer wood abrasives to expose ring details to the cellular level (Stokes and Smiley 1968). The collected cores from each site were crossdated by matching patterns of relatively wide and narrow rings to account for the possibility of ring-growth anomalies such as missing or false rings (Douglass 1941). Each of the two living-tree sites was crossdated by different people to independently verify their dating. Year dates of formation were then assigned to all the rings back in time, beginning with the known year of 1993 for the outermost ring.

The archaeological specimens were air dried and then cleaned with knife blades or polished with abrasives. Chalk was used to improve the contrast of the surfaces. For each cross section, the best radius without growth irregularities was selected for the analysis. Some of the increment cores had very narrow rings, making it impossible to clearly determine individual rings; these samples were excluded from further analysis. The archaeological collection was crossdated independently from the living-tree collection, and 45 samples were used for the construction of the archaeological chronology from Dulan.

Widths of all dated rings were measured to ±0.01 mm and values were checked for dating and measurement errors using cross-correlation testing at multiple time lags (Program COFECHA, Holmes 1983; Grissino-Mayer 2001). The archaeological chronology and the Dulan living-tree chronology crossdated very strongly with one another (correlation $r = +0.62$), with an overlap of 642 years. This crossdating allowed calendar dates to be assigned to the archaeological chronology and identified a missing ring for AD 682 in the living-tree chronology from Dulan.

Series-length growth trends of all the samples were removed by dividing measured values by fitted values from modified negative-exponential curves or straight lines which were estimated using iterative least squares regression (Fritts 1976). This step resulted in dimensionless index series, which were averaged together into a standard chronology using a robust mean calculation (Cook 1985). No variance stabilization techniques were used during any of these steps. Because the two living-tree chronologies correlated strongly with one another and with the archaeological chronology, all three series were merged into a single chronology.

The strongest climate–tree growth model was identified starting with correlations between the standard tree-ring chronology, and monthly temperature and precipitation data from the nearby town of Dulan. Correlations were calculated on a monthly basis beginning with July of the year prior to ring growth and ending with December of the current year of ring growth. Various multimonth seasons of climate, the averages of temperatures or totals of precipitation, were also tested. Based on these correlations, a reasonable and representative season of climate was chosen for reconstruction using the full chronology. Owing to the shortness of the meteorological record, the data were not split into subperiods for separate calibration and verification of the dendroclimatic model (Jacoby et al. 1999). Instead, the reconstruction equation was calibrated using the full period of meteorological data, and the regression model was verified using the press-R^2 value (Montgomery and Peck 1992). Residuals of the final model were checked for normality, correlation with predictors and predictands, and autocorrelation (Weisburg 1980).

This reconstruction was compared with various combinations of atmospheric geopotential height data for the northeastern quarter-sphere to discern relationships between the climate of Qinghai and the synoptic-scale atmospheric features (Hirschboeck et al. 1996). The climate reconstruction was also compared with other records of climate from the region, including a precipitation record from Chinese historical documents (Gong and Hameed 1991) and a temperature record from $\delta^{18}O$ of the nearby Dunde ice cap (Thompson et al. 1989) (Fig. 1). Finally, the reconstruction was compared with a time series of human occupation in the region (Chen et al. 1999).

3 Results

3.1 Chronologies

The average age of Shenge samples is 862 years, with the earliest ring dating to AD 840 (Fig. 3a). The average age of Dulan samples is 683 years, with the earliest ring at Dulan dating to AD 159 from one sample of a remnant snag (Fig. 3b). Both chronologies have strong signal strength, with correlations between individual series and their respective chronologies averaging 0.6 or better. Both chronologies have typical autoregressive properties, with first-order autocorrelation coefficients averaging +0.36. The living-tree chronologies correlate significantly with one another ($r = +0.55$) and also share decadal-scale variation, including periods of good growth in the 1300s, 1500s, late 1800s, and late 1900s as well as periods of poor growth in the late 1400s and centered on 1700. These similarities justified merging the series into a single living-tree chronology. The recent period of above-average growth corresponds well to other research showing increasing net primary productivity in alpine vegetation types of western China since 1982 (Fang et al. 2003).

Archaeological tomb specimens are shorter in time span, with an average length of 374 years, but the entire length of the archaeological chronology is over 1,300 years, ranging from 515 BC to AD 800 (Fig. 3c). The archaeological chronology expresses variation at the multidecadal frequencies as well as typical autoregressive properties. It correlates significantly with the living-tree chronology ($r = +0.7$), and after the merging of the living-tree and archaeological chronologies, the single regional chronology is just over 2,500 years long.

Sample depth is high for most of the combined chronology, especially for 100 BC to AD 700 and again since AD 900 (Fig. 3d). For the combined chronology, a subsample signal strength (Wigley et al. 1984) of 85% of the fully replicated chronology is achieved with as few as nine samples, so periods with weak sample depth extend from 515 to 100 BC as well as from AD 700 to 900, and caution will be merited while interpreting the reconstructed climate of these periods of low sample depth. The sample depth of the Shenge living-tree chronology dips during the periods AD 1250–1270, 1475–1500, and 1710–1730 due to suppressed growth where rings could not be confidently crossdated in many trees. Indeed, the index values are quite low during those periods based on crossdated ring growth of other trees.

3.2 Dendroclimatic modeling

On the monthly scale, winter–spring precipitation correlates mostly positively with tree growth while winter–spring temperature correlates negatively (Fig. 4). For precipitation, the full water-year from previous July through current June correlates the strongest as a single

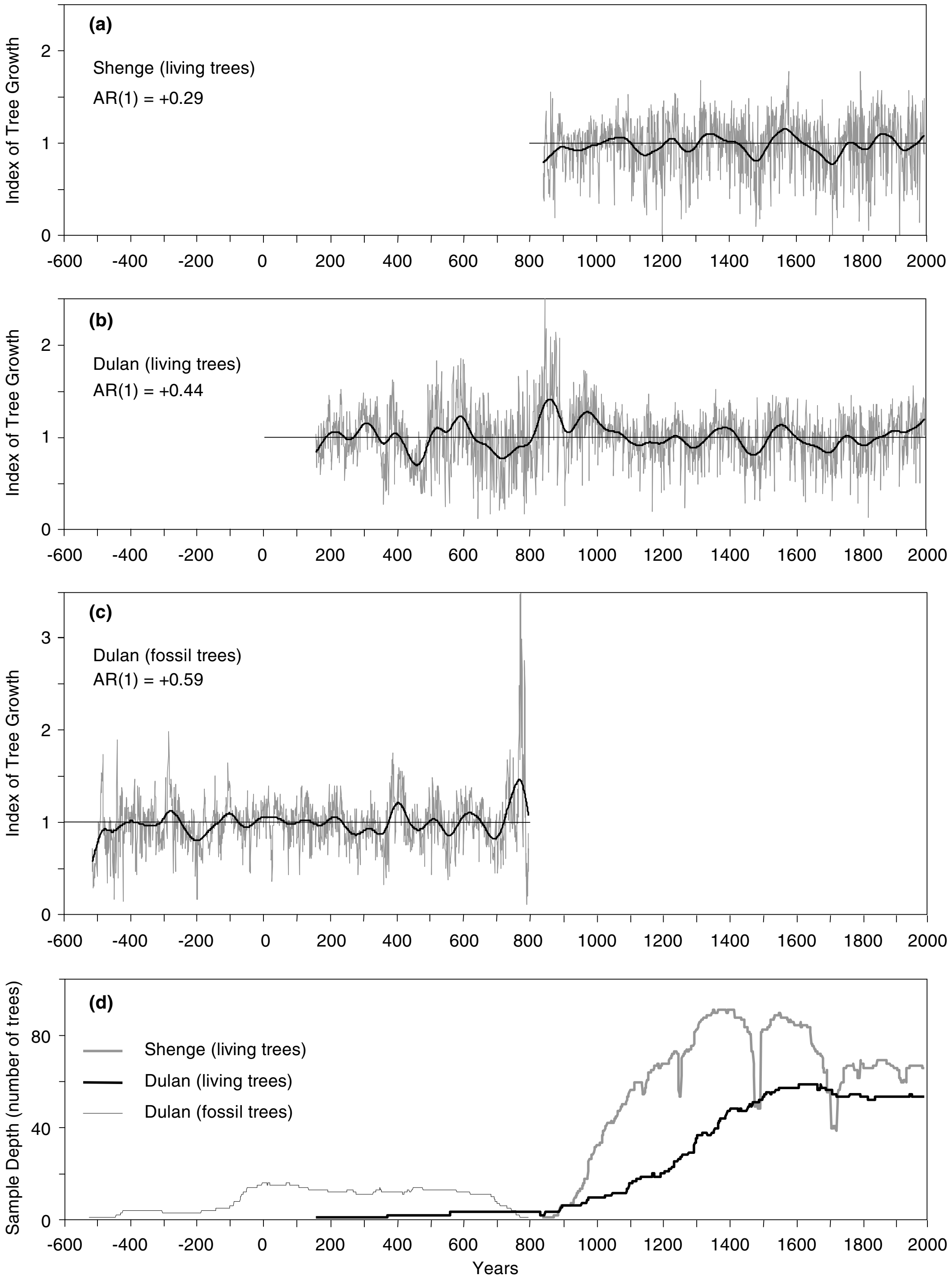


Fig. 3 Standard ring-width index chronologies from **a** Shenge and **b** Dulan living-tree sites and **c** the Dulan archaeological collection. **d** shows the sample depth series for all three collections. AR(1) refers to first-order autocorrelation coefficient. Smoothed lines are the 100-year cubic smoothing spline (Cook and Peters 1981)

season with a value of +0.70. For temperature, April through June correlates the strongest as a single season with a value of −0.42. These results combine to indicate that pre-growing season moisture availability is the most important factor limiting tree growth at these juniper stands, with precipitation of the entire year of previous July through current June being the critical weather variable affecting soil moisture availability. This finding is consistent with other well-replicated juniper sites in the region (Zhang and Wu 1992), with sites farther away such as to the east in the Qinling Mountains (Wu 1994) and to the north in Mongolia (Jacoby et al. 1999), and

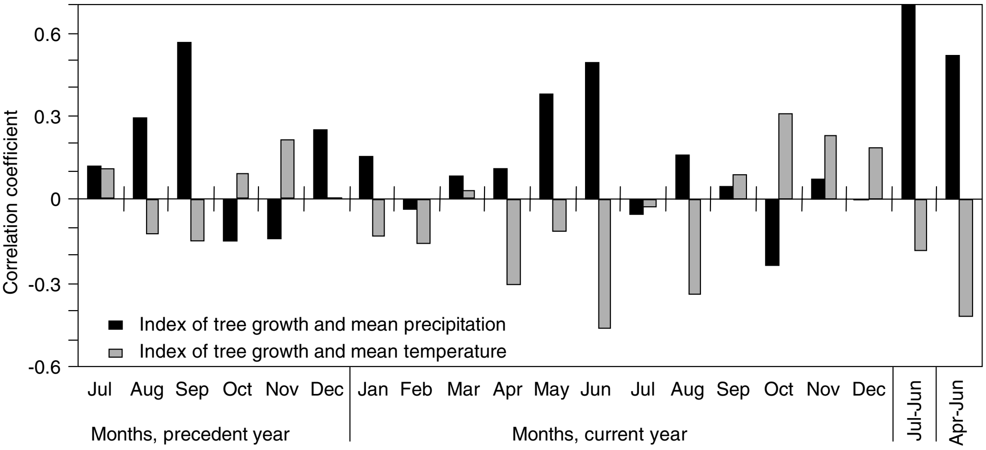


Fig. 4 Monthly correlations using ring-width indices from the combined juniper chronology and meteorological data from Dulan (1955–1988) for precipitation (*black bars*) and temperature (*gray bars*). The critical correlation value for $n = 30$ and alpha = 0.05 is ±0.30 (Rohlf and Sokal 1981)

with sites of juniper and pines in other semiarid sites (e.g., Schulman 1956; Grissino-Mayer et al. 1997). This full water-year precipitation model differs from that reported by an independent dendroclimatic analysis of similar (although shorter in time) data from Dulan that concluded that the May–June precipitation was the main factor controlling juniper growth in the area, with a correlation value of +0.58 (Zhang et al. 2003).

The precipitation period of July to the following June was chosen for reconstruction. The regression model accounts for 47.8% of the variance in July through June precipitation, which is very significant ($p < 0.001$). The press-R^2 value is also high at 42.8%. Both low- and high-frequency variations are modeled reasonably well (Fig. 5). Predicted values match actual values particularly well during the 1960s, though not so well as in the 1980s. Years of low precipitation match better than those with high precipitation, which is often true in dendrochronological reconstructions of moisture availability (Schulman 1956). Model residuals are reasonably normally distributed, show low autocorrelation (AR(1) = +0.20, with a nonsignificant Durbin–Watson statistic), and do not correlate with the predictor or the predictand. This model was deemed acceptable and applied to the full chronology since 515 BC.

Reconstructed values of annual precipitation vary mostly from 100 to 300 mm and thus are no different from the modern instrumental record in Dulan (Fig. 6a). However, relatively dry years with below-average precipitation occurred more frequently during the past than at present. Periods of relatively dry years occurred during 74–25 BC, AD 51–375, 426–500, 526–575, 626–700, 1100–1225, 1251–1325, 1451–1525, 1651–1750 and 1801–1825. Periods with a relatively wet climate occurred during AD 376–425, 576–625, 951–1050, 1351–1375, 1551–1600 and the present.

3.3 Synoptic circulation analysis

During winter, the weather in Asia is dominated by an intense anticyclone over Siberia and Mongolia (Domrös and Peng 1988). At 3,000 m altitude, zonal westerlies prevail across eastern Asia (Trewartha 1981). Indeed, the average winter climatology for Qinghai as expressed by December through February geopotential heights of the 700 mb pressure zone shows an approximately zonal flow for the northeastern quarter-sphere, with maximum westerly winds just west of Qinghai located at about 40°N (Fig. 7a).

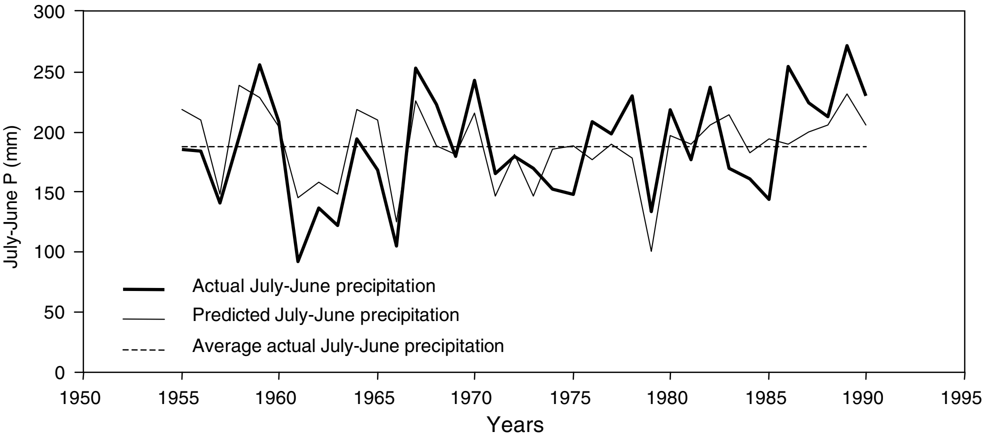


Fig. 5 Actual (*thick line*) and predicted (*thin line*) precipitation for the season prior to July through current June. *Horizontal dashed line* indicates the mean value for the meteorological record

Most winter weather systems of the Qinghai Plateau occur in westerly troughs or ridges coming from central Asia (Yuan 1981). In the central, western provinces of China, winter rains are mainly frontal westerlies and are frequently associated with wave-depressions aloft in the atmosphere (Watts 1969). An important feature of the upper-level westerlies is the presence of troughs and fronts (Thompson 1951). The average circulation pattern for wet years shows that the maximum winds were shifted southward by about one degree of latitude, while the driest years show a shift northward by about one degree. The difference between atmospheric circulation for wet versus dry years shows high pressure over the Mediterranean and eastern Siberia, separated by low pressure over central Asia just west of Qinghai (Fig. 7b).

Droughts lasting longer than one month are typically associated with anomalies of large-scale circulation (Wang et al. 1994). While planetary scale systems do not directly produce rain storms, they can influence precipitation by changing important characteristics of synoptic systems (Wang et al. 1994). The upper-level (i.e. 700 mb level) westerly flow rarely varies during winter, though the exact extent of the airflow varies somewhat each year (Thompson 1951). It appears that whatever interannual variation exists in the upper-level waveform at the 3,000-m height can alter winter precipitation over northeastern Qinghai and perhaps other semiarid regions of northwestern and northern China. Accordingly, the complete yearly precipitation over Qinghai correlates directly with this atmospheric circulation pattern, showing positive correlations with high pressure zones and a negative correlation with the low pressure zone (Fig. 7c). Thus, the average zonal atmospheric circulation pattern is either shifted southward slightly and/or it becomes more meridional during wet years over Qinghai and vice versa. This synoptic climatology is similar to that of the semiarid American Southwest (Sheppard et al. 2002).

3.4 Multiproxy comparison

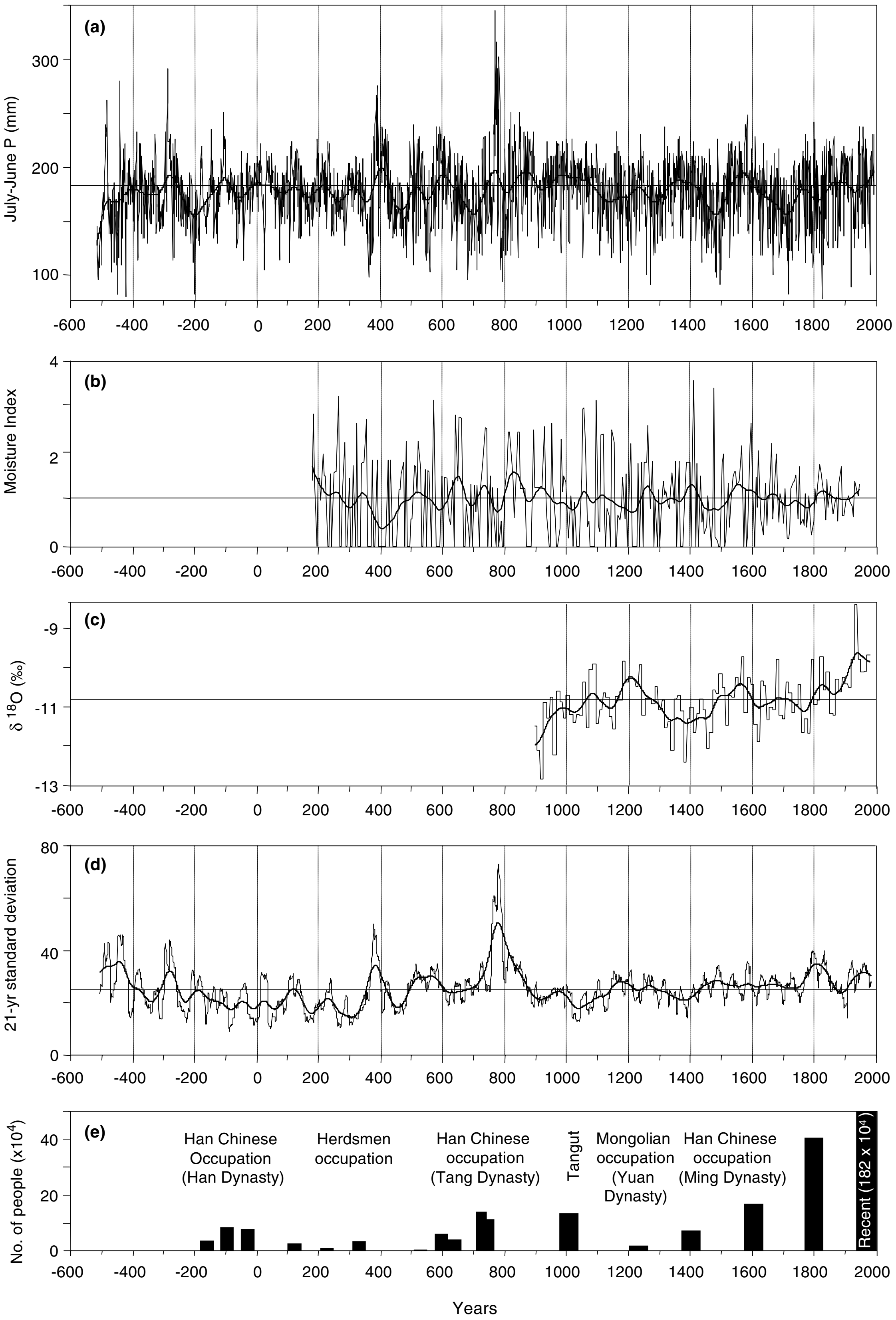
On the century scale, this dendrochronological reconstruction of moisture availability matches reasonably well since AD 1000 with a moisture index derived from historical documents (Gong and Hameed 1991). Common periods of above-average moisture occurred during the late 1300s, AD 1551–1625, and 1850 to the present (Fig. 6a, b). Similarly, common periods of below-average moisture occurred during AD 1100–1225, 1275–1325, 1451–1525 and 1675–1750. Especially notable is the long period of declining moisture in both series from AD 1550 to 1700. These two series do not match as well prior to AD 1000, which might be due to relatively few historical documents during that period (Gong and Hameed 1991) and/or relatively low sample depth for the archaeological chronology. The region covered by the moisture index series (Region *C* in Fig. 1) receives 300–500 mm of rain per year, which is more than that for northeastern Qinghai but is still considered semiarid (Gong and Hameed 1991). Given that moisture indices reconstructed for that region show similar low-frequency variation to the precipitation reconstruction, perhaps synoptic-scale climatic features control winter precipitation similarly over both regions.

In combination with the $\delta^{18}O$ temperature record (Fig. 6c) from the nearby Dunde ice cap (Thompson et al. 1989), which is well confirmed by other reconstructions of temperature for China (Wang and Wang 1990), major climatic periods can be identified. These two records often vary congruously. For example, the period AD 900 to 1100 was wet with increased warming, the 1100s were cool and dry, the late 1500s were warm and wet, the 1600s were cooler and dryer, and after 1825 to the present the climate has been generally warm and wet (Fig. 6a, c). These two records varied inversely to each other from 1300 to the mid-1400s, which were cool and wet.

Also of interest is comparing interannual variability in the tree-ring precipitation record and the ice core temperature record. A running standard deviation with a window length of 21 years (Grissino-Mayer et al. 1997) was calculated from the dendrochronological reconstruction. As partial validation of this Qinghai series, the period of relatively decreased interannual variability in water-year precipitation during the mid- to late 1800s (Fig. 6d) corresponds to a similar finding for annual precipitation and for streamflow discharge for northeastern Mongolia (Pederson et al. 2001). Since AD 900, above-average interannual variability in precipitation has coincided with warm periods (Fig. 7c, d). Conversely, below-average interannual variability in precipitation has coincided with cool periods, which is especially notable for the 1300s and 1400s. On the millennial scale, both temperature and interannual variability in water-year precipitation have been increasing since AD 1000. This direct association between temperature and interannual variability in precipitation corresponds with other findings on rainfall variability across regional scales (McDonald 1956).

As for the archaeological time period of this reconstruction, pollen and sedimentary records from Telmen Lake (48°50′N, 97°20′E, 1,789 m) in central Mongolia suggest an arid excursion dated to about 50 BC (Fowell et al. 2003), corresponding to the relatively dry interval in our Qinghai record (Fig. 6a). A dry period between AD 350 and 750 suggested by the pollen record also corresponds to the interval with predominantly dry years in Dulan. This correspondence is not perfect, as two short wet periods occurred around AD 400 and around AD 600. In general, however, hydrological regimes of western Qinghai and Central Mongolia are reasonably similar.

Furthermore, approximately synchronous arid periods are reported for sites located between Qinghai and Telmen Lake. For example, sedimentary records from Yiema Lake (39°06′N, 103°40′E) suggest a drought around AD 450 (Chen et al. 1999), and sedimentary records from Eastern Juyanze Lake (41.89 N, 101.85E,


(a)
July-June P (mm)
300
200
100
(b)
Moisture Index
4
2
0
(c)
δ 18O (‰)
-9
-11
-13
(d)
21-yr standard deviation
80
40
0
(e)
No. of people (x10⁴)
40
20
0
Han Chinese Occupation (Han Dynasty)
Herdsmen occupation
Han Chinese occupation (Tang Dynasty)
Tangut
Mongolian occupation (Yuan Dynasty)
Han Chinese occupation (Ming Dynasty)
Recent (182 x 10⁴)
-600
-400
-200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Years

◀

Fig. 6 a Reconstructed precipitation July through June (this study), **b** moisture indices from Chinese historical documents (area *I* of Gong and Hameed 1991, data obtained from the Carbon Dioxide Information Analysis Center), **c** δ^{18}O isotope variation from ice layers at the Dunde Ice Cap (Thompson et al. 1989), **d** a 21-year running standard deviation of reconstructed precipitation from Qinghai junipers (this study), and **e** the number of citizens belonging to the central Chinese state (after Chen et al. 1999) in the Shiyang River catchment area (region *D* in Fig. 1). The smoothed lines are 100-year cubic smoothing splines

892 m) in the Alashan Gobi, northwestern China, indicate drying after AD 320 (Herzschuh et al. 2004). Both these dry periods are indicated by the Qinghai precipitation reconstruction (Fig. 6a).

4 Discussion: human interactions with climate variability

4.1 Past

Knowledge about human population density and land use in Qinghai area during the last 2,500 years is relatively sparse. The political history of Qinghai is marked by the frequently changing dominance of different ethnic groups that were alien or neighbors to the Chinese. Not until 1720 did Qinghai become part of the Chinese empire. Prior to that time, it was of only episodic interest to central China because the environment was regarded as unsuitable for promoting permanent settlement.

Qinghai first came into the purview of Chinese historiography during the early part of the Han dynasty (202 BC–AD 23) when the Han influence extended westward. In Han documents, the native inhabitants of Qinghai were called Qiang and described as seminomadic herdsmen (Bielenstein 1995). It was generally assumed that field cultivation was first introduced to Qinghai by Han-Chinese peasants who settled around modern Xining, in the valley of the Huang He (Yellow River) and as far west as around the Qinghai Lake (Fig. 1). On the other hand, recent excavation of a late Bronze Age settlement in the vicinity of Xining has proved that the subsistence of settlers around 1000 BC was dominated by farming in which barley was the main crop (Xu et al. 2003).

The first wave of Chinese occupation was short-lived. By the second century AD, there were mass movements eastward bringing herdsmen from the mountains down into the western loess lands close to the Han capital of Chang'an (modern Xi'an). Between AD 2 and 140, approximately 70% of the Han-Chinese inhabitants left the territory of Qinghai (Bielenstein 1995) due to pressure from the Qiang, who filled the emptied areas. The same tendency and drastic decrease in the number of agrarians can be observed in the Shiyang River basin (Region *D* in Fig. 1, Fig. 6e). Tribes of herdsmen migrated into the western Chinese territories with so many people that they soon outnumbered the Chinese settlers there (Yü 1995).

After the later Han dynasty ended in AD 220, northern China split up into several independent, short-lived kingdoms of tribal origin. During the fourth century AD, the area around Qinghai Lake and the eastern part of the Qaidam Basin became the grazing territory of the Tuyuhun, a Tibetanized Xianbei people (Wechsler 1997; Wright 1997), who reigned until they were overthrown by the Tibetans by AD 680. The Tibetan kingdom of Tubo (Tufan) grew in power beginning in the first half of the seventh century, and expanded its territory rapidly by mid-century. By destroying the Tuyuhun kingdom, the Tibetans became the immediate northwestern neighbors of the Chinese Tang Empire (AD 618–907), persistently threatening trade routes (Twitchett and Wechsler 1997). The grave goods that were left by the robbers in Dulan (Xu 2002) demonstrate the enormous benefit that the Tibetans earned from controlling long-distance trade. Military colonies and fortresses became part of the defensive system along the northwestern frontier for which local agricultural activities had to be intensified to sustain permanent military forces (Twitchett and Wechsler 1997). This policy was partly successful in the Gansu corridor and in the Shiyang River basin, resulting in the agrarian population growth (Fig. 6e).

The remarkable Qiang mass-migration into the western Chinese territories (de Crespigny 1984) coincides with the reconstructed dry interval starting in the first century AD and continuing until the end of fourth century when the Tuyuhun settled around Qinghai Lake. As the Qiang settled east of the Huang He during the first century AD, pastoral tribes generally dominated the whole of northern China for about 350 years until the next central Chinese empire, the Sui dynasty, was founded in AD 581. Below-average precipitation during this period might have been one of the main factors in shifting cultural trends from Chinese-style peasant agriculture to a non-Chinese pastoral economy (de Crespigny 1984). During the relatively wet period between AD 576 and 625 a strong Tibetan kingdom opposed the Chinese Tang dynasty.

In the seventh and eighth centuries, the territory of Qinghai belonged to the Tibetan kingdom, which limited the Chinese expansion. At that time (at least from AD 626 to 700), the climate reconstruction suggests rather dry conditions.

Our reconstruction suggests that the climate became more favorable for agriculture between the late 900s and AD 1100. At about that time, Chinese sources report that many of the formerly nomadic Uighurs became sedentary agriculturalists in the oasis of the Gansu corridor and Xinjiang (Twitchett 1997). The population peak in the Shiyang River area at AD 1000 (Fig. 6e) was associated with intensified irrigation and land use under the rule of the Tangut dynasty Xixia (AD 1038–1227), which controlled the steppes between the Ordos Plateau and the Tarim Basin (Franke and Twitchett 1994). Sedentary populations of the Shiyang (Region *D* in Fig. 1) decreased drastically in the twelfth century, when reconstructed

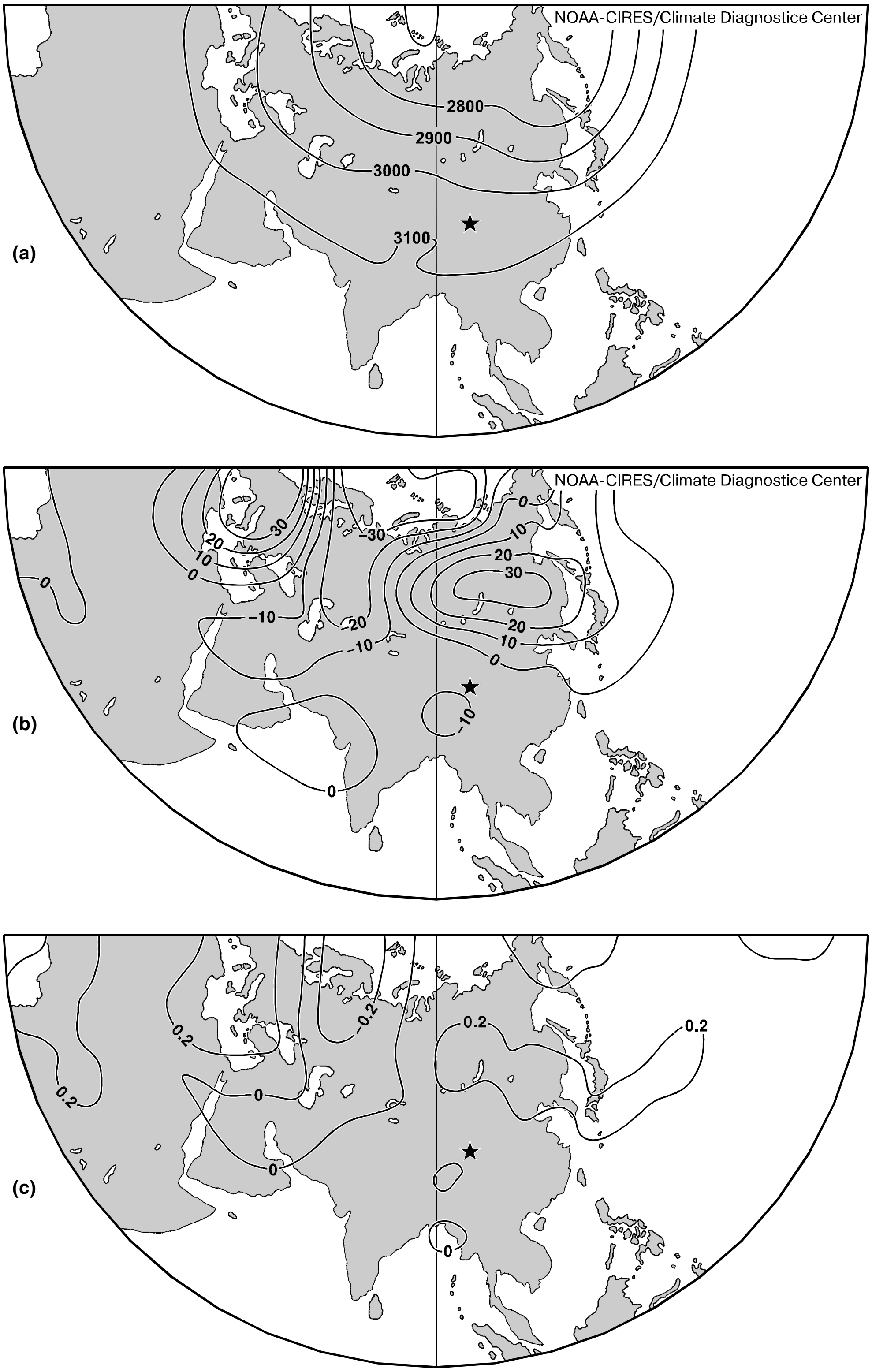


Fig. 7 Synoptic climatology of the northeastern quarter-sphere: **a** average geopotential heights of the 700-mb zone for the winter season (December through February), **b** geopotential height differences between the five wettest years minus the five driest years of the meteorological record, and **c** correlation field between the reconstructed winter precipitation series and 700-mb geopotential heights. Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/ (Kalnay et al. 1996). The Qinghai tree-ring sites are marked with a star

precipitation in Dulan was low. Generally dry conditions continued during the time of Mongolian occupation of the Yuan dynasty (AD 1279–1368). Population growth in the Gansu corridor and in the Shiyang River basin is registered at about AD 1400 during the Chinese Ming dynasty (AD 1368–1644). This rise is synchronous with the precipitation increase reconstructed in Dulan (Fig. 6a) and in the region *C* (Fig. 6b, Gong and Hameed 1991). Whether early human migrations and associated changes in land use in the region were caused by the climatic changes or were simply coincidental to climatic changes remains an unsolved question at the moment. The answer requires additional historical-environmental study, which is the objective of future work.

4.2 Future

Given the direct association between temperature and interannual variability in precipitation found in this study and the prediction of increased warming on a global scale throughout the twenty-first century (IPCC 2001), interannual precipitation variability for Qinghai can be projected to increase in the future. Indeed, it has been concluded independently that increased annual variability in precipitation is generally "very likely" (IPCC 2001 p. 13). While the annual mean for precipitation might also continue increasing for Qinghai throughout the twenty-first century, the increased variability might be especially difficult for human societies to adjust to. With a considerable surface area above 3,000 m elevation, there are no good opportunities for large-scale water storage strategies to help smooth out annual variability in rainfall. Consequently, Qinghai residents might face increased occurrences of both floods and droughts in the near future, perhaps causing hardship to urban and agricultural systems (Collier and Webb 2002).

5 Conclusions

Junipers growing in semiarid sites of the northeastern Qinghai are useful for reconstructing soil moisture availability for that area going back for more than two millennia. The reconstructed moisture availability represents primarily the complete yearly precipitation prior to tree growth each year. This climatic feature has varied dramatically on multiple time scales over the last 2,500 years, with Qinghai currently in a relatively wet period. On the decadal scale, variability in precipitation appears to correlate directly with warm and cold spells as reconstructed from Dunde ice core δ^{18}O data. Northeastern Qinghai is currently in a warm phase, suggesting that the relatively wet period with high interannual variability occurring at present might continue into the future.

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References

Bielenstein H (1995) Wang Mang, the restoration of the Han dynasty, and later Han. In: Twitchett D, Loewe M (eds) The Cambridge history of China, vol 1: The Ch'in and Han empires, 221 B.C.–A.D. 220. Cambridge University Press, New York, pp 223–290

Bradley RS (1985) Quaternary paleoclimatology: methods of paleoclimatic reconstruction. Allen and Unwin, Boston

Bradley RS (ed) (1989) Global changes in the past. Papers arising from the 1989 symposium on global change Inst. UCAR/office for interdisciplinary earth studies boulder, Colorado

Bradley RS, Diaz HF, Jones PD, Kelly PM (1987) Secular fluctuations of temperature over Northern Hemisphere land areas and mainland China since the mid-19th century. In: Ye D, Fu C, Chao J, Yoshino M (eds) The climate of China and global climate. China Ocean Press, Beijing, pp 76–87

Bräuning A (1994) Dendrochronology for the last 1400 years in eastern Tibet. Geo J 34:75–95

Bräuning A (1999) Dendroclimatological potential of drought-sensitive tree stands in southern Tibet for the reconstruction of monsoonal activity. IAWA J 20:325–338

Bräuning A (2001) Climate history of the Tibetan Plateau during the last 1000 years derived from a network of juniper chronologies. Dendrochronologia 19(1):127–137

Bräuning A (2003) Climatic changes on the Tibetan Plateau during the last 2000 years derived from tree-ring studies. Berliner Paläobiologische Abhandlungen 2:22–25

Briffa KR, Osborn TJ (1999) Seeing the wood from the trees. Science 284:926–927

Chen F-H, Shi Q, Wang J-M (1999) Environmental changes documented by sedimentation of Lake Yiema in arid China since the Late Glaciation. J Paleolimnol 22:159–169

Collier M, Webb RH (2002) Floods, droughts, and climate change. University of Arizona Press, Tucson

Cook ER (1985) A time series analysis approach to tree-ring standardization. Ph.D. Dissertation, University of Arizona

Cook ER, Kairiukstis LA (1990) Methods of dendrochronology: application in the environmental science. Kluwer, Dordrecht

Cook ER, Peters K (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree Ring Bull 41:45–53

De Crespigny R (1984) Northern frontiers: the policies and strategy of the later Han Empire. Australian National University Press, Canberra

Domrös M, Peng G (1988) The climate of China. Springer, Berlin Heidelberg New York

Douglass AE (1941) Crossdating in dendrochronology. J For 39:825–831

Fang J, Piao S, Field CB, Pan Y, Guo Q, Zhou L, Peng C, Tao S (2003) Increasing net primary production in China from 1982 to 1999. Front Ecol Environ 1:293–297

Fowell S, Hansen B, Peck J, Khosbayar P, Ganbold E (2003) Mid to late Holocene paleoclimate evolution of the Lake Telmen Basin, north central Mongolia, based on palynological data. Q Res 59:353–363

Franke H, Twitchett D (eds) (1994) The Cambridge history of China, vol 6: Alien regimes and border states. Cambridge University Press, New York, pp 907–1368

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

Gao YX, Li C (1980) Influences of Qinghai-Xizang Plateau on seasonal variation of general atmospheric circulation. In: Liu D (ed) Geological and ecological studies of Qinghai-Xizang Plateau: proceedings of symposium on Qinghai-Xizang (Tibet) Plateau (Beijing, China). Science, Beijing, pp 1477–1484

Gao Y, Tang M, Luo S, Shen Z, Li C (1981) Some aspects of recent research on the Qinghai-Xizang plateau meteorology. Bull Am Meteorol Soc 62:31–35

Gong G, Hameed S (1991) The variation of moisture conditions in China during the last 2,000 years. Int J Clim 11:271–283

Grissino-Mayer HD (2001) Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree Ring Res 57(2):205–221

Grissino-Mayer HD, Fritts HC (1997) The International Tree-Ring Data Bank: an enhanced global database serving the global scientific community. Holocene 7:235–238

Grissino-Mayer HD, Swetnam TW, Adams RK (1997) The rare old-aged conifers of El Malpais—their role in understanding climatic change in the American Southwest. In: Mabery K (ed) Natural history of El Malpais national monument, vol 156. New Mexico Bureau of Mines and Mineral Resources Bulletin, pp 155–161

He H, McGinnis J, Song Z, Yanai M (1987) On the onset of Asian summer monsoon in 1979 and the effect of the Tibetan plateau. Mon Weath Rev 115:1966–1995

Herzschuh U, Tarasov P, Wünnemann B, Hartmann K (2004) Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data. Palaeogeogr Palaeoclimatol Palaeoecol 211(1–2):1–17

Hirschboeck KK, Ni F, Wood ML, Woodhouse CA (1996) Synoptic dendroclimatology: overview and outlook. In: Dean JS, Meko DM, Swetnam TW (eds) Tree rings, environment, and humanity, pp 205–223

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree Ring Bull 43:69–77

Hughes MK, Wu X, Shao X, Garfin GM (1994) A preliminary reconstruction of rainfall in north-central China since A.D. 1600 from tree-ring density and width. Q Res 42(1):88–99

IPCC (Intergovernmental Panel on Climate Change) (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge

Jacoby G, D'Arrigo RD, Pederson N, Buckley B, Dugarjav C, Mijiddorj R (1999) Temperature and precipitation in Mongolia based on dendroclimatic investigations. IAWA J 20:339–350

Kalnay E et al (1996) The NCEP/NCAR reanalysis 40-year project. Bull Am Meteorol Soc 77:437–471

Lau KM, Li MT (1984) The monsoon of east Asia and its global associations—a survey. Bull Am Meteorol Soc 65:114–125

Lin Z, Wu X (1981) Climatic classification of Qinghai-Xizang Plateau. In: Liu D (ed) Geological and ecological studies of Qinghai-Xizang Plateau: proceedings of symposium on Qinghai-Xizang (Tibet) Plateau (Beijing, China). Science, Beijing, pp 1575–1580

Lin Z, Wu X (1987) Some features of climatic fluctuation over the Qinghai-Xizang plateau. In: Ye D, Fu C, Chao J, Yoshino M (eds) The climate of China and global climate. China Ocean Press, Beijing, pp 116–123

McDonald JE (1956) Variability of precipitation in an arid region: a survey of characteristics for Arizona. University of Arizona, Institute of Atmospheric Physics, Technical Reports on the Meteorology and Climatology of Arizona, No. 1

Montgomery DC, Peck EA (1992) Introduction to linear regression analysis, 2nd edn. Wiley, New York

Pederson N, Jacoby GC, D'Arrigo RD, Cook ER, Buckley BM (2001) Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. J Climatol 14:872–881

Phipps RL (1985) Collecting, preparing, crossdating, and measuring tree increment cores. U.S. Geological Survey Water-Resources Investigations Report 85-4148

Richardson SD (1990) Forests and forestry in China. Island Press, Washington

Rohlf FJ, Sokal RR (1981) Statistical tables. WH Freeman, San Francisco

Schulman E (1956) Dendroclimatic changes in semiarid America. University of Arizona Press, Tucson

Schweingruber FH (1996) Tree-rings and environment: dendroecology. Paul Haupt, Bern

Sheppard PR, Comrie AC, Angersbach K, Packin GD, Hughes MK (2002) The climate of the Southwest. Clim Res 21(3):239–258

Stokes MA, Smiley TL (1968) An introduction to tree-ring dating. Chicago University Press, Chicago

Thompson BW (1951) An essay on the general circulation of the atmosphere over South-East Asia and the West Pacific. Q J Roy Meteorol Soc 77:569–597

Thompson LG, Mosley-Thompson E, Davis ME, Bolzan JF, Dai J, Yao T, Gundestrup N, Wu X, Klein L, Xie Z (1989) Holocene-late Pleistocene climatic ice core records from Qinghai-Tibetan plateau. Science 246:474–477

Thompson LG, Mosley-Thompson E, Davis M, Lin PN, Yao T, Dyurgerov M, Dai J (1993) "Recent warming": ice core evidence from tropical ice cores with emphasis on central Asia. Global Plan Change 7:145–156

Trewartha GT (1981) The earth's problem climates. Wisconsin University Press, Madison

Twitchett D (1997) Introduction. In: Twitchett D, Fairbank JK (eds) The Cambridge history of China, vol 3: Sui and T'ang China, 586–906, Part I. Cambridge University Press, New York, pp 1–47

Twitchett D, Wechsler HJ (1997) Kao-tsung (reign 649–83) and the empress Wu: the inheritor and the usurper. In: Twitchett D, Fairbank JK (eds) The Cambridge history of China, vol 3. Sui and T'ang China, 586–906, Part I. Cambridge University Press, New York, pp 242–289

Wagner M, Heussner K-U, Wang S (2002) Die neue dendrochronologische Standardkurve für Qinghai, NW China (515 BC bis heute). Terra Nostra 6:401–404

Wang S, Wang R (1990) Seasonal and annual temperature variations since 1470 AD in East China. Acta Meteorol Sin 4(4):428–439

Wang X, Corte-Real J, Zhang X (1994) Large-scale circulation regimes and precipitation anomalies over China. J Meteorol Soc Jpn 72:841–857

Watts IEM (1969) Climates of China and Korea. In: Arakawa H (ed) Climates of northern and eastern Asia. Elsevier, Amsterdam, pp 1–117

Wechsler HJ (1997) T'ai-tsung (reign 626–49) the consolidator. In: Twitchett D, Fairbank JK (eds) The Cambridge history of China, vol 3. Sui and T'ang China, 586–906, Part I. Cambridge University Press, New York, pp 188–241

Weisburg S (1980) Applied linear regression. Wiley, New York

Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteoro 23:201–213

Wilkinson E (2000) Chinese history, a manual. Harvard-Yenching institute monograph series 52. Harvard University Press, London

Wright AF (1997) The Sui dynasty (581–617). In: Twitchett D, Fairbank JK (eds) The Cambridge history of China, vol 3. Sui and T'ang China, 586–906, Part I. Cambridge University Press, New York, pp 48–149

Wu X (1992) Dendroclimatic studies in China. In: Bradley RS, Jones PD (eds) Climate since AD 1500. Routledge Press, London, pp 432–445

Wu X (1994) Tree-ring with chronologies and their response to climate in the Qinling Mountains, China. Terr Atmos Ocean Sci 5:272–365

Wu X, Zhan X (1991) Tree-ring width and climatic change in China. Quatern Sci Rev 10:545–549

Wu X, Cheng Z, Sun L (1987) Status of dendrochronological work in China. Dendrochronologia 5:127–133

Xu XG (2002) Zhongguo Qinghai sheng Dulan Tubo muqun de faxian, fajue yu yanjiu [Discovery, excavation and study of Tubo tombs in Dulan, Qinghai Province, China]. Silk Roadology 14, Studies of the Silk Road in Qinghai Province, China, pp 212–225

Xu XG, Zhao F (1996) A preliminary study of the silk textiles excavated at Dulan. China Archaeology Art Digest 1(4):13–34

Xu XG, Wang W, Wagner M, Heussner K-U, Tarasov PE, Grieß B, Niu SS, Song JN, Xiao YM, Cai LH (2003) Results of the first archaeological excavation and environmental survey at Fengtai, Qinghai Province, PR China, in 2001. Eurasia Antiqua 9:85–111

Yü Y (1995) Han foreign relations. In: Twitchett D, Loewe M (eds) The Cambridge history of China, vol 1. The Ch'in and Han Empires, 221 B.C.– A.D. 220. Cambridge University Press, New York, pp 377–462

Yuan F (1981) Characteristics of weather systems of Qinghai-Xizang Plateau. In: Liu D (ed) Geological and ecological studies of Qinghai-Xizang Plateau: proceedings of symposium on Qinghai-Xizang (Tibet) Plateau (Beijing, China). Science Press, Beijing, pp 1569–1574

Yuan Y (2003) Estimating annual precipitation in the period of glacier advance from tree-rings for the north slope of the middle Tianshan Mountains. Berliner Paläobiologische Abhandlungen 2:134

Zhang Z, Wu X (1992) Utilizing two Qinghai tree-ring chronologies to reconstruct and analyze local historical precipitation. Quart J Appl Meteorol 3:61–69 (Chinese)

Zhang QB, Cheng GD, Yao TD, Kang XC, Huang JG (2003) A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau. Geophys Res Lett 30(14): DOI 10.1029/2003GL017425

Zhao S (1986) Physical geography of China. Wiley, New York

Zheng S, Wu X, Lin Z (1982) Asia. In: Hughes MK, Kelly PM, Pilcher JR, LaMarche VC (eds) Climate from tree rings. Cambridge University Press, Cambridge, pp 155–157

Zou J (1987) The influence of plateau on the climate over China. In: Ye D, Fu C, Chao J, Yoshino M (eds) The climate of China and global climate. Ocean Press, Beijing, pp 345–346