

Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961–2003

Xiaodong Liu,^{1,2} Zhi-Yong Yin,³ Xuemei Shao,⁴ and Ningsheng Qin⁵

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[1] Daily and monthly maximum and minimum surface air temperatures at 66 weather stations over the eastern and central Tibetan Plateau with elevations above 2000 m were analyzed for temporal trends and spatial variation patterns during the period 1961–2003. Statistically significant warming trends were identified in various measures of the temperature regime, such as temperatures of extreme events and diurnal temperature range. The warming trends in winter nighttime temperatures were among the highest when compared with other regions. We also confirmed the asymmetric pattern of greater warming trends in minimum or nighttime temperatures as compared to the daytime temperatures. The warming in regional climate caused the number of frost days to decrease significantly and the number of warm days to increase. The length of the growing season increased by approximately 17 days during the 43-year study period. Most of the record-setting months for cold events were found in the earlier part of the study period, while that of the warm events occurred mostly in the later half, especially since the 1990s. The changes in the temperature regime in this region may have brought regional-specific impacts on the ecosystems. It was found that grain production in Qinghai Province, located in the area of prominent warming trends, exhibited strong correlations with the temperatures, although such relationships were obscured by the influence of precipitation in this arid/semiarid environment in juniper tree ring records. In western Sichuan Province under a more humid environment, the tree growth (spruces) was more closely related to the changing temperatures.

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1. Introduction

[2] Global warming and associated regional climatic changes have attracted much attention in recent years. Most of the scientific community agrees that significant increases in global temperature (“temperature” in this article means surface air temperature, unless otherwise indicated) have occurred in the past century and will continue into the foreseeable future. The Third Assessment Report of the IPCC showed an increase in global mean temperature of approximately 0.6°C during the twentieth century [Houghton

et al., 2001], although the climatic warming has not been uniform either spatially or temporally as indicated by observed changes and modeling studies [Folland et al., 2001; McAvaney et al., 2001]. An important aspect of climate change involves the changing characteristics of daily temperature and in particular, the changes in the extremes of the daily temperature distribution. Increases in mean temperature are expected to be accompanied by increased frequencies of hot days and warm nights. Given these identifiable changes, it is expected that there will also be changes in the extreme temperature events, such as the frequency of days with extremely low or extremely high temperatures. As has been shown by Katz and Brown [1992], extreme climatic events are more sensitive to climatic changes than their mean values. This means that if global climate change is a real phenomenon, it should be detected and clearly revealed in the behavior of the extreme climatic events. Climate-change-induced variations in global or regional extreme air-temperature events are receiving more attention recently [e.g., Easterling et al., 2000; Meehl et al., 2000; Frich et al., 2002], because living creatures and ecosystems, as well as the human society, are sensitive to the severity, frequency, and persistence of extreme temperature events [Wigley, 1985]. Examination of the changes in variation patterns in

¹State Key Laboratory for Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China.

²Also at Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China.

³Department of Marine Science and Environmental Studies, University of San Diego, San Diego, California, USA.

⁴Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.

⁵Qinghai Climate Data Center, Qinghai Meteorological Bureau, Xining, China.

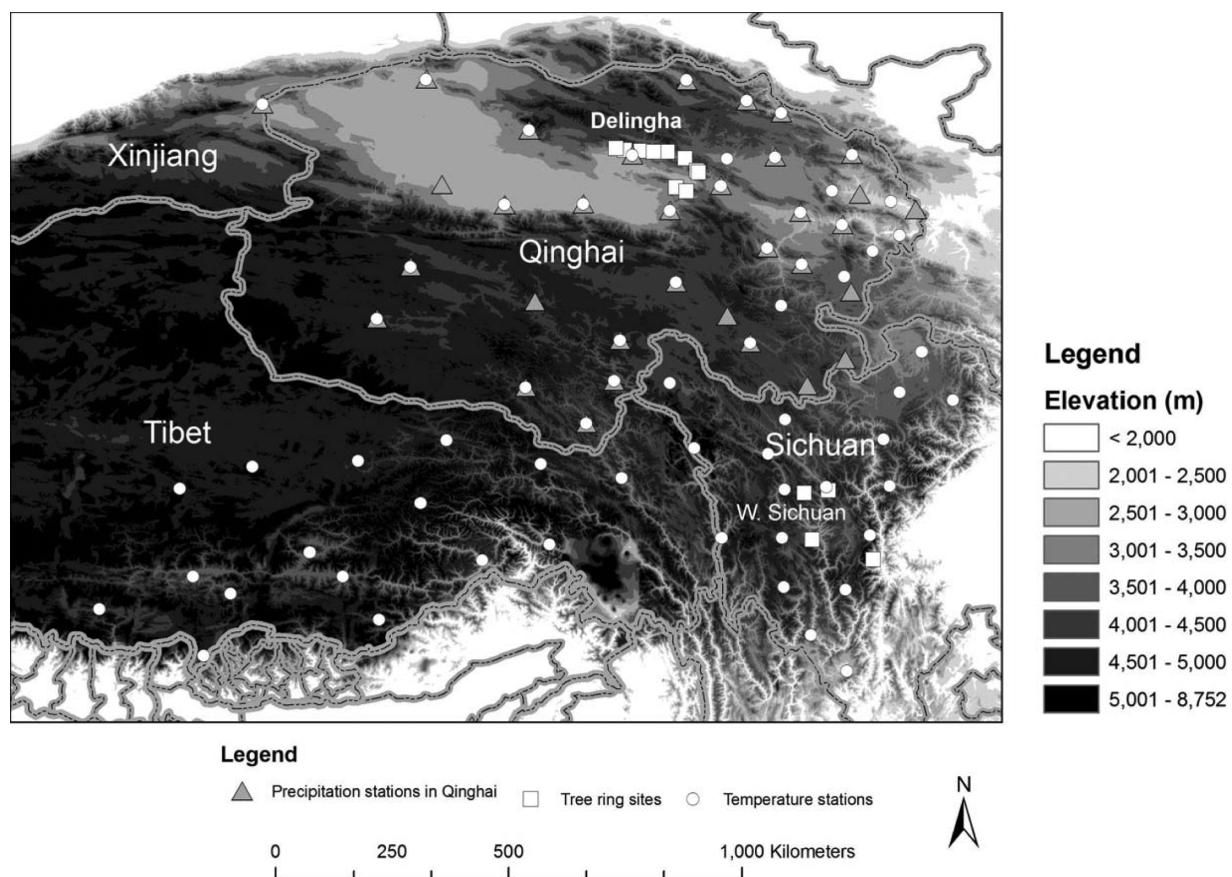


Figure 1. Study area, locations of the 66 weather stations with daily maximum and minimum temperature observations, precipitation stations in Qinghai Province, and the tree ring sampling sites in Delingha, Qinghai Province, and western Sichuan Province.

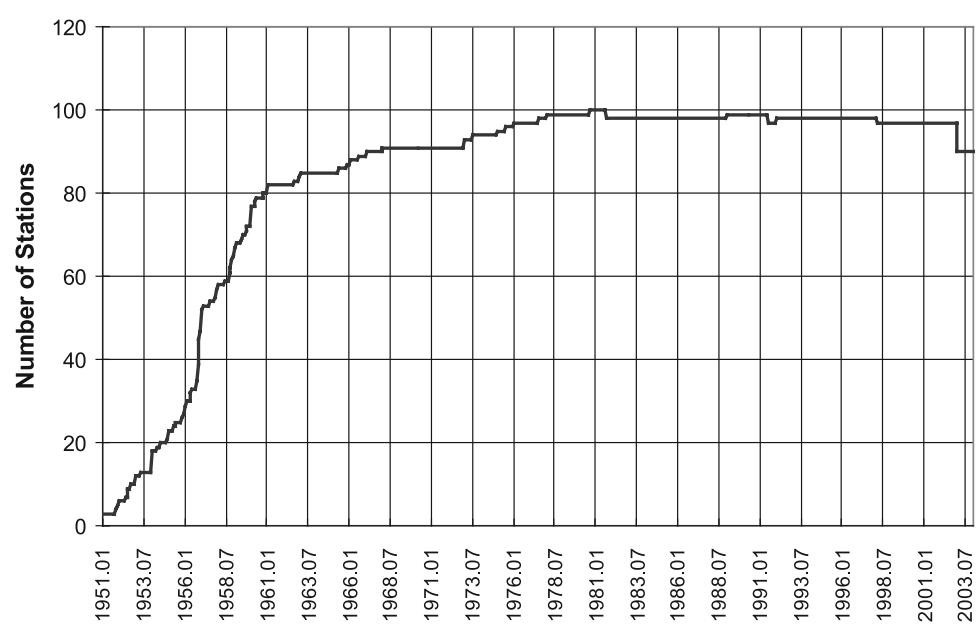
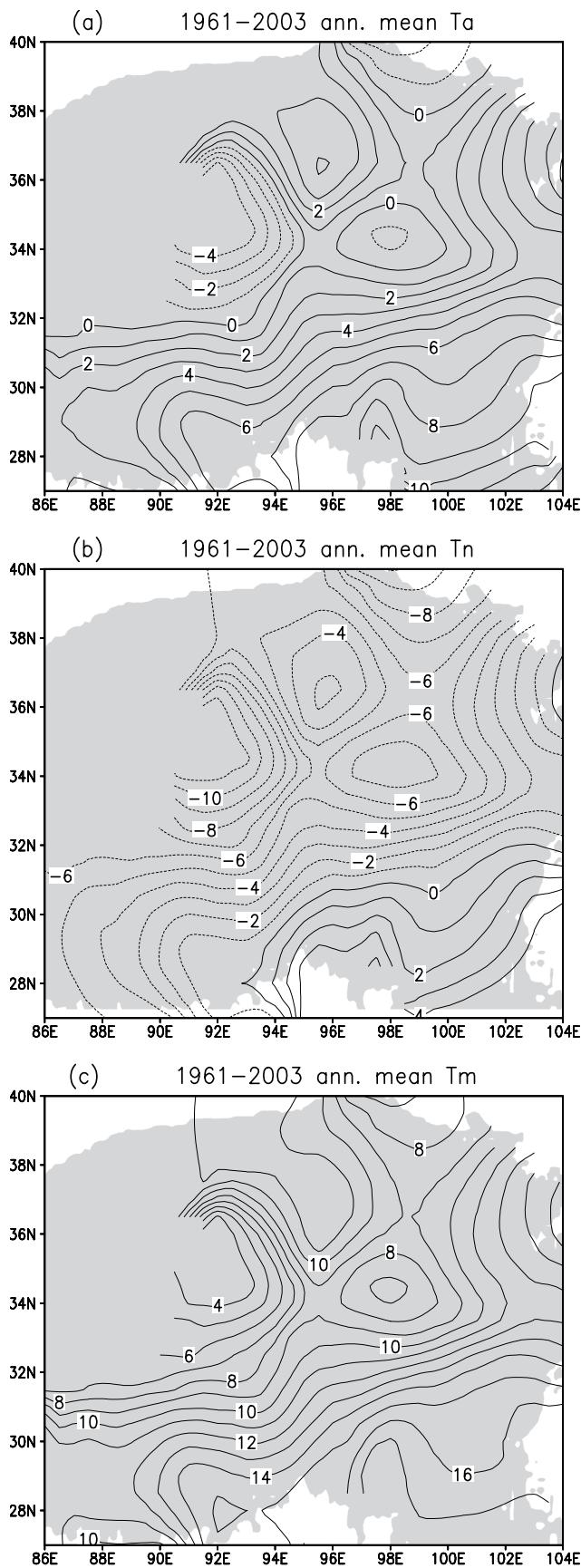


Figure 2. The number of weather stations over the study area with daily maximum and minimum temperature observations since 1951.



the past not only can establish a foundation for a better understanding to recent climatic changes, but may also provide a historical analog that can be used to estimate the range of possible responses of the climatic system to global warming.

[3] *Houghton et al. [2001]* showed schematically the effects of a constant and increasing variance on extreme temperatures as temperature rises for a normal distribution. Many scientists have noted that this warming has not been uniform throughout the day, with less warming observed in maximum temperatures and substantially more warming in minimum temperatures [*Karl et al., 1993; Easterling et al., 1997*]. For example, *Karl and Easterling [1999]* found that during 1951–1990 global daytime and daily mean temperature increased by 0.28°C, while the nighttime temperature (daily minimum) temperature increased three times as much by 0.84°C. In other words, the warming in daily minimum is stronger than that for maximum temperatures. As a result over vast land areas of the world, the near-surface diurnal temperature range (DTR) has been decreasing. Such asymmetric changes in daytime and nighttime temperatures have been confirmed in many other studies [e.g., *Türkes and Sümer, 2004; Weber et al., 1997; Qian and Lin, 2004*], but with various magnitudes and regional differences. Similar asymmetric patterns have also been found between cold-season and warm-season temperatures [*Weber et al., 1997; Zhai et al., 1999; Shrestha et al., 1999*].

[4] In recent years a growing number of studies dealt with observational analyses involving the variability and tendencies of extreme temperature events over various regions of the world, considering larger amplitudes of extremes at regional scales than extremes at the global scale and the importance of regional studies of climate change in evaluating climate impacts. For example, various analyses of daily minimum, maximum or extreme temperatures were conducted over North America [*Robeson, 2004*], Canada [*Bonsal et al., 2001*], Europe [*Klein Tank and Konnen, 2003*], Australia and New Zealand [*Plummer et al., 1999*], eastern Africa [*King'uyu et al., 2000*], India [*Roy and Balling, 2005*], and South Korea [*Ryoo et al., 2004*]. Like most of the world, China also experienced various degrees of warming [*Zhai et al., 1999; Zhai and Pan, 2003; Wang and Gaffen, 2001*], and there was an overall tendency of greater warming rates for minimum and winter temperatures as compared to maximum and summer temperatures [*Zhai et al., 1999; Liu et al., 2004*]. *Zhai et al. [1999]* also showed that the number of days with extreme low temperatures has been decreasing in northern China. Recent studies [*Yan et al., 2002; Zhai and Pan, 2003; Qian and Lin, 2004; Gong et al., 2004*] further documented China's temperature extremes and trends.

[5] *Beniston et al. [1997]* pointed out the significance and difficulties in studying climate change in high-elevation regions, while *Diaz et al. [2003]* recognized the complexity of studies on climate in mountainous regions. *Messerli and*

Figure 3. Long-term means of (a) mean annual daily mean (Ta), (b) minimum (Tn), and (c) maximum (Tm) temperatures over the eastern and central Tibetan Plateau (unit is °C) during 1961–2003. The shaded area indicates the areas above 2000 m a.m.s.l.

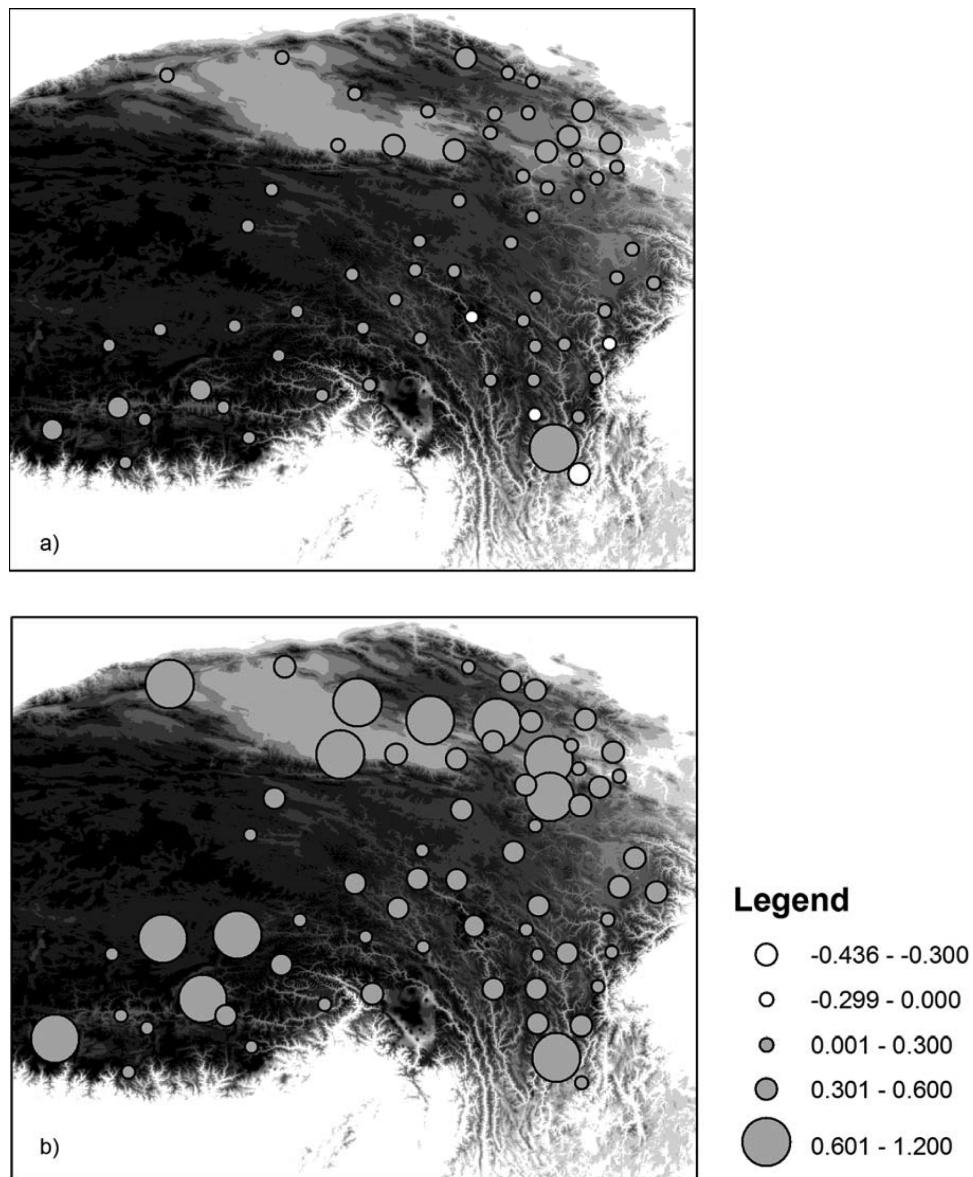


Figure 4. Trend slopes of the annual mean daily (a) maximum temperature and (b) minimum temperature in the eastern and central Tibetan Plateau during 1961–2003. Unit is $^{\circ}\text{C}/\text{decade}$.

Ives [1997] proposed that mountainous regions are more sensitive and vulnerable to climate changes than other regions at the same latitudes on Earth. Thus one can state that the detection of global climate changes should be most observable at their early stage by analyzing tendencies in climate variability and the occurrence of extreme events in mountainous regions. For example, the warming during the twentieth century in the European Alps was greater than the global mean warming trend [Beniston *et al.*, 1997]. Moreover, greater warming was found at high-elevation sites than at low-lying sites in the Alps by comparing the trends in maximum and minimum temperatures [Weber *et al.*, 1997; Jungo and Beniston, 2001]. Related to the changes in minimum and maximum temperatures, the changes in DTR in high-elevation regions were also found to have different magnitudes and patterns in various regions [Weber *et al.*, 1997; Diaz and Bradley, 1997].

[6] This study examines the trends and variation patterns in daily maximum (daytime) and minimum (nighttime) temperatures over the Tibetan Plateau (TP). The TP is a major geomorphic unit on the Eurasian continent (Figure 1), well known for its impacts on regional climate through its thermal and dynamic forcing mechanisms. Previous studies have examined various aspects of the temperature changes over the TP. For example, Liu and Chen [2000] examined monthly mean temperature trends at 97 stations located above 2000 m on the TP (including three stations in the former Soviet Union states) and reported an overall warming trend during 1955–1996, which was more pronounced in winter and at stations of higher elevations when compared with the temperature trends at stations in the surrounding region. However, Yadav *et al.* [2004] used tree rings to reconstruct premonsoon temperature records in the western Himalayas and found a decreasing trend during the

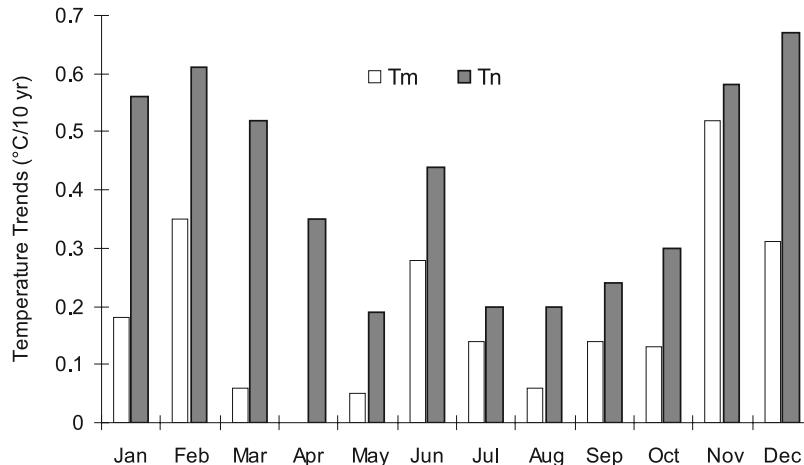


Figure 5. Trends in monthly mean daily Tm and Tn averaged for the study area during 1961–2003.

second half of the twentieth century. Such decreasing trends in premonsoon and warm season temperatures were also supported by tree ring records in Asian mountainous regions such as Tibet [Briffa *et al.*, 2001], Nepal [Cook *et al.*, 2003], and central Asia [Briffa *et al.*, 2001].

[7] Over the TP, there have been relatively few studies regarding daily and extreme temperature trends and their variability, mostly owing to the difficulties in data collection in vast remote areas. Du [2001] analyzed monthly temper-

ature variation patterns for 16 stations on the TP during the period 1961–2000 and found that most stations display warming trends, and that the warming trends in minimum temperature were greater than that in maximum temperature, similar to the results from Diaz and Bradley [1997] of a comparison between high-elevation sites and those near the sea level. The main aim of this current study is to present the results of analyses on trends and variability in daily minimum (Tn) and maximum (Tm) temperatures over

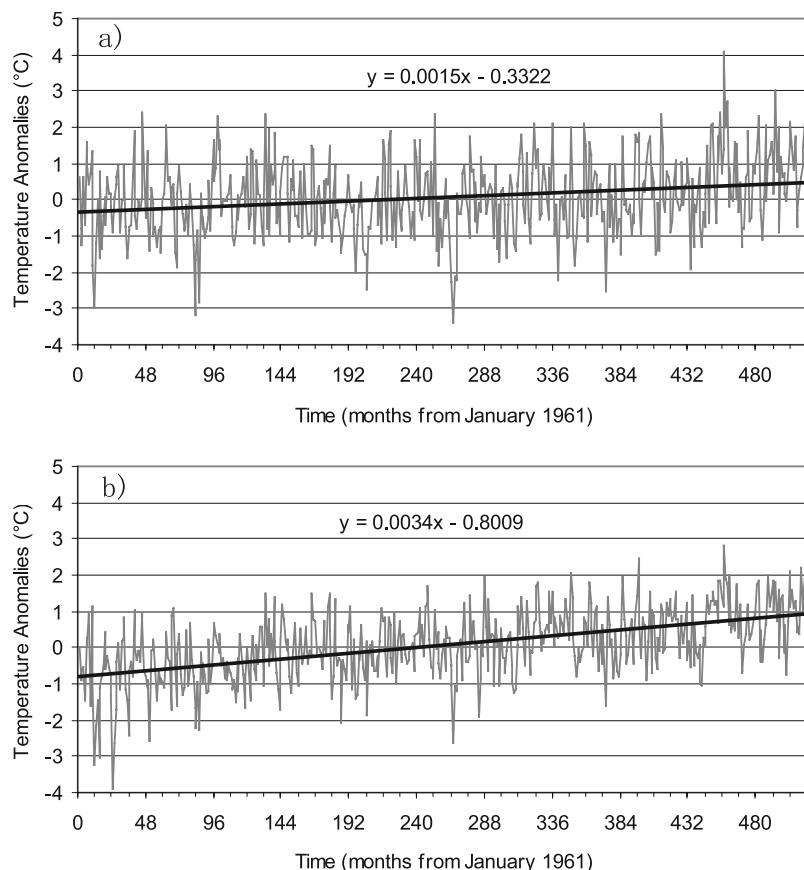


Figure 6. Monthly mean (a) Tm anomalies and (b) Tn anomalies, and their linear trends (thick lines) averaged for the study area from January 1961 to December 2003.

Table 1. Trend Slopes in Various Temperature Measures Obtained From a Survey of Studies in China and Mountainous Regions

| Regions | Time Period | Parameters | Trend Slopes, °C/10 a |
|-------------------------------------|-------------|--------------------|----------------------------|
| <i>Current Study</i> | | | |
| Eastern and central Tibetan Plateau | 1961–2003 | monthly Tm anomaly | 0.18 |
| Eastern and central Tibetan Plateau | 1961–2003 | monthly Tn anomaly | 0.41 |
| <i>Zhai et al. [1999]</i> | | | |
| China | 1951–1995 | spring mean Tm | 0.027 |
| China | 1951–1995 | summer mean Tm | -0.006 |
| China | 1951–1995 | fall mean Tm | 0 |
| China | 1951–1995 | winter mean Tm | 0.144 |
| China | 1951–1995 | annual mean Tm | 0.03 |
| China | 1951–1995 | spring mean Tn | 0.179 |
| China | 1951–1995 | summer mean Tn | 0.001 |
| China | 1951–1995 | fall mean Tn | 0.153 |
| China | 1951–1995 | winter mean Tn | 0.417 |
| China | 1951–1995 | annual mean Tn | 0.175 |
| <i>Wang and Gaffen [2001]</i> | | | |
| Northeast China | 1951–1994 | winter T | 0.35 |
| Northwest China | 1951–1994 | winter T | 0.31 |
| China | 1951–1994 | winter T | 0.23 |
| China | 1951–1994 | nighttime warming | 0.26 |
| <i>Liu et al. [2004]</i> | | | |
| China | 1955–2000 | winter Tm | 0.265 |
| China | 1955–2000 | spring Tm | 0.094 |
| China | 1955–2000 | summer Tm | 0.054 |
| China | 1955–2000 | fall Tm | 0.095 |
| China | 1955–2000 | winter Tn | 0.557 |
| China | 1955–2000 | spring Tn | 0.296 |
| China | 1955–2000 | summer Tn | 0.19 |
| China | 1955–2000 | fall Tn | 0.275 |
| <i>Yan et al. [2002]</i> | | | |
| Beijing | 1961–1997 | mean winter T | 0.59 |
| Shanghai | 1961–1997 | mean winter T | 0.44 |
| <i>Weber et al. [1997]</i> | | | |
| Central European Mountains | 1951–1990 | annual Tm | 0.12 |
| Central European Mountains | 1951–1990 | annual Tn | 0.14 |
| Central European Mountains | 1951–1990 | winter Tm | 0.37 |
| Central European Mountains | 1951–1990 | winter Tn | 0.36 |
| Central European Mountains | 1951–1990 | summer Tm | -0.03 |
| Central European Mountains | 1951–1990 | summer Tn | -0.02 |
| Central European Mountains | 1951–1990 | annual Tm | 0.11 |
| Central European Mountains | 1951–1990 | annual Tn | 0.18 |
| Central European Mountains | 1951–1990 | winter Tm | 0.30 |
| Central European Mountains | 1951–1990 | winter Tn | 0.31 |
| Central European Mountains | 1951–1990 | summer Tm | 0.08 |
| Central European Mountains | 1951–1990 | summer Tn | 0.11 |
| <i>Shrestha et al. [1999]</i> | | | |
| Nepal | 1977–1994 | annual mean Tm | 0.59 |
| Nepal | 1977–1994 | winter mean Tm | 0.61 |
| Nepal | 1977–1994 | June–Sept. mean Tm | 0.51 |
| Trans-Himalaya and Himalaya | 1977–1994 | annual mean Tm | 0.9–0.57 |
| Trans-Himalaya and Himalaya | 1977–1994 | winter mean Tm | 1.24–0.90 |
| Trans-Himalaya and Himalaya | 1977–1994 | June–Sept. mean Tm | 1.09–0.62 |
| Trans-Himalaya and Himalaya | 1977–1994 | Tn | lack of significant trends |
| <i>Diaz et al. [2003]</i> | | | |
| Himalaya | 1958–2000 | mean annual T | 0.06 |
| Mediterranean | 1958–2000 | mean annual T | 0.23 |
| Caucasus | 1958–2000 | mean annual T | 0.14 |
| East Africa | 1958–2000 | mean annual T | 0.18 |
| Cordillera | 1958–2000 | mean annual T | 0.09 |
| <i>Jungo and Beniston [2001]</i> | | | |
| Swiss Alps | 1961–1999 | low-altitude Tm | 0.5 |
| Swiss Alps | 1961–1999 | low-altitude Tn | 0.43 |
| Swiss Alps | 1961–1999 | high-altitude Tm | 0.6 |
| Swiss Alps | 1961–1999 | high-altitude Tn | 0.69 |

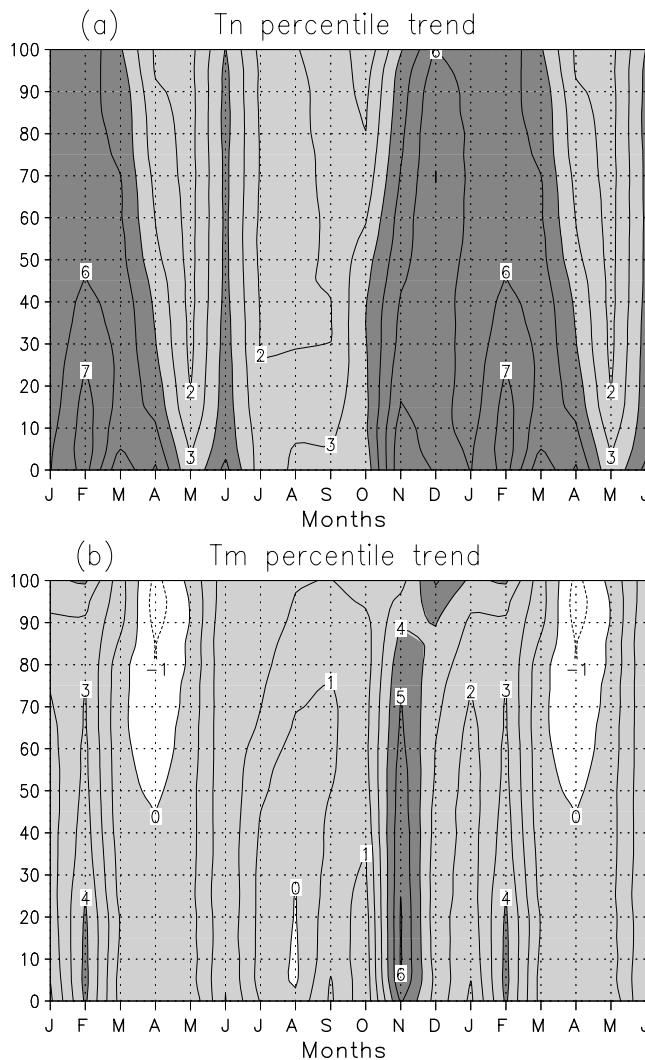


Figure 7. Spatially averaged trends ($^{\circ}\text{C}/\text{century}$) in the time-varying percentiles of (a) Tn and (b) Tm over eastern and central Tibetan Plateau from 1961 to 2003. Please note that the section after December is a repeat of the months from January to June for the ease of graphing and interpretation.

the eastern and central TP, including both annual and seasonal means and extreme events. In the mean time, we would like to compare the trends and variability in various temperature measures over the study region with the results from other regions. Another objective is to determine how much of the temperature increases, if any, is caused by changes in the nighttime temperature (daily minimum) and how much by the daytime temperature (daily maximum). Finally, we would like to investigate the consequences of temperature increases, including changes in growing season length, annual number of frost-free days, and the potential impact on agriculture and ecosystems in the region.

2. Data and Methods

[8] Daily minimum and maximum temperature data for weather stations in the eastern and central TP were collected from the provincial meteorological bureaus of Qinghai

and Sichuan Provinces and Xizang (Tibet) Autonomous Region. In the study area, there were 102 weather stations in the original data set and 82 stations maintained daily maximum and minimum observations since January of 1961 (Figure 2). Of the 82 stations, 16 stations were excluded owing to problems in data (six stations stopped operation during the 1980s–1990s; seven stations showed significant inconsistencies in data due to probable station relocation or change of equipment; and three stations lacked the data for 2003). The remaining 66 stations are located at elevations of 2000 m or higher above the mean sea level (a.m.s.l.), except for two stations close to 2000 m, with data from 1961 to 2003 (Figure 1). In the study area, the mean annual temperature ranged from -4°C to 10°C , while the annual mean minimum temperature varied from -10°C to 4°C , and the annual mean maximum temperature from 4°C to 17°C (based on the period 1961–2003) (Figure 3).

[9] The data were subject to a vigorous quality assessment/quality control procedure to eliminate any spurious values and fill in missing values by interpolation. Great efforts were made to ensure that extreme values within the data set are true events, rather than errors. For the 66 stations used in this study, we first performed routine quality assessment procedures to evaluate the records of daily mean, maximum, and minimum temperatures. For any data values higher or lower than 2.0 standard deviations from the mean, we examined each case individually against the data from the neighboring stations and corrected the value (if deemed problematic) using multiple linear regression analysis based on values from the surrounding stations. We also used regression analysis to fill relatively few missing values in the 66 records. We examined the station histories and evaluated any potential discontinuities caused by station relocation. For two stations, we made adjustments to the pre-move records based on the means and variances of the data recorded after the station relocation to remove discontinuities in data. In this way, we obtained complete and reliable daily records of maximum and minimum temperatures for the 66 stations used in this study.

[10] For each station, we examined the temporal trend slopes of various measures of the temperature regime using regression analysis with time (year or month) as the independent variable, while the statistical significance was determined using the nonparametric Spearman's correlation [Mitchell et al., 1966]. We investigated the spatial pattern of the temperature trends within the study area. Additionally, we calculated the number of record-setting stations for each month using the 43-year study period. To objectively define and process the temperature data for growing season length, we first defined growing season as the period of a year in which the daily minimum temperature is consistently above 0°C , similar to the conventional definition of growing season from the last spring freeze to the first fall freeze. In calculation, however, we used a fifth-order polynomial equation to fit the annual cycle of the minimum temperature for each station year to avoid any subjectivity in defining the beginning or the end of the growing season, especially when the temperature fluctuated around the freezing point. Then we used the equation-predicted Julian dates to determine the growing season length and examined its temporal trends and spatial variations.

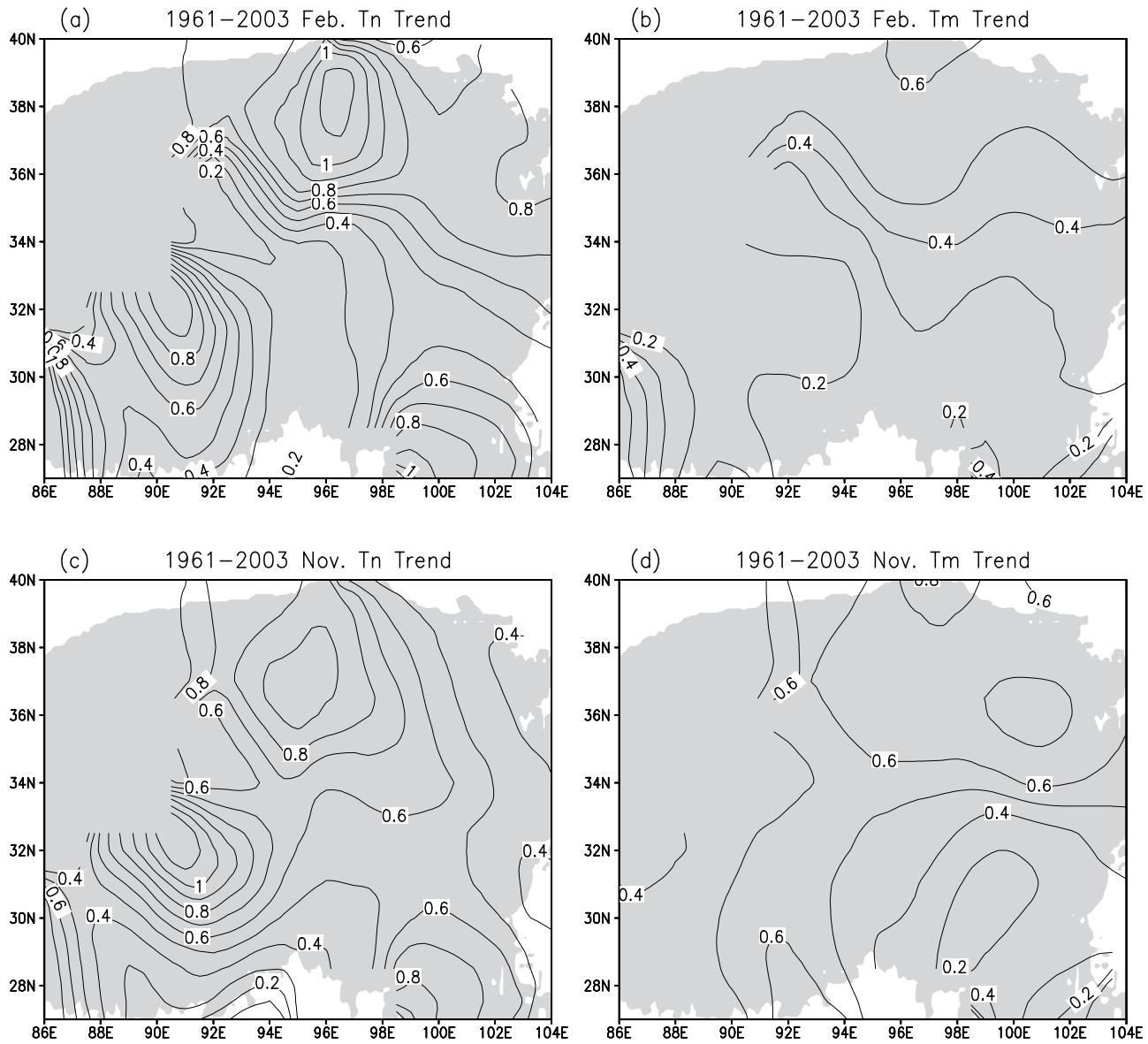


Figure 8. (a–d) Spatial patterns of the trends in February and November daily minimum and maximum temperatures ($^{\circ}\text{C}/10 \text{ yr}$).

[11] For each station year, we summed the number of frost days ($\text{Tn} \leq 0^{\circ}\text{C}$) and warm days ($\text{Tm} > 15^{\circ}\text{C}$) and examined the temporal trends over the study period. Although such measurements have significant meanings in agriculture and ecosystem conditions, they may not be suitable for interstation comparisons owing to the differences in elevation and geographic locations among the stations. Therefore, for interstation comparisons of the variability in the extreme (relatively rare) cold and warm events, we calculated the time-varying percentiles of the daily Tn (for cold events) and daily Tm (for warm events), respectively [Robeson, 2004]. For each month, the daily Tn and Tm of a given station were ranked, then the temperature values at various percentile breaks were selected. For a hypothetical example, in January of 1990 the ninetieth percentile of daily Tm (or the tenth percentile of daily Tn) of station A as 5°C (or -10°C) would mean that 10% of the 31 observations of that month were higher (or lower)

than this specific value. We then examined the temporal trends in the temperature percentiles for each month of the year after averaging the monthly percentiles for the entire study region. For example, temperatures of relatively rare warm extreme events can be defined as the temperature of those days that exceed the ninetieth percentile of Tm , while temperatures of the cold extreme events can be defined as the temperature of those days that are below the tenth percentile of Tn [Robeson, 2004].

[12] Standard deviation is a measure of the departure from the mean condition and therefore a measure of temporal variability. In our study, the annual cycle was first eliminated and then the standard deviations of the daily maximum and minimum temperature anomalies for each year were used as a measure of intraannual variability. We also examined spatial variability of daytime and nighttime temperatures in different years in the study region and correlated that with the mean regional Tm and Tn to

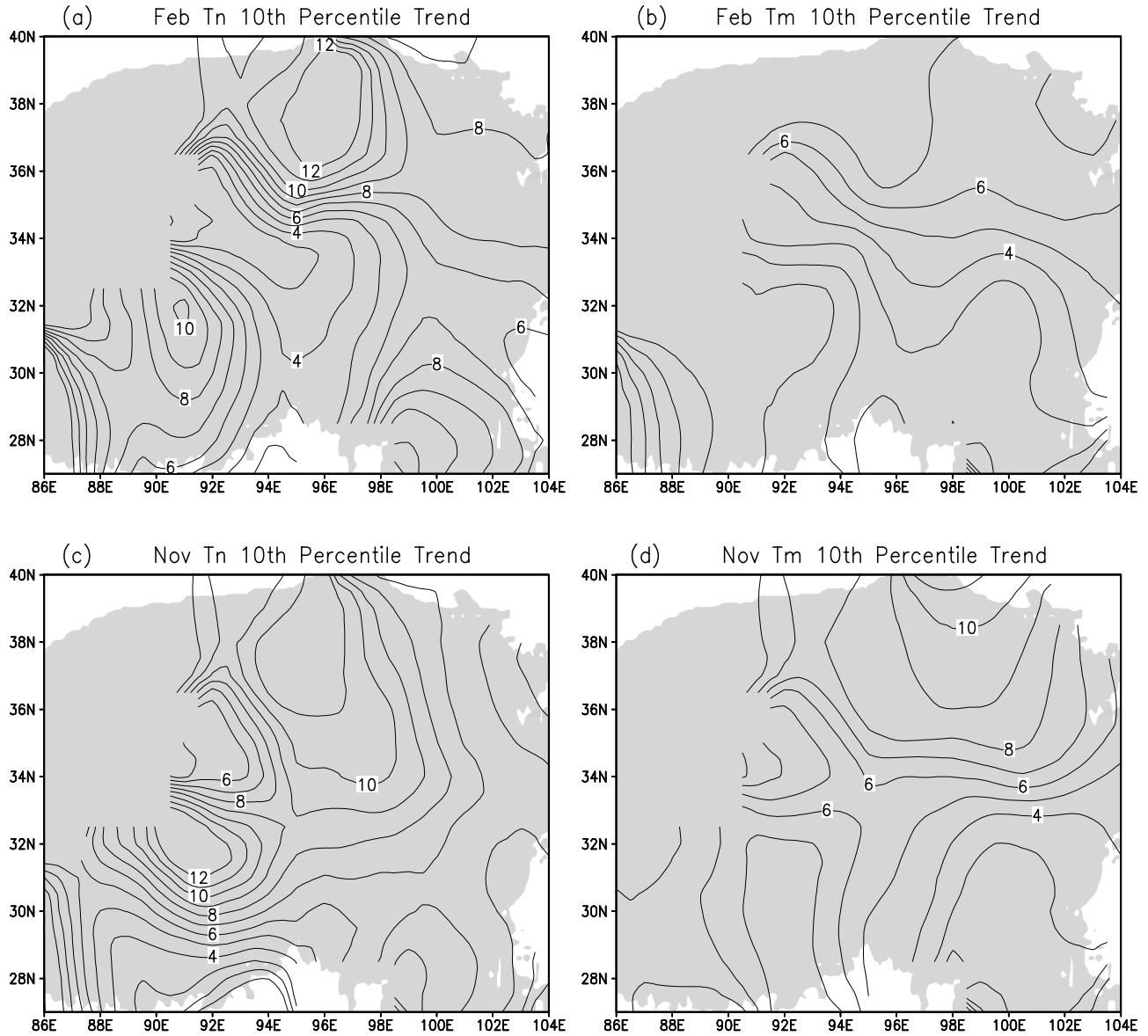


Figure 9. (a–d) Spatial patterns of the trends in the tenth percentiles (cold events) of February and November minimum and maximum temperatures ($^{\circ}\text{C}/\text{century}$).

determine whether warm years or cold years tended to have high variabilities. Finally, in order to evaluate the possible impact of temperature changes on agriculture and ecosystems, we performed a preliminary investigation on the relationships between temperature regimes, crop yield, and tree ring widths at sites along the eastern margin of the TP.

3. Results and Discussion

3.1. Trends in Daytime and Nighttime Temperatures

[13] Figure 4 shows the spatial distribution pattern of the temporal trends in annual mean daily Tn and Tm for the 66 weather stations. Apparently, there were more stations with greater increases in Tn than in Tm. This conforms to the results of previous studies that the warming of nighttime temperature is more prominent than that of the daytime temperature. Another point revealed by Figure 4 is that the increasing trends of Tn in the northern, southeastern, and

southwestern parts of the study area seemed to be more consistent than those in other areas. However, there were no discernable patterns to show the relationship between the trends in maximum and minimum temperatures and altitude in the study area, the interior of the TP with elevations up to 4700 m. This is not contradicting to the result of an earlier study [Liu and Chen, 2000] in which the trends in monthly mean surface air temperature were found to be positively correlated with altitude when stations in the interior of the TP were compared with stations in the surrounding low-altitude regions. Additionally, high sensitivity of daily maximum and minimum temperatures to local topographic and vegetation conditions may have obscured the impact of elevation. When monthly trends were averaged for the entire study region, it is clear that the warming trends of the monthly mean daily Tn were consistently greater than that of the daily Tm, especially in the winter and spring months (Figure 5). In the mean time,

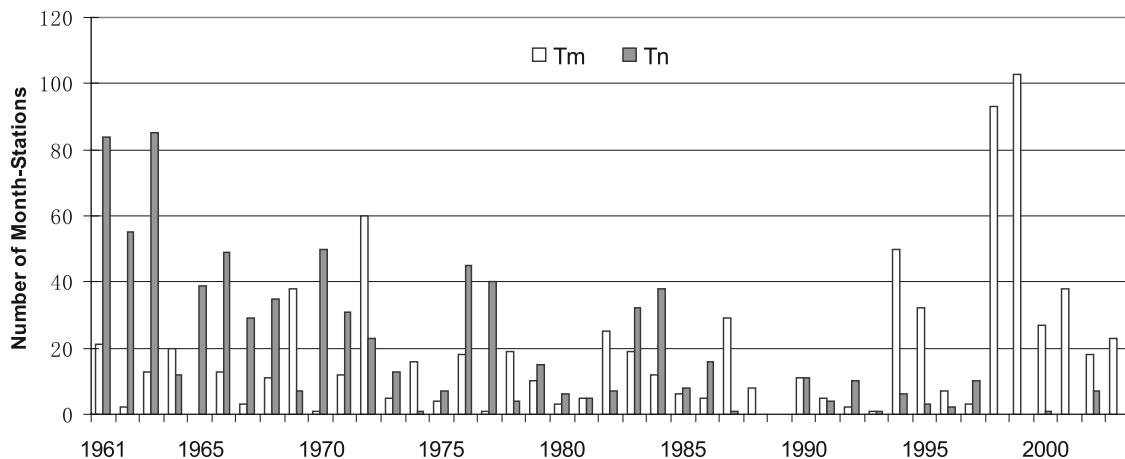


Figure 10. Annual month-station numbers of the record-setting Tm and Tn over the central and eastern Tibetan Plateau from 1961 to 2003.

the increasing trends in warm months were lower than those in cold months. We then calculated the anomalies of Tn and Tm from long-term monthly means to remove the seasonality. The trends of temperature anomalies are displayed in Figure 6. The trend slope of Tn (nighttime temperature) anomalies is more than twice that of the daytime temperature anomalies, equivalent to a rate of increase of $0.41^{\circ}\text{C}/10\text{ yr}$ as compared to a rate of $0.18^{\circ}\text{C}/10\text{ yr}$ in the daytime temperature anomalies, both statistically significant at the 0.001 level.

[14] To put these rates in context, we listed trend slopes from various studies in different regions of the world in Table 1. One issue of cross-comparisons among different studies is the influence of the beginning and ending years on trend slopes. The trend slopes and statistical significance may be strongly influenced by adding a single extreme year at the beginning or end of the time series [Rebetez, 2004]. Therefore caution is necessary when using the information in Table 1 to compare results from different studies. Although our survey is far from complete, it provides sufficient background for comparison. It can be seen that the magnitude of the temporal trend in monthly anomalies of the nighttime temperatures from our study was not as large as some of those listed in Table 1 for winter temperatures, but still larger than most of the other seasons. According to Figure 5, where trends are displayed for each individual month, the trends of nighttime temperatures in winter months would be among the highest values as those listed in Table 1, with the warming trends from November to March reaching higher than $0.5^{\circ}\text{C}/10\text{ yr}$ during the study period.

3.2. Trends in Temperatures of Cold and Warm Events

[15] To examine the trends in frequencies of warm and cold events, we calculated spatially averaged time-varying percentiles and plotted the percentile values against the months to display the annual cycle (Figure 7). On these diagrams, one can specify the characteristics of trends for cold (low percentile) or warm (high percentile) events. For the monthly means of daily Tn, high warming rates ($>4^{\circ}\text{C}/\text{century}$) were found for all percentiles from late fall (October) to early summer months, except for a gap in May; while the highest rates ($>6^{\circ}\text{C}/\text{century}$) are found

mostly for the relatively rare cold events (low percentiles). In other words, for these months, the temperatures of relatively cold nights and relatively warm nights all had experienced significant increases. For the monthly means of daily Tm, however, trends of such magnitude were only found in February for cold events (low percentiles) and then in November for all percentiles. Low warming rates were found for temperatures of relatively warm/hot days in most months, and in spring there were slightly cooling trends for middle to high percentiles.

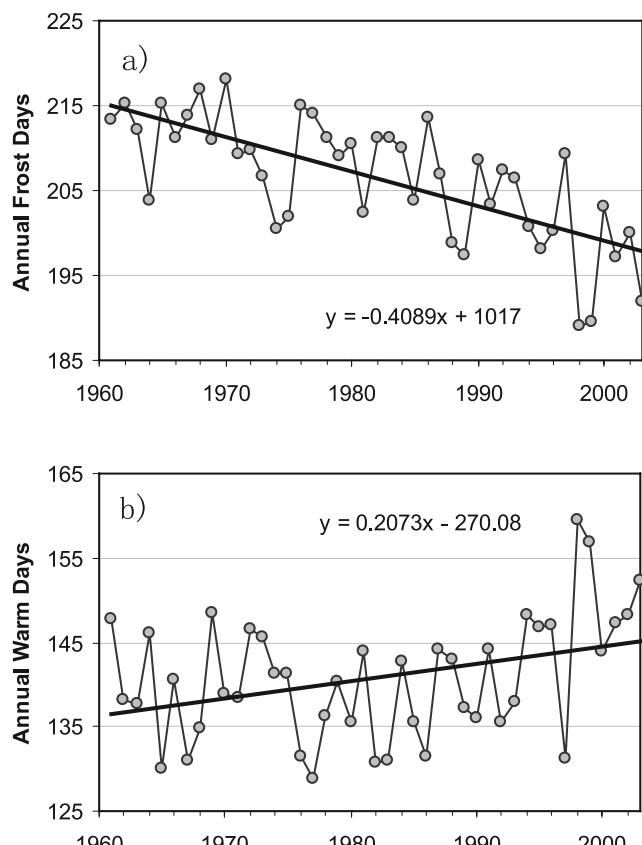


Figure 11. Trends in annual total (a) frost days and (b) warm days, averaged for the entire study regions.

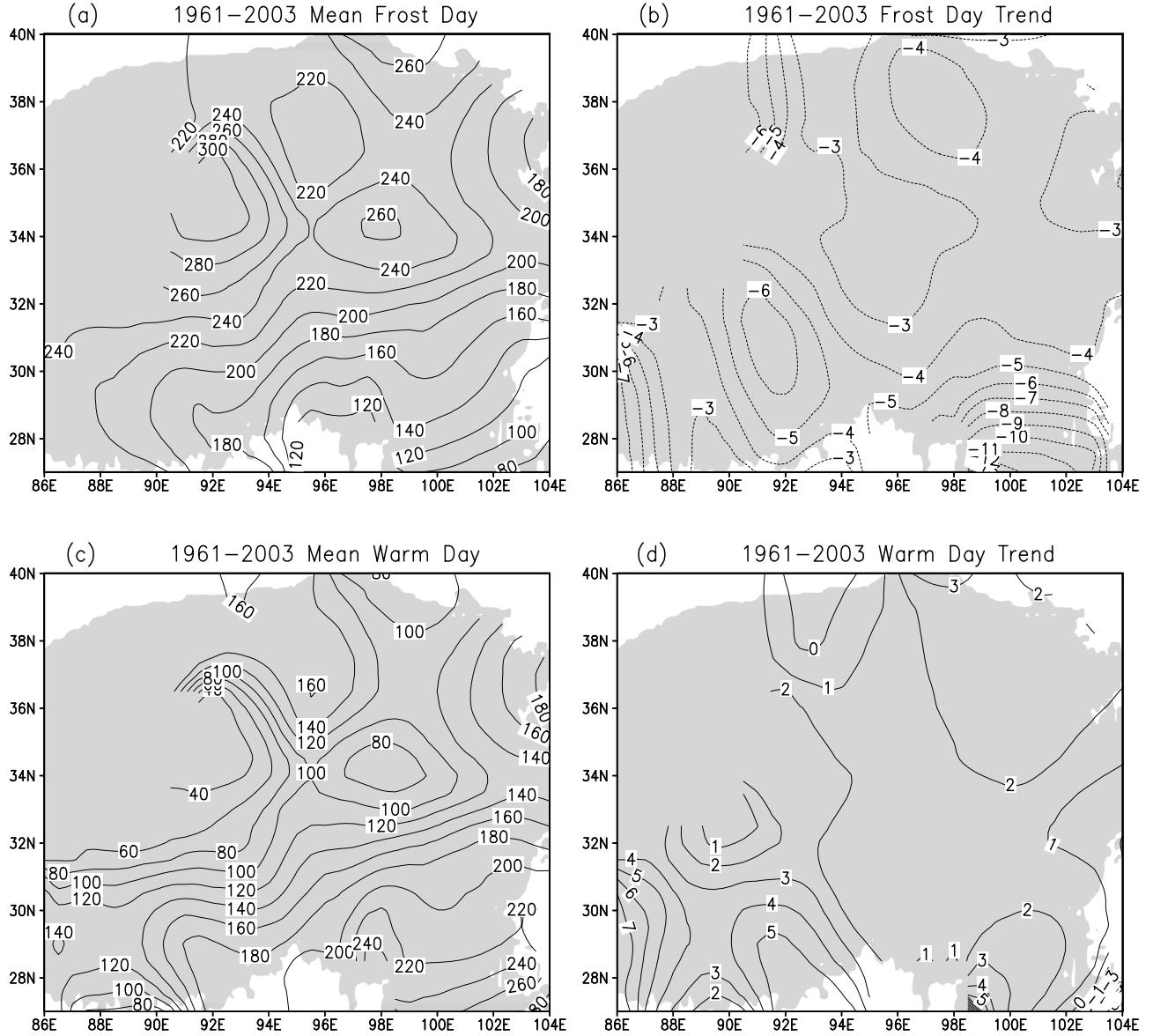


Figure 12. (a) Spatial pattern of the annual number of frost days. (b) The frost day trend. (c) Spatial pattern of the annual number of warm days. (d) The warm day trend.

[16] Since February and November were the months in which relatively significant trends were found in both T_n and T_m , we mapped the trend slopes of February and November T_n and T_m (Figure 8) and the trend slopes of the tenth percentiles (Figure 9) for those two months. The tenth percentiles of T_n can be regarded as the temperature of the relatively cold nights, while the tenth percentiles of T_m represent the temperature of relatively cold days during those months. Although the increasing trends prevailed over the entire study area, we can identify three centers of higher trend slopes for T_n , one in the north, one in the southeast, and one in the southwest of the study area. Again, the trend slopes in the T_n had greater magnitudes than that of T_m . When compared to the monthly mean T_n and T_m trends in Figure 5, it can be seen that the trends in the temperatures of the tenth percentiles were in general greater than the trends in mean monthly values for T_n , but approximately at the same magnitudes for T_m .

[17] For any month during a year, we can determine the historical extreme T_n and T_m values for a station and see when these extreme events occurred. In order to investigate the impact of the changing temperature regimes on the occurrence of extreme events, we summed up the number of stations that had record-setting months for all the months during a given year for both T_m (hot/warm extreme events) and T_n (cold/cool extreme events). There was a clear trend during the study period, with more cold extreme events occurring in the 1960s and 1970s, but more hot extreme events occurring in the late 1990s and more recent years (Figure 10).

3.3. Annual Frost Days, Warm Days, and Growing Season Length

[18] The asymmetric pattern of T_m and T_n changes undoubtedly influences temperature parameters important for the ecosystems and agricultural practice in the study region.

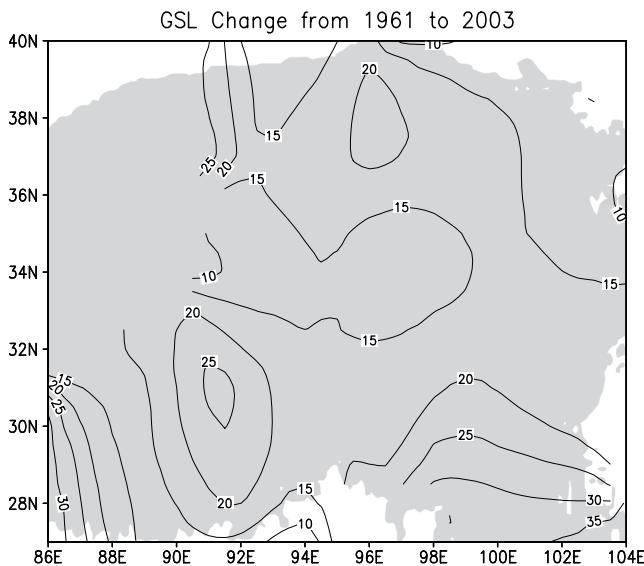


Figure 13. Spatial pattern of the changes in growing season length (days).

The number of frost days in any given year and the growing season length are important agricultural climatic indices, which may significantly alter the phenology of plants and crops [Sparks and Menzel, 2002]. Figure 11 shows the trends of annual numbers of frost and warm days averaged for the study region. The number of frost days decreased at a rate of 4.1 days/10 yr with a statistical significance of 0.001, while the number of warm days increased at a rate of 2.1 days/10 yr significant at the 0.05 level. Figure 12 shows the spatial pattern of the mean numbers of frost and warm days and their trend slopes. Generally speaking, for areas with more frost days, there will be fewer warm days in terms of long-term averages (Figures 12a and 12c). The annual number of frost days had stronger decreasing trends in the north, southwest, and southeast (Figure 12b), while the number of warm days had increasing trends with high values to the south (Figure 12d). Figure 13 displays the

spatial pattern of the changes in the growing season length, which is a very useful measure of temperature regimes for the farmers. Again there were three centers of high increasing trends, one to the north, one to the southwest, and one to the southeast of the study area, similar to the pattern of daily T_n . According to the trend slope for the entire study region, the length of growing season increased by 17 days during the 43-year study period (Figure 14). This change in the length of growing season is highly significant as compared to the increase in the frost-free season length in the U.S. by approximately 2 weeks during the entire twentieth century [Kunkel et al., 2004].

3.4. Changes in Temperature Variability

[19] One measure of temperature variability is the diurnal temperature range (DTR). Our analyses suggest that in the study region, daytime and nighttime temperatures both had increasing trends, but the rates of warming were different, with a greater nighttime warming. This pattern should bring changes to the DTR in the study region. Figure 15 shows the differences between mean monthly anomalies of T_m and T_n averaged for the entire study region, which can be considered as a measure of DTR. As expected, there was a declining trend during the study period with a rate equivalent to $-0.228^{\circ}\text{C}/10\text{ yr}$, significant at the 0.001 level. This rate of decrease conformed to many previous studies in China (Table 2), but was much higher compared to those in the central European mountains [Weber et al., 1997]. Figure 16 shows the spatial patterns of the trend slopes of monthly differences between mean T_m and T_n anomalies for January, April, July, and October, each as the representative month for a season. The pattern with three centers (north, southwest, and southeast) was visible in all seasons, but it was most obvious in winter and spring. This further confirmed the significance of cold season temperature variations in the overall changes of the temperature regime in the study area. While all these months had significant portions of the study regions with decreasing trends, the map for January obviously shows the greatest area and most negative trends. In contrast, the one for July shows the smallest area with negative trends.

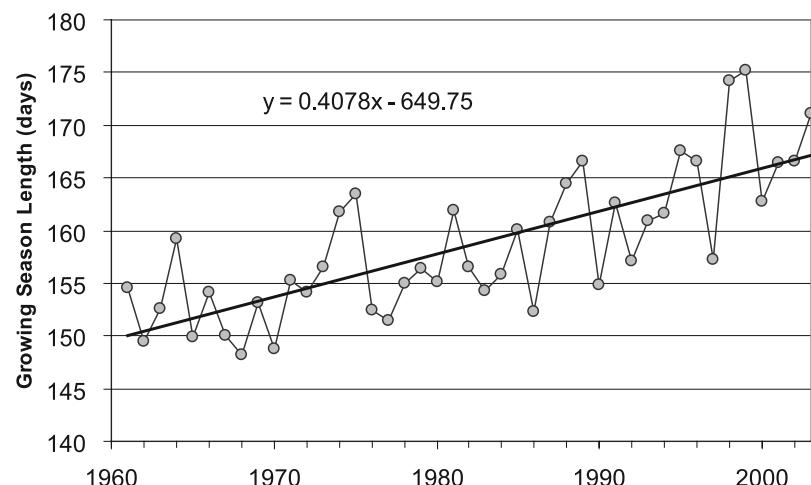


Figure 14. The trend in growing season length averaged for the entire study region for the period 1961–2003.

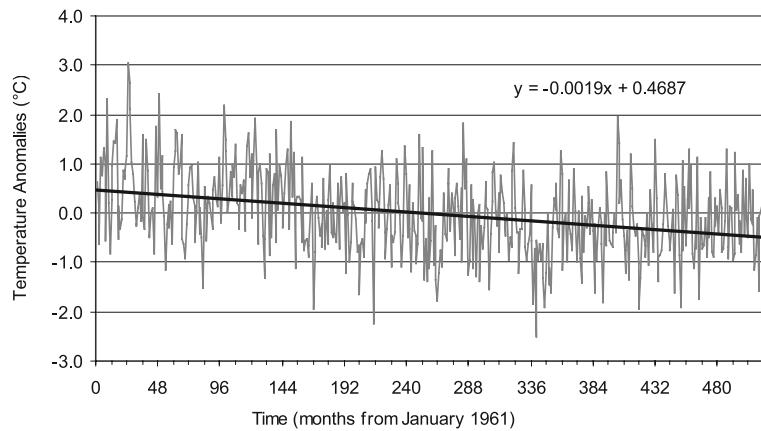


Figure 15. The difference between monthly mean T_m and T_n anomalies averaged for the study region.

[20] Another measure of temperature variability is the annual range of the nighttime temperatures (July–January) and that of the daytime temperatures. The difference between July and January mean T_n again showed declining trends across the study area with the three-center pattern (Figure 17). For the difference between July and January T_m , there were mostly weak increasing trends in the northern part of the study area and decreasing trends in the south, with much reduced magnitudes as compared to the annual range of T_n .

[21] We calculated annual values of the standard deviation of daily T_m and T_n as a measure of intraannual day-to-day variability (Figure 18). For the entire study region

as a whole, there was apparently an increasing trend for the standard deviation of T_m and a decreasing trend for that of T_n . However, the trend in the standard deviation of T_m was not statistically significant according to the Spearman's nonparametric correlation ($\alpha = 0.240$), while that of T_n was ($\alpha = 0.014$). In other words, temporal variability in the nighttime temperature decreased significantly during the study period. Correlation analysis indicated that the standard deviation of daytime temperature was positively correlated with regional mean T_m ($r = 0.224$), but not statistically significant ($\alpha = 0.149$), while the standard deviation of nighttime temperature was negatively correlated to regional mean T_n with statistical significance ($r =$

Table 2. Trends of Mean Monthly T_m - T_n and DTR From Other Studies

| Regions | Time Period | Parameters | Trend Slopes, $^{\circ}\text{C}/10\text{a}$ |
|-------------------------------------|-------------|--|---|
| Eastern and central Tibetan Plateau | 1961–2003 | <i>Current Study</i> monthly mean T_m – T_n anomalies | –0.228 |
| NE China | 1951–2000 | <i>Qian and Lin [2004]</i> winter DTR | –0.37 |
| NE China | 1951–2000 | spring DTR | –0.33 |
| NE China | 1951–2000 | summer DTR | –0.25 |
| NE China | 1951–2000 | fall DTR | –0.35 |
| NE China | 1951–2000 | annual DTR | –0.33 |
| South China | 1951–2000 | winter DTR | –0.24 |
| South China | 1951–2000 | spring DTR | –0.19 |
| South China | 1951–2000 | summer DTR | –0.18 |
| South China | 1951–2000 | fall DTR | –0.06 |
| South China | 1951–2000 | annual DTR | –0.17 |
| Xinjiang | 1951–2000 | winter DTR | –0.32 |
| Xinjiang | 1951–2000 | spring DTR | –0.31 |
| Xinjiang | 1951–2000 | summer DTR | –0.24 |
| Xinjiang | 1951–2000 | fall DTR | –0.16 |
| Xinjiang | 1951–2000 | annual DTR | –0.26 |
| China | 1955–2000 | <i>Liu et al. [2004]</i> winter DTR | –0.29 |
| China | 1955–2000 | spring DTR | –0.2 |
| China | 1955–2000 | summer DTR | –0.13 |
| China | 1955–2000 | fall DTR | –0.179 |
| Central European Mountains | 1951–1990 | <i>Weber et al. [1997]</i> annual DTR – high stations | –0.01 |
| Central European Mountains | 1951–1990 | winter DTR – high stations | 0.01 |
| Central European Mountains | 1951–1990 | summer DTR – high stations | –0.01 |
| Central European Mountains | 1951–1990 | annual DTR – low stations | –0.07 |
| Central European Mountains | 1951–1990 | winter DTR – low stations | –0.01 |
| Central European Mountains | 1951–1990 | summer DTR – low stations | –0.03 |

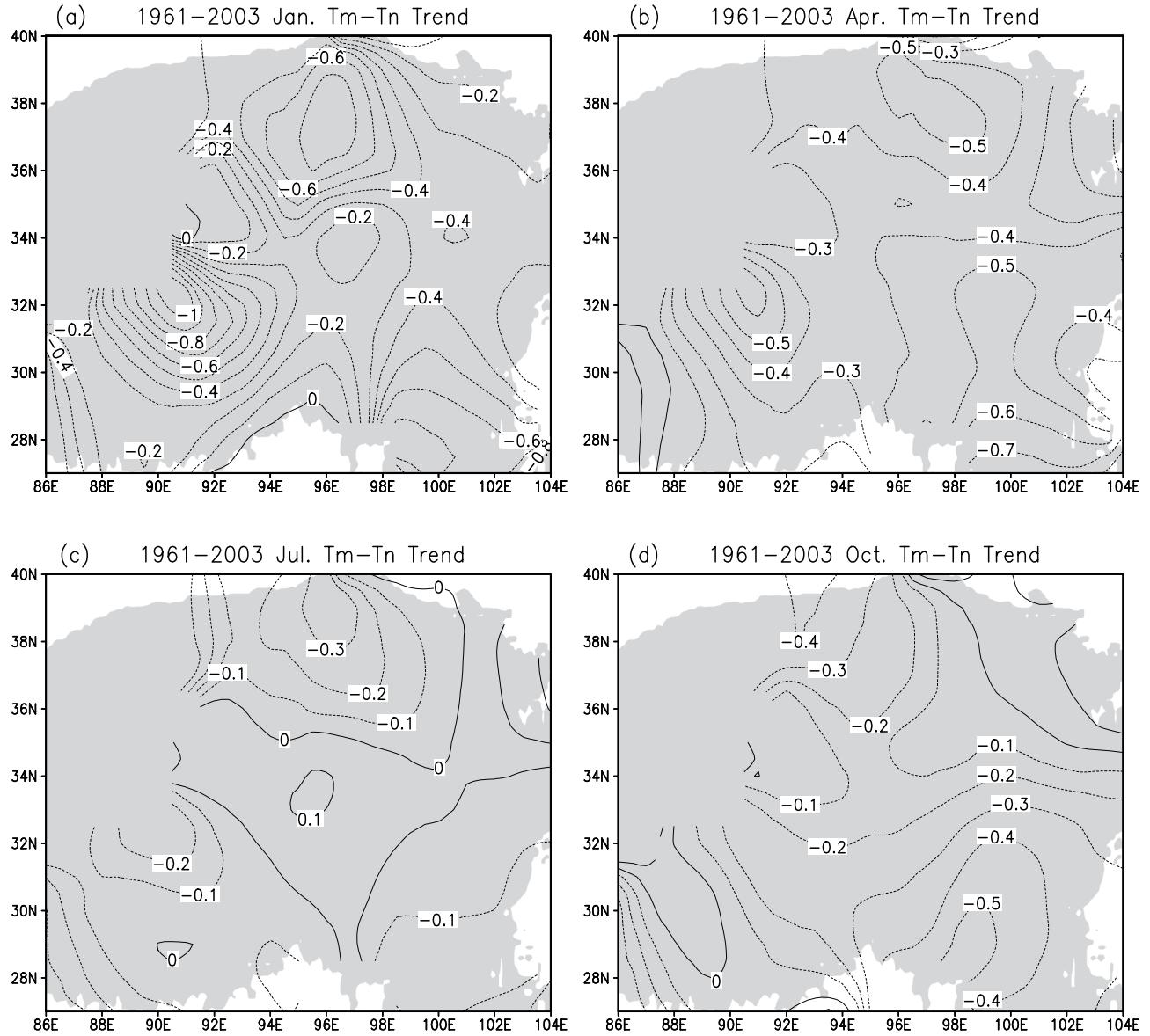


Figure 16. Spatial pattern of the trends in the difference between Tm and Tn anomalies (equivalent to DTR) in (a) January, (b) April, (c) July, and (d) October.

-0.381 , $\alpha = 0.012$). For years with low nighttime temperatures, the variability in nighttime temperature tended to be high.

[22] To examine the spatial variability of mean daily Tn and Tm in relation to climate change, we calculated the standard deviation of annual mean Tm and Tn for each year of the 66 weather stations. We then examined the correlations between the temperature standard deviation and the spatially averaged mean daily Tn and Tm values, as well as the trends in spatial variability. We found that the spatial variability was inversely related to the temperatures as indicated by statistically significant negative correlation coefficients. In other words, there was a greater spatial variability when the region was colder and vice versa. In addition, the correlation between the standard deviation and mean Tm ($r = -0.569$, $\alpha = 0.001$) was stronger than that between the standard deviation and mean Tn ($r = -0.492$, $\alpha = 0.001$). Compared to the correlations between temporal

variability and temperatures, the correlations between spatial variability and temperatures were much stronger. With warming temperatures, the spatial variability of Tm and Tn decreased during the study period (Figure 19), both with statistical significance, $\alpha = 0.037$ and $\alpha = 0.023$ for Tm and Tn, respectively.

[23] We used regression analysis to quantify the effect of daytime and nighttime temperature trends on trends of other related climate variables based on the standardized regression coefficients of the independent variables. In other words, when using the trends in Tm and Tn to predict the trend of another climate variable using the regression model, the standardized regression coefficients can be considered as the weights to represent the importance of the trends of Tm and Tn, respectively. The statistical significance of the independent variables was determined by the *Student's t* test on regression coefficients. In the analysis, the trend of a given climate

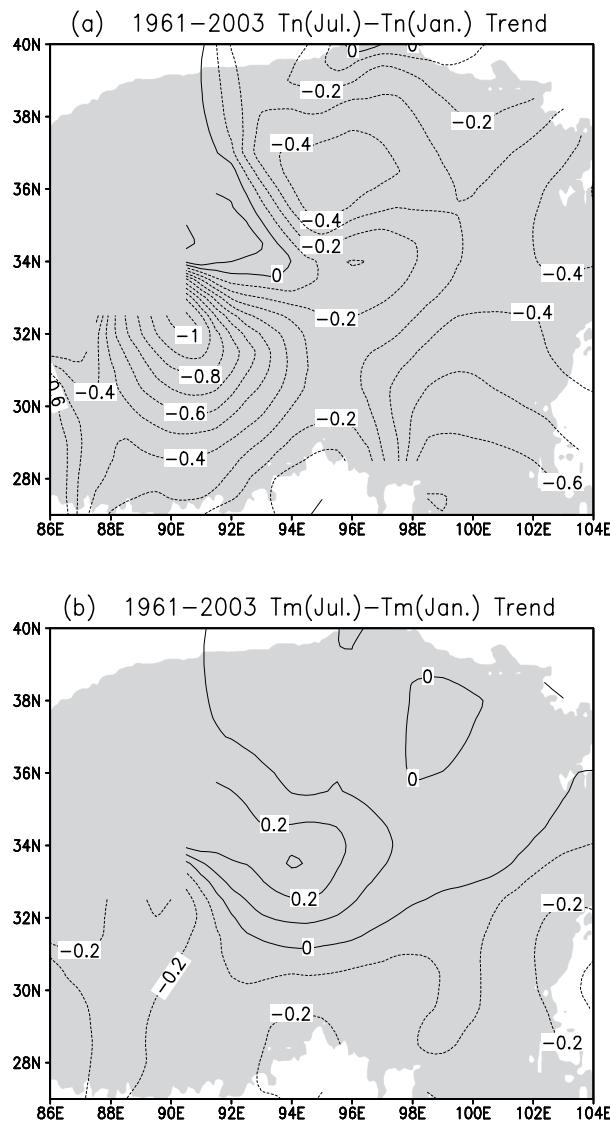


Figure 17. Trends in the annual range (July–January) of (a) nighttime temperatures and (b) daytime temperatures during 1961–2003 ($^{\circ}\text{C}/10 \text{ yrs}$).

element, such as annual mean daily temperature, was the dependent variables, while the trends in Tm and Tn were the independent variables. Table 3 summarizes the results of regression analysis. All models are statistically significant except for the one of the trend of annual range of Tm, although not all independent variables (trends in Tm and Tn) were statistically significant. For the trend in annual mean daily temperature, the trend in Tn contributed more than the trend in Tm. For the numbers of warm days and frost days, the trends in Tm and Tn took turns as the main contributor as expected. For the change of growing season length, however, the trend in Tn was the main contributor, while the trend in Tm had a negative impact as a minor contributor. Finally, for the annual range in mean temperature, daytime and nighttime temperatures, the trend in Tn remained as the main contributor with a negative impact, while the trend in Tm was a minor contributor with a positive impact.

3.5. Impact of Temperature Changes on Crop and Vegetation Growth

[24] In order to evaluate the potential impact of temperature changes on vegetation growth, we examined grain yield and spring wheat yield in Qinghai Province. The farms in the region are largely under irrigation and the crop yield demonstrated clearly upward trends during the study period (Figure 20). We used correlation and regression analyses to examine the impact of annual rainfall and temperatures. It is not surprising that annual precipitation is not significantly correlated with crop yield in Qinghai Province ($r = 0.04$) because of the effect of irrigation, while both temperature measures were positively correlated with crop yield with statistical significance, and the average Tn had the strongest correlations ($r = 0.82$ for total grain and $r = 0.77$ for spring wheat, respectively). Therefore we used Tn and Tm as the independent variables in regression analysis to predict crop yield. We found that the combination of the annual mean daily maximum and minimum temperatures explained over 70% of the total variance in total grain yield and spring wheat yield in the province (Table 4). The annual mean Tn entered the model with a positive impact, but the annual mean Tm entered with a negatively impact. Since this is an

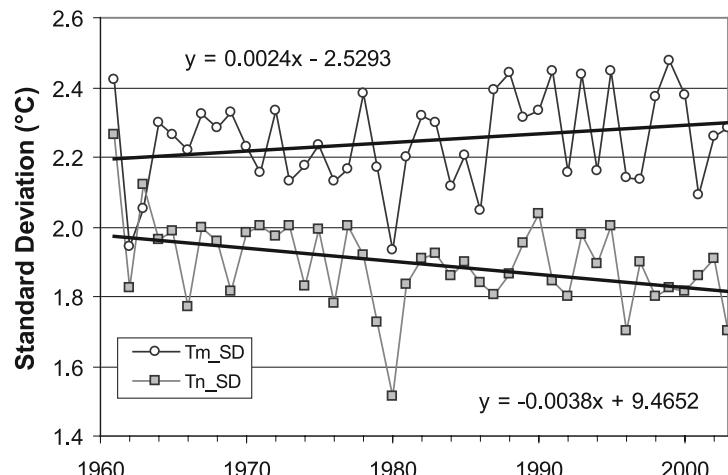


Figure 18. Interannual fluctuations in the standard deviations of daytime and nighttime temperature anomalies (after removing the annual cycle) averaged for the eastern and central Tibetan Plateau.

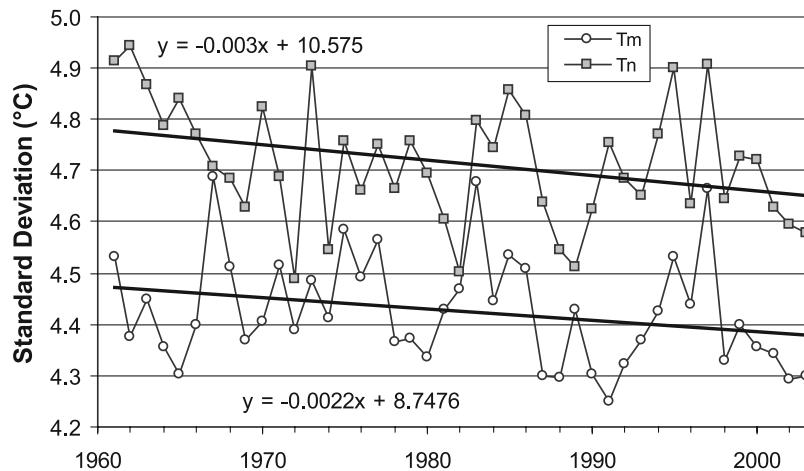


Figure 19. Interannual fluctuations in the spatial variability of T_m and T_n as represented by spatial standard deviation.

arid/semiarid region, the daytime temperature may have an adverse impact on crop growth by increasing the water use demand and creating a shortage during the growing season when it was used together with the nighttime temperature as the independent variable. In Qinghai Province, where we have seen prominent warming trends, the changes we found in the temperature regime should benefit crop production if such trends continue. In both regression models, the influence of the mean T_n on crop yield is twice as much as that of the mean T_m , as indicated by the standardized regression coefficients. One factor that we did not consider in this analysis was the agricultural input in the forms of fertilizer and pesticide usage, which without any doubt would have played significant roles in crop production during the study period.

[25] To avoid the human interference problem associated with the crop yield analysis, we also used tree ring width data to examine the impact of extreme temperature changes. We used tree ring samples in two locations: eastern Qaidam Basin around the Delingha area of Qinghai Province [Shao et al., 2005] and western Sichuan Province [Shao and Fan, 1999]. For the Delingha area along the northeastern margin of the TP, we obtained ring width data from Qilian junipers (*Sabina przewalskii* Kom.) at 11 sampling sites from 1955 to 2002. For western Sichuan Province along the eastern margin of the TP, we used ring widths data of Western Sichuan spruce (*Picea balfouriana*) at four sites from 1960 to 1994. We first used correlation analysis to identify various combinations of monthly, seasonal, and annual precipitation and temperature measures that are strongly correlated with the tree ring widths. Then multiple regression analysis was used to establish the relationships of tree growth to precipitation and temperature in these two regions.

[26] Table 5 presents the result of multiple regression analysis. In the Delingha area, May–June precipitation and the cumulative precipitation from previous July to current June can explain up to 60% of the variance in the tree ring widths. Cold month mean T_n only entered the model for one site (WL2), while May–June mean T_m entered 10 out of 11 models with negative impact on tree growth. Obviously, the impact of high daytime temperature on water use

demand during the growing season was much stronger than any limiting influence of minimum temperature on tree growth in this region. With both precipitation and temperature variables, the regression models can explain up to 70% of the total variance in tree ring widths, with precipitation as the dominant factor. For the sites in western Sichuan Province, however, precipitation appeared to be an insignificant factor for tree growth, while various measures of temperature entered the models and explained up to 50% of the total variance in tree ring widths (Table 5). Mean daily T_m of the fall months in the previous year had a negative influence, but only entered one model (KDP). Mean daily T_n of the summer months had a significant positive influence on tree ring widths at KDP and DFP, while mean T_n of winter and early spring months also had a significant positive influence at DFP, WLP, and YJP (Table 5). At this location, therefore, warming temperatures should induce better tree growth.

[27] Our analysis suggests that the response of vegetation to changes in extreme temperatures over time can be complex and differ from place to place. For irrigated crops in arid and semiarid high-elevation regions, precipitation fluctuations will have a minor impact on crop yield, while temperature changes may have significant impacts. In our case, the increasing night-temperature apparently has a beneficial influence on crop yield, while the daytime temperature, with smaller increasing rates, may have some

Table 3. Relative Contribution of the Trends in Daily Maximum and Minimum Temperatures on Trends of the Other Climate Variables at the 66 Weather Stations

| Dependent Variable | R^2 | Standardized Coefficient | | F Statistic of the Model |
|-----------------------|-------|--------------------------|---------------------|----------------------------|
| | | T_m | T_n | |
| Ta | 0.879 | 0.468 ^a | 0.674 ^a | 229.330 ^a |
| Number of Warm Days | 0.664 | 0.834 ^a | -0.063 | 62.342 ^a |
| Number of Frost Days | 0.409 | -0.006 | -0.638 ^a | 21.776 ^a |
| Change of GSL | 0.582 | -0.319 ^a | 0.804 ^a | 48.780 ^a |
| Annual Range of Ta | 0.339 | 0.313 ^a | -0.603 ^a | 16.125 ^a |
| Annual Range of T_m | 0.015 | 0.124 | -0.004 | 0.479 |
| Annual Range of T_n | 0.396 | 0.401 ^a | -0.633 ^a | 20.629 ^a |

^aStatistically significant at the 0.01 level.

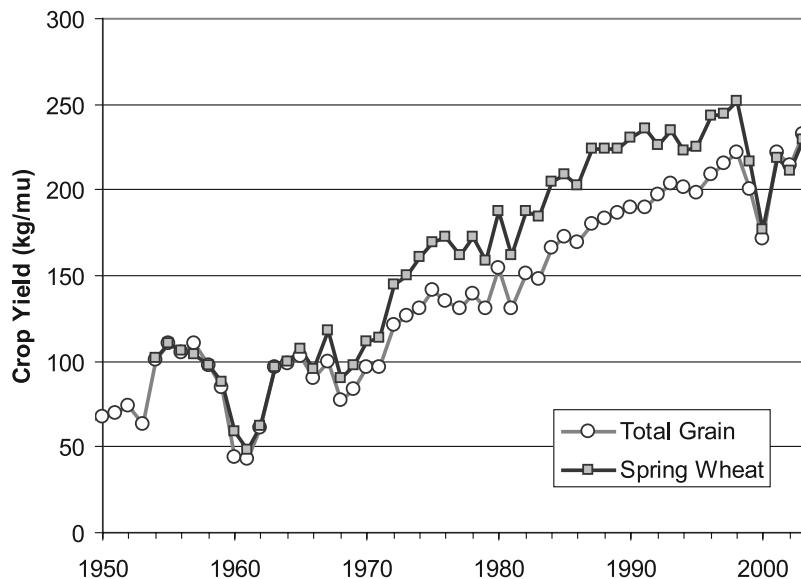


Figure 20. Grain and spring wheat yields in Qinghai Province. The unit is kg/mu, where mu is the Chinese area unit equivalent to 1/15 of a hectare.

negative influence because it would enhance the water use demand and cause water shortages. In areas where precipitation is the dominant limiting factor, as in the case of natural vegetation in eastern Qaidam Basin, the effect of nighttime temperature may be minor, while daytime temperature has a significant negative influence owing to its effect on vegetation water use. On the other hand, in places where temperature is the dominant limiting factor, the change of temperature regimes, including the changes in growing season length, may have a significant impact on vegetation growth. One question we were unable to answer with full satisfaction is the relative significance of warmer winters together with cooler and wetter summers. It is difficult at this stage to distinguish which is more important in influencing the trends in tree ring widths. Although, on the basis of the covariation patterns of ring widths corresponding to the short-term or high-frequency climatic fluctuations, it seems that the cooler and wetter summers may have a greater influence on tree growth.

4. Conclusions

[28] In this study, daily nighttime and daytime temperatures were examined for 66 weather stations with elevations above 2000 m over the central and eastern TP for changes in the temperature regime during 1961–2003. In this region, the linear trends of mean daily minimum temperature and maximum temperature reached $0.41^{\circ}\text{C}/10 \text{ yr}$

and $0.18^{\circ}\text{C}/10 \text{ yr}$, respectively during the study period. The greatest warming is found in wintertime for both daytime and nighttime temperatures. Similarly, temperatures associated with relatively cold events (tenth percentile) showed the greatest increases in winter and spring months. For the entire region, the annual number of frost days decreased and the number of warm days increased. When compared with other regions, the warming trends over the central and eastern TP were among the highest ones, especially for the nighttime temperatures during the months from November to March ($> 0.5^{\circ}\text{C}/10 \text{ yr}$).

[29] The changes in the temperature regime were reflected in the increases in growing season length by approximately 17 days on the basis of the prediction of the regression model during the 43-year study period. Because of the asymmetric pattern of greater warming trends in nighttime than daytime temperatures, the diurnal temperature range became smaller over time. Associated with the warming trends, we also found that temporal variability of night-temperature was negatively correlated with temperature with statistical significance, while the spatial variability showed stronger negative correlations to temperatures. Therefore, as the warming trend continues, temperatures in the region should become more temporally and spatially homogeneous. In terms of spatial patterns of the temperature changes, greater and more consistent warming was found in the north, southwest, and southeast of the study region.

Table 4. Results of Regression of Crop Yield Against Province-Wide Temperature Measures

| Model | Unstandardized Coefficients | Standardized Coefficients | t | Sig. | R ² | Adj R ² | Standard Error of Estimates |
|---------------|-----------------------------|---------------------------|---|---------|----------------|--------------------|-----------------------------|
| <i>Grain</i> | | | | | | | |
| Constant | 885.6 | | | 5.4039 | 0.0000 | 0.7436 | 0.7308 |
| Grain AVGTMIN | 89.9 | 1.1051 | | 9.2945 | 0.0000 | | 25.5 |
| Grain AVGTMAX | -38.9 | -0.3812 | | -3.2064 | 0.0026 | | |
| <i>Wheat</i> | | | | | | | |
| Constant | 1242.4 | | | 6.5762 | 0.0000 | 0.7327 | 0.7193 |
| Wheat AVGTMIN | 108.0 | 1.1765 | | 9.6903 | 0.0000 | | 29.4 |
| Wheat AVGTMAX | -62.9 | -0.5456 | | -4.4939 | 0.0001 | | |

Table 5. Results of Regression Analysis on Tree Ring Width Against Temperature and Precipitation^a

| Sites | Variables (Sign) That Entered the Model | R ² | Adj-R ² |
|-------------------------------|---|----------------|--------------------|
| <i>Delingha, Qaidam Basin</i> | | | |
| DLH1 | AccP (+), Tm56 (-) | 0.504 | 0.480 |
| DLH2 | AccP (+), P56 (+) | 0.548 | 0.527 |
| DLH3 | AccP (+), P56 (+), Tm56 (-) | 0.568 | 0.537 |
| DLH4 | AccP (+), P56 (+), Tm56 (-) | 0.598 | 0.569 |
| DLH5 | AccP (+), P56 (+), Tm56 (-) | 0.676 | 0.653 |
| DLH6 | AccP (+), P56 (+), Tm56 (-) | 0.701 | 0.680 |
| WL1 | AccP (+), Tm56 (-) | 0.428 | 0.401 |
| WL2 | AccP (+), Tm56 (-), Tn11_3 | 0.600 | 0.570 |
| WL3 | AccP (+), P56 (+), Tm56 (-) | 0.649 | 0.623 |
| WL4 | AccP (+), P56 (+), Tm56 (-) | 0.703 | 0.681 |
| TJ1 | AccP (+), P56 (+), Tm56 (-) | 0.441 | 0.416 |
| RC | AccP (+), P56 (+), Tm56 (-) | 0.671 | 0.647 |
| <i>Western Sichuan</i> | | | |
| KDP | TmpFall (-), Tnsum (+) | 0.451 | 0.416 |
| DFP | Tn12_4 (+), Tnsum (+) | 0.506 | 0.474 |
| XLP | Tn12_4 (+) | 0.248 | 0.225 |
| YJP | Tn12_4 (+) | 0.171 | 0.145 |

^aDLH1–6, WL1–4, and TJ1 are sampling sites in Delingha of eastern Qaidam Basin; RC is a regional chronology for the Delingha area. KDP, DFP, XLP, and YJP are sampling sites in western Sichuan Province. AccP is precipitation from July of previous year to June of current year. Tm56 is May–June mean maximum temperature. P56 is May–June total precipitation. Tn11_3 is mean minimum temperature from November of previous year to March of current year. TmpFall is mean maximum temperature of fall months (SON) of previous year. Tnsum is mean minimum temperature of summer months (JJA). Tn12_4 is mean minimum temperature of December of previous year to April of current year.

[30] Through analysis of crop yield and tree growth based on annual tree ring widths, we demonstrated that the impact of the changes in temperature regimes can be quite significant, as in the case of grain production, but it can also be complex and obscured by other limiting factors, such as precipitation in an arid/semiarid region. Annual mean maximum and minimum temperatures explained more than 70% of the variance in grain and spring wheat yields in Qinghai Province, one of the areas in the study region experiencing prominent warming. In the mean time, however, annual growth of junipers under the arid/semiarid climate was more related to precipitation, while the growth of spruces in a wetter climate was more influenced by temperatures. Therefore different ecosystems and different species may have variable responses to the temperature changes.

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X. Liu, SKLLQG, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China. (liuxd@loess.llqg.ac.cn)

N. Qin, Qinghai Climate Data Center, Qinghai Meteorological Bureau, Xining 810001, China. (wldnqin@public.xn.qh.cn)

X. Shao, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China. (shaoxm@igsnrr.ac.cn)

Z.-Y. Yin, Department of Marine Science and Environmental Studies, 5998 Alcala Park, University of San Diego, San Diego, CA 92110, USA. (zyin@sandiego.edu)