Evidence of Warming and Wetting Climate over the Qinghai-Tibet Plateau

Authors: Li, Lin, Yang, Song, Wang, Zhenyu, Zhu, Xide, and Tang, Hongyu

Source: Arctic, Antarctic, and Alpine Research, 42(4) : 449-457

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1938-4246-42.4.449

Arctic, Antarctic, and Alpine Research, Vol. 42, No. 4, 2010, pp. 449–457

Evidence of Warming and Wetting Climate over the Qinghai-Tibet Plateau

Lin Li†*
Song Yang‡
Zhenyu Wang†*
Xide Zhu† and*
Hongyu Tang†*

*Qinghai Climate Center, Xining, Qinghai 810001, China
†Qinghai Center on Climate Change Monitoring and Evaluation, Xining, Qinghai 810001, China
‡Corresponding author: NOAA Climate Prediction Center, 5200 Auth Road, Room 605, Camp Springs, Maryland 20746, U.S.A.
Song.Yang@noaa.gov

Abstract

In this study, we apply temperature, precipitation, and other data from 66 Chinese meteorological stations including Xining and Lhasa to analyze the extreme climate events and their impacting factors over the Qinghai-Tibet Plateau during the period 1961–2007. We focus on the spatial and temporal features of extreme climate events and their long-term changes over five climate zones of alpine grassland, meadow, and desert areas.

Results show that, during the past decades, the changes in climate over the Qinghai-Tibet Plateau present trends towards warm and wet conditions. These changes in temperature and precipitation are evident in both seasonal means and extreme events, and the changes in precipitation are apparent in both precipitation amount and number of precipitation days. Clearly, warm and wet events increase, but cold and dry events decrease over the plateau region. Features of the warming climate are relatively consistent in spatial and seasonal distributions, with the most significant changes in winter and autumn and at nighttime. Northern Qinghai exhibits the greatest and most significant decrease in the frequency of extremely low-temperature events. However, the wetting trend shows more distinctive spatial features and is more seasonally dependent. While the trends in both precipitation amount and the number of precipitation days are positive in all climate zones for winter and spring, both positive and insignificant negative trends appear in summer and autumn. The largest decrease in the frequency of severely dry events is found over southeastern Tibet and western Sichuan.

DOI: 10.1657/1938-4246-42.4.449

Introduction

The Qinghai-Tibet Plateau (QTP; referred to the central and eastern portion of the Tibetan Plateau in this study) is one of the major regions of biological species in China. The unique plateau ecosystem is an important part of the ''eco-source'' of China and plays a significant role in maintaining the ecological security of the country (e.g. Xiao and Li, 2000; Qian et al., 2007; Li et al., 2010). As reviewed by Li et al. (2007), Liu et al. (2007), and Bianduo et al. (2009), changes in the climate over the plateau are important not only for local ecology and environment but also for the climate outside the region (also see Trenberth and Chen, 1988; Murakami, 1987; Yanai and Wu, 2006).

Previous studies (e.g., Zhou et al., 2006; Cui et al., 2007; Li et al., 2007; Sato et al., 2009) have shown that the alpine ecosystems in the QTP region are extremely sensitive to climate conditions and the changes in climate and eco-environment over the plateau have directly affected the development of local natural resources. In past decades, the mean temperature over QTP has increased (Liu and Chen, 2000), and this warming has resulted in ecological degradation and shortage of water resources and affected the socioeconomic sustainable development in the region (Tang, 1998; Niu et al., 2005). Previous studies have also shown that the effects of QTP, both thermal and dynamic, lead to changes in the climate over Asia (Terao, 1999; Wang, 2002; Wu et al., 2007) and even the Asian-Pacific-American sector (Broccoli and Manabe, 1992; Zhang et al., 2005). It is well known that the changes in the Asian monsoon are closely related to the thermal conditions over QTP (He et al., 1987; Yang et al., 2004; Sato and Kimura, 2007; Gao and Yang, 2009; Bao et al., 2010). Recently, Nan et al. (2009) indicated that low (high) temperatures over the Tibetan plateau in spring is followed by increase (decrease) in sea surface temperatures over the tropical central-eastern Pacific Ocean in summer, implying an antecedent signal of El Niño–Southern Oscillation in the plateau thermal condition.

Studies of the QTP climate have focused more on the change in temperature than on the change in precipitation (e.g. Tang et al., 1998; Yao et al., 2000). As reviewed above, the mean temperature in QTP has apparently increased (e.g. Liu and Chen, 2000). In recent years, several studies have been conducted to understand the climate extremes over the region (Liu et al., 2006; Li et al., 2007; You et al., 2008). In particular, Liu et al. (2006) have investigated the trends of daily and monthly maximum and minimum temperatures, number of frost days, and length of growing season for 1961–2003. They found that the warming trend in the plateau region, where the winter nighttime trend was larger than in other regions, decreased the number of frost days and lengthened the growing season. You et al. (2008) have further analyzed the changes in climate extremes associated with daily temperature and precipitation over the Tibetan plateau. The authors showed that, besides the warming trends of temperature events measured by various indices, the number of consecutive dry days decreased significantly. Smaller and insignificant trends were also found in maximum pentad precipitation and consecutive wet days. The climate over QTP also tends to be warmer in later years, which may exert a greater impact on the ecosystem and lead to more complicated and uncertain relationships between climate change and the ecosystem (Duan et al., 2006; Xu et al., 2005).

1523-0430/10 $7.00

Many studies have explained the past and possible future changes over and near the plateau in the global warming scenario (e.g., Jiang et al., 2008a, 2008b; Dong et al., 2010; Zhao et al., 2010).

Apparently, previous studies of the climate over QTP have mainly focused on the seasonal or monthly means of total climate conditions and their temporal changes. Relatively less effort has been devoted to understanding the characteristics of extreme climate events, especially their long-term changes. In spite of the limited studies reviewed above, many detailed features about the climate extremes over the plateau region still remain unknown. For example, to understand the more detailed features of temperature and precipitation events, finer classifications of these events with more characteristic classes are needed. There exists also a lack in characterizing complex regional features, especially those involved with change of precipitation. In addition, the data that have been analyzed in many previous studies are usually sparse and do not have long records. The quality of many data, especially the proxy data, analyzed may be low, due partially to the difficulties in obtaining reliable and long-recorded observational data over high-altitude regions.

In this study, we apply daily data from dense meteorological stations over the QTP region that cover several decades to reveal detailed features of the change in plateau climate. We analyze not only the features of mean climate conditions but also the detailed characteristics of extreme temperature and precipitation events using the same data sets. We conduct a quality control of the data sets, analyze the quantity of aridity, divide the analysis region into different climate zones, and categorize temperature and precipitation events into different classes. In the next section, we describe the major features of the data sets and analysis methods applied. In section three, we present the results obtained from the analysis. Here, we first depict the trends of changes in mean climate conditions and then analyze the characteristics of long-term changes in extreme temperature and precipitation events. Conclusions of the results obtained are provided in section four.

Data and Calculation Methods

This study analyzes the station data of annual, monthly, and daily temperature and precipitation from the China Meteorological Administration for the time period of 1961–2007. The stations are distributed in Qinghai Province, the Tibet Autonomous Region, and the Autonomous Prefectures of Gannan in Gansu Province, Garze and Aba in Sichuan Province, and Diqing in Yunnan Province. As shown by Feng et al. (2004), data quality control is important for producing reliable features in analyzing daily meteorological data for western China. In this study, we conduct a quality control for the data sets obtained, which yields 66 stations for analysis. For missing data, we examine the information over the surrounding stations and apply the data that is are reliable as determined by the running *t*-test method. For the stations with records that may be affected by change in meteorological instruments, we correct the data using the difference in the data values averaged before and after instrument change, mainly for temperature, so that the corrected data is fitted into the data series after the change in instruments. Lastly, for relocated stations, we correct both precipitation and temperature data also using the mean series of the surrounding five stations that have not been relocated to avoid any data discontinuity due to relocation of stations. The specific locations of the 66 Chinese meteorological stations are shown in Figure 1.

We apply a rotational empirical orthogonal (REOF; Gutzler et al., 1988) analysis to determine climate zones for the region of

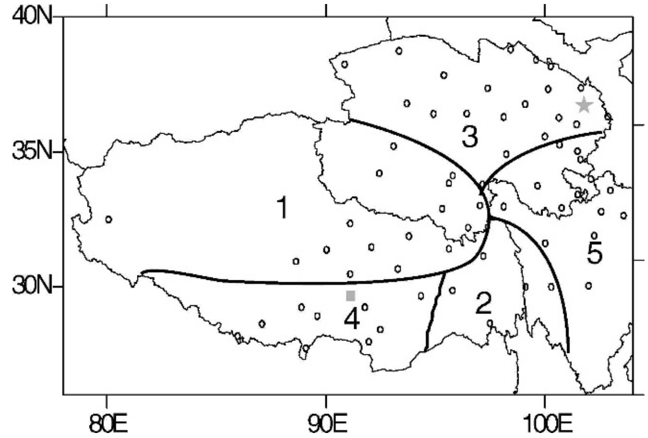

FIGURE 1. Distributions of meteorological stations and typical climate zones in the Qinghai-Tibet Plateau. The star represents Xining (52866; capital of Qinghai Province) and the square represents Lhasa (55591; capital of Tibet Autonomous Region).

study. Other statistical analysis methods including the least-squares method for linear trend analysis, correlation analysis, and the Mann-Kendall test (M-K test; Kendall and Gibbons, 1981) for abrupt climate changes are also applied. Extreme climate events are determined by the following statistical methods for each station and analysis domain.

(1) For seasonal and annual means, we first organize temperature in the descending order of five classes: warm, slightly warm, normal, slightly cool, and cool. Among the five classes, warm and cool classes are set as 12.5% of the total samples, respectively, and each of the other three classes takes up 25%. The threshold values of the mean temperature are delineated for each of the four seasons and for the whole year. Similar analysis can be found in Han and Gong (2003) and Zhai and Pan (2003).

(2) Following the standards for the drought and flood events in China (Zhang et al., 1983; Shi, 1995), the amounts of seasonal and annual precipitation over QTP are divided, respectively, into five dryness (or wetness) classes: wet, $R_i > (R + 1.17\sigma)$, slightly wet, $(R + 1.17\sigma) \geq R_i > (R + 0.33\sigma)$, normal $(R + 0.33\sigma) \geq R_i > (R - 0.33\sigma)$, slightly dry $(R - 0.33\sigma) \geq R_i > (R - 1.17\sigma)$, and dry $R_i \leq (R - 1.17\sigma)$. Here, R_i is the annual or seasonal mean precipitation for individual years and R is the climatological average of precipitation. σ is the standard deviation of annual or seasonal mean precipitation.

(3) From the daily mean temperature of all years, we define the top (bottom) 2.5% of temperature, i.e. the highest (lowest) 2.5%, as the extremely high (low) temperature events (also see Zhang et al., 1983).

(4) We determine dry events based on the consecutive days without precipitation and define the seriously dry events as those events in which no precipitation occurs in 10 days or more. The seriously dry events over the plateau are computed as the sum of those events over all stations.

(5) We define heavy rain events as those events in which daily precipitation is more than 25 mm, consistent with the definition by the Quality and Technology Administration in Qinghai Province (2001). The definition of 25 mm is also the criterion of meteorological operations of the China Meteorological Administration for northwestern China. The heavy rain events over the plateau are computed as the sum of those events over all stations.

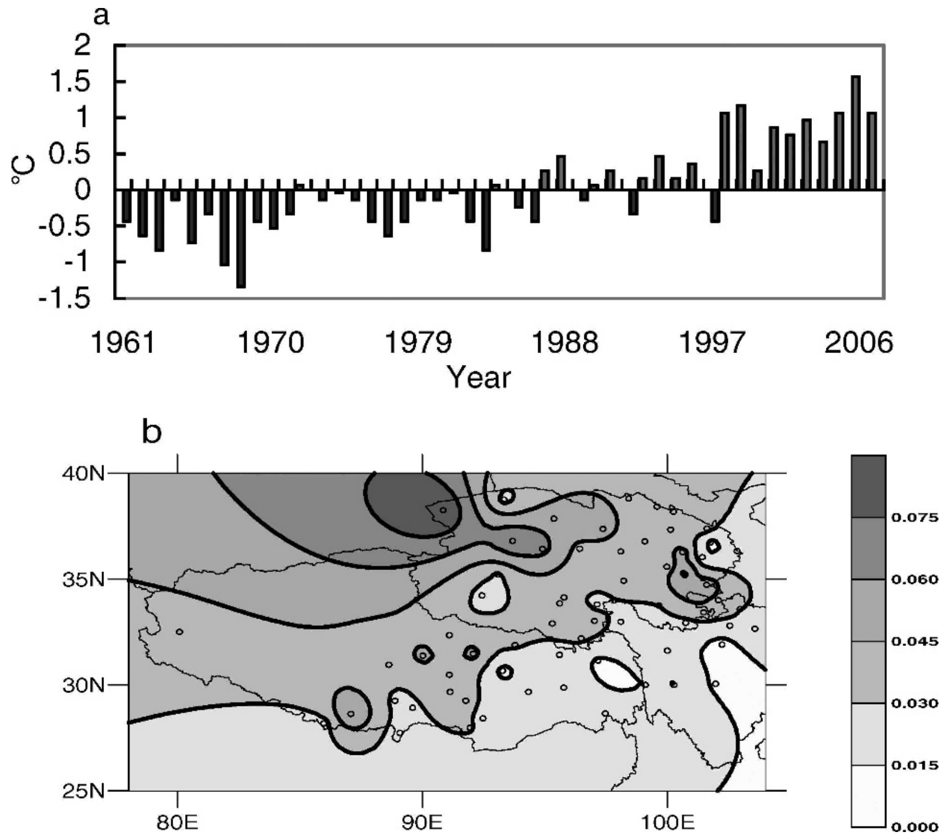

FIGURE 2. Anomalies of area-averaged annual mean temperature (a, in °C) and rates of change in station annual temperature (b, in °C yr^{-1}) over the Qinghai-Tibet Plateau from 1961 to 2007.

Results

We first apply a REOF analysis to the time series of aridity over the 66 stations for 1961–2007 to determine the climate zones over the QTP region, with additional considerations of geographical factors including land cover and terrains. The aridity (I) is computed using temperature (T) and precipitation (P) as $I = (T + 10) P^{-1}$, following Meng et al. (2004). More specifically, we divide the plateau region into five climate zones based on the REOF patterns, with considerations of the difference in grassland, meadow, and desert and the orientation of mountains and highland. The variances explained by the first five REOF modes are 28.45, 9.0, 8.0, 6.36, and 5.58, respectively. These climate zones are: the alpine grassland area in northern Tibet and the Yangtze River source region (Zone 1), the alpine meadow area in southeastern Tibet and western Sichuan (Zone 2), the alpine desert area in northern Qinghai (Zone 3), the alpine meadow area in southern Tibet (Zone 4), and the alpine meadow area in the upper Yellow River (Zone 5). The geographical distribution of these climate zones is shown in Figure 1. Compared to previous studies (Li and Tang, 2000; Li et al., 2003), we have considered multiple climate factors and the difference in grassland resource between different areas of the plateau.

WARMING AND WETTING TRENDS

Uniform Increase in Temperature

Figure 2 provides the distributions of annual mean temperature and the rates of temperature change for each meteorological station over QTP from 1961 to 2007, consistent with the results of previous studies. The annual mean temperature exhibits an apparent warming trend (Fig. 2a), with a significant rise in temperature from cool to warm in 1987 as determined by the M-K test. The warming trend appears from all stations and the most obvious warming is found over the northwest (Fig. 2b). As shown in Figure 3, significantly warming trends are also observed in seasonal mean temperatures, especially in winter and autumn. In particular, the temperature in spring, summer, autumn, and winter increases at a rate of 0.025 °C, 0.026 °C, 0.038 °C, and 0.059 °C per year, respectively, all exceeding the 99.9% confidence level. The annual-averaged daily maximum and minimum temperatures also increase at a rate of 0.028 °C and 0.051 °C per year, respectively. These features indicate that the changes in temperature over QTP are most significant in winter and at nighttime, consistent with the result of Liu et al. (2006), in spite of different periods of time and stations analyzed.

To further depict the details of climate change over QTP, we show in Table 1 the change rates of mean, maximum, and minimum temperature for the annual means and various seasons and for different climate zones (see Fig. 1). For the values shown in the table, we first calculate the means for all stations for each zone and each season and then use the computer to generate the long-term changes in these means for each field. Several features can be identified from the table. First, temperatures tend to increase uniformly in all seasons and all climate zones, not only for the mean temperature, but also for maximum and minimum temperatures. Second, for the various climate zones, the rises of means and maximum and minimum temperatures are more significant in autumn and winter, especially in winter, than in spring and summer. Third, the changes in the annual mean temperature are largest and most significant in northern Qinghai (Zone 3) but smallest and least significant in southern Tibet (Zone 4), indicating that the warming trend measured by annual mean temperature is more distinct at higher latitudes than at lower latitudes. Furthermore, the increases in minimum temperature are larger than those increases in the mean and maximum tempera-

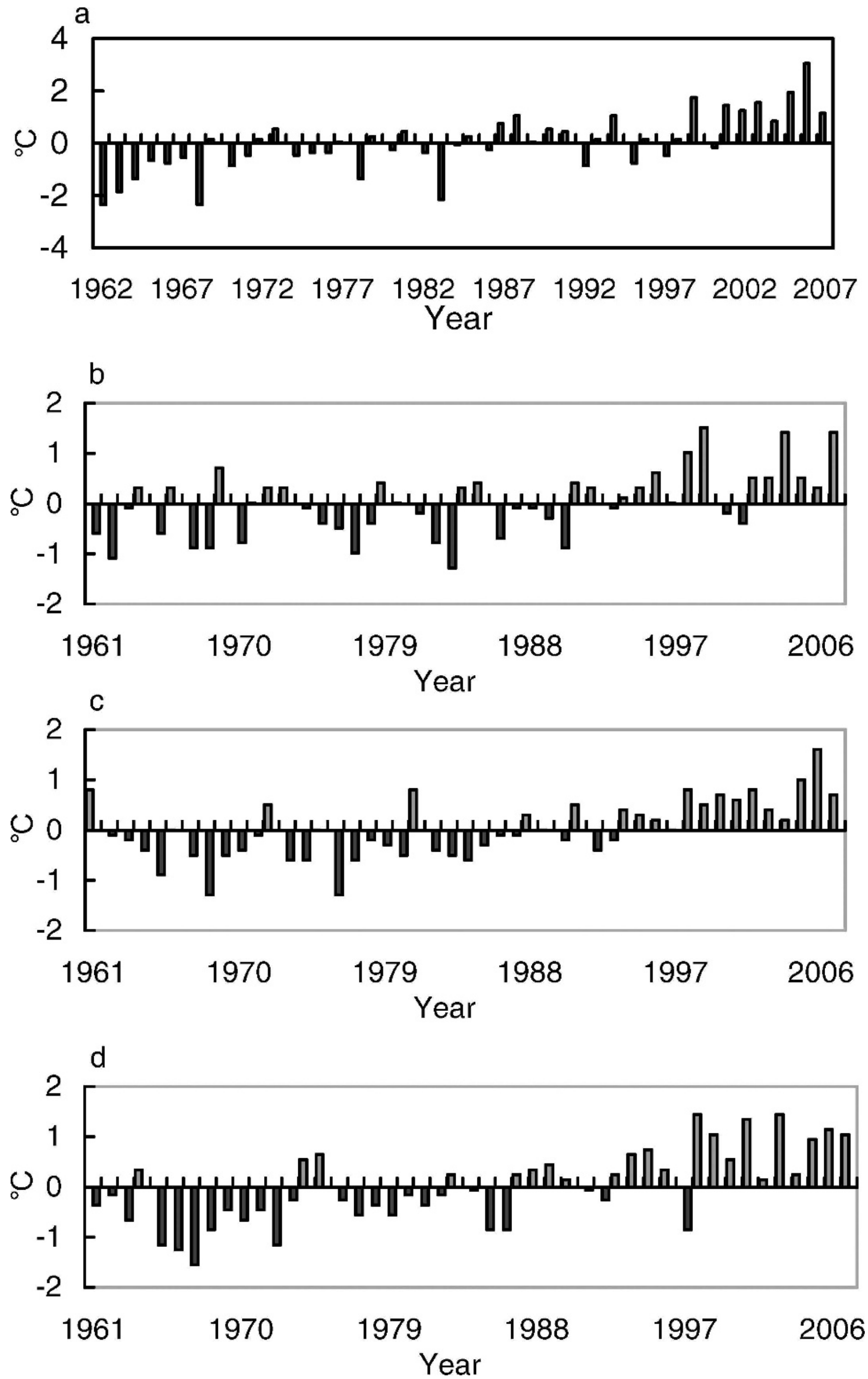

FIGURE 3. Same as in Figure 2, but for winter (a), spring (b), summer (c), and autumn (d).

ture. Table 1 provides detailed features about the changes in temperature for various climate zones, compared with many previous studies.

Diversified Increase in Precipitation

Figure 4, which shows the changes in annual precipitation, clearly indicates a positive trend of precipitation, with a rate of 0.91 mm per year (significantly exceeding the 99% confidence level). A significant change from dry to wet climate over the plateau occurs as early as 1974, as determined by the M-K test. However, the changes in annual precipitation are also characterized by large regional features (Fig. 4b). Specifically, the trends are positive in the central-eastern Qaidam Basin of northern Qinghai, southeast Tibet, and northwest Sichuan. Negative trends are seen in other regions, especially over Hequ in the upper Yellow River basin (the area encircled by red line on the right of the figure). Comparison of Figures 2 and 4 shows that large increases in temperature occur over the regions with small changes in precipitation, whereas small increases in temperature appear over the regions with large changes in precipitation.

TABLE 1

Averaged rates of changes in mean, maximum, and minimum temperatures over the various climate zones in the Qinghai-Tibet Plateau from 1961 to 2007 (°C yr^{-1}). Results are shown for seasonal and annual means, and values that significantly exceed the 95%, 99%, and 99.9% confidence levels (*F*-test) are indicated by *, **, and *, respectively.**

Temperature	Zone	Spring	Summer	Autumn	Winter	Annual
Mean	1	0.0229**	0.0238***	0.0351***	0.051***	0.0333***
	2	0.0247***	0.0259***	0.0324***	0.0496***	0.0343***
	3	0.0273***	0.0335***	0.0426***	0.0646***	0.0419***
	4	0.0234**	0.0161**	0.0314***	0.0458***	0.0297***
	5	0.0204**	0.0276***	0.0344***	0.0567***	0.0341***
Maximum	1	0.0112	0.02*	0.0265*	0.038**	0.0241***
	2	0.0161	0.0237**	0.0255**	0.044***	0.0283***
	3	0.0157	0.0279***	0.0441***	0.0512***	0.035***
	4	0.0135	0.0073	0.0221*	0.0306**	0.0195**
	5	0.0009	0.0209**	0.0301***	0.0398**	0.023**
Minimum	1	0.0387***	0.03***	0.0424***	0.0647***	0.0434***
	2	0.0389***	0.0298***	0.0417***	0.0622***	0.0461***
	3	0.042***	0.0485***	0.0497***	0.0807***	0.0559***
	4	0.0424***	0.0288***	0.0439***	0.0636***	0.0446***
	5	0.0389***	0.0362***	0.0394***	0.0736***	0.0464***

The changes in precipitation are, respectively, 0.47, 0.17, 0.11, and 0.14 mm per year for spring, summer, autumn, and winter, and the changes in spring and winter significantly exceed the 99.9% confidence level. A further analysis shows that the number of annual precipitation days (precipitation greater than 0.1 mm per day) also tends to increase, with a rate of 0.13 days per year (exceeding the 95% confidence level). For the individual seasons, the rates are 0.067 and 0.091 days per year in winter and spring, significantly exceeding the 99% and 99.9% confidence levels, respectively. Insignificant negative trends are found for summer and autumn, with a rate of −0.006 and 0.019 days per year, respectively.

Table 2 shows the changes in precipitation amount and the number of precipitation days for various seasons and various climate zones. It reveals the following major features. (1) The trends in both precipitation amount and the number of precipitation days are positive in all zones for winter, spring, and annual means. (2) In summer and autumn, both positive and

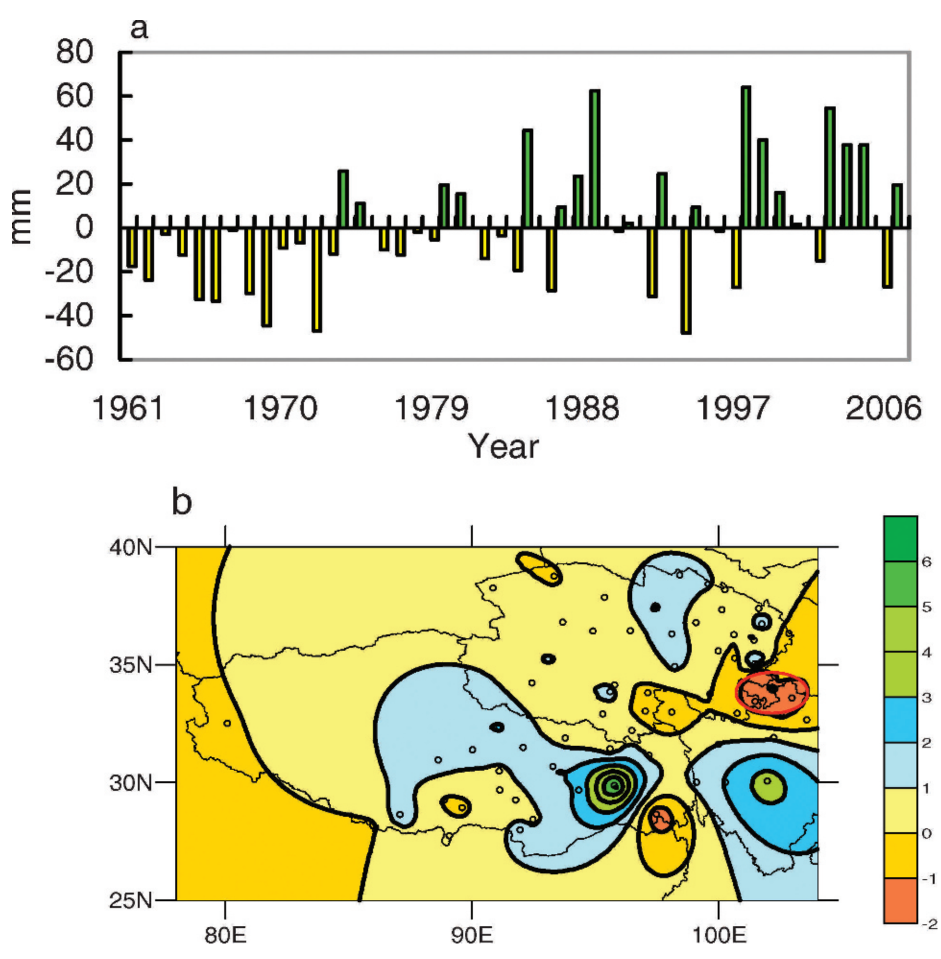

FIGURE 4. Anomalies of area-averaged annual mean precipitation (a, in mm) and rates of changes in station annual precipitation (b, mm yr^{-1}) over the Qinghai-Tibet Plateau from 1961 to 2007. The red line on the right encircles the Hequ region.

TABLE 2

Averaged rates of changes in precipitation amount (mm yr^{-1}) and number of precipitation days (day yr^{-1}) over the various climate zones in the Qinghai-Tibet Plateau from 1961 to 2007. Results are shown for seasonal and annual means, and values that significantly exceed the 95%, 99%, and 99.9% confidence levels (*F*-test) are indicated by *, **, and *, respectively.**

Precipitation	Zone	Spring	Summer	Autumn	Winter	Annual
Amount	1	0.3896*	0.011	0.081	0.1089**	0.5681
	2	1.0247***	−0.0429	0.7961**	0.1793**	1.9885**
	3	0.0752	0.4211	0.0061	0.0406***	0.5406
	4	0.6878***	−0.1555	0.2089	0.2755*	0.9663
	5	0.4459**	0.0795	−0.33	0.145***	0.3697
No. of days	1	0.0923	0.0008	−0.0053	0.0927*	0.1757
	2	0.1137**	−0.0449	0.0249	0.0681*	0.1631
	3	0.0101	0.0272	−0.0371	0.0249	0.0216
	4	0.1915***	−0.0387	0.0099	0.0876***	0.2328**
	5	0.1113**	−0.0528	−0.0577	0.0959*	0.0844

negative trends appear. However, the negative trends are insignificant. (3) The most significant increase in precipitation amount occurs in southeastern Tibet and western Sichuan (Zone 2), while the most significant increase in the number of precipitation days occurs in southern Tibet (Zone 4). In general, the changes are large over the climate zones with large precipitation amount and large number of precipitation days. The above analyses indicate the change in precipitation is more regionally complicated, compared to the change in temperature over the plateau region.

CHANGES TOWARDS WARMING AND WETTING EXTREME CLIMATE EVENTS

Increase in Warm and Wet Events

We further analyze the various classes of cool-warm and dry-wet climate to better determine and describe the changes in temperature and precipitation events. Figure 5 shows the changes in cool-warm and dry-wet classes in the QTP region. There are positive trends in both cool-warm and wet-dry classes, which are significant at the 99.9% and 95% confidence levels, respectively. As shown above, the year 1987 is a turning point of the warming climate over the plateau (determined by the M-K test). There are 3 slightly warm years before 1987, and 16 slightly-warm and warm years since then. There are 4 slightly-wet and wet years before 1987, and 11 slightly-wet and wet years after that, showing a trend towards a warming and wetting climate. This result is consistent with that of Qian and Qin (2008) who showed a rapid increase in the annual precipitation over Northwest China (Xinjiang) in 1987. A more detailed analysis indicates that there are warming and wetting trends measured by the cool-warm and dry-wet classes for all climate zones except a slightly decreasing trend in dry-wet class in the upper Yellow River valley (Zone 5). The largest and most significant upward trends in cool-warm and dry-wet classes are found in northern Qinghai (Zone 3).

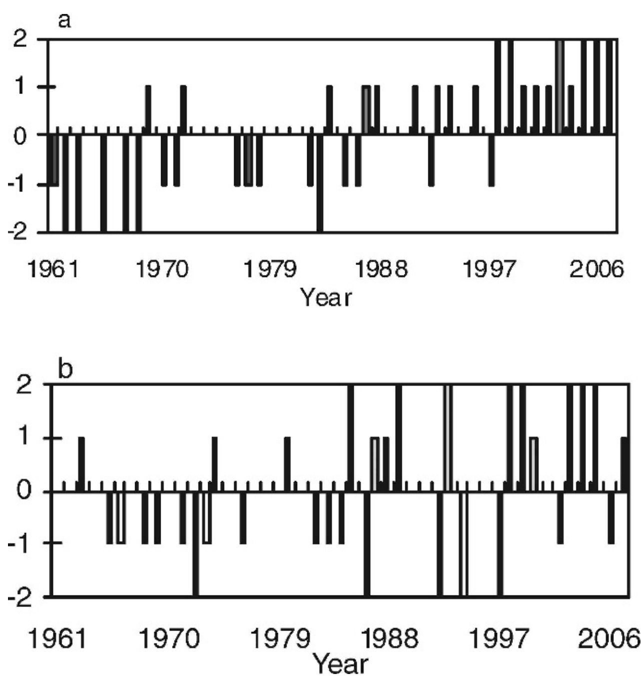

FIGURE 5. Changes in cool-warm classes (a) and dry-wet classes (b) over the Qinghai-Tibet Plateau from 1961 to 2007. Upward order of −2, −1, 0, 1, and 2 is set for cool, slightly cool, normal, slightly warm, and warm in (a), and for dry, slightly dry, normal, slightly wet, and wet in (b).

Figure 6 displays the anomalies of the frequencies of extremely high temperature and heavy rain occurrences in the QTP region. There are increasing trends in both temperature and precipitation events, with the trend of extremely high temperature reaching the 99.9% confidence level. Eight heavy-rain events occurred in the 21 years after 1987, with a frequency of 38% for positive anomalies, higher than the frequency of 27% before 1987. For the trends of both temperature and precipitation events, all climate zones present upwards trends, with an exception in the upper Yellow River basin (Zone 5) showing a slight decrease in heavy rain occurrence. Southern Tibet (Zone 4) has the largest and most significant upward trend.

Negative Trends in Dry and Cool Events

Figure 7 shows the changes in frequencies of extremely low temperature and severely dry events. There exist negative trends in both extremely low temperature and severely dry events in the 47-year period, significant at the 99% and 99.9% confidence levels, respectively. Here, we also take 1987 as a turning point of climate change. Among the 26 years before 1987, 11 years experienced extremely low temperature events and 10 years experienced severely dry events. After 1987, 15 and 18 years witnessed the two categories, respectively. There have been significant decreases in the frequencies of both extremely low temperature and severely dry events, similar to the result of You et al. (2008). Furthermore, there has also been a decreasing trend in the frequency of extremely low temperature events for each climate zone (Fig. 8). Particularly, northern Qinghai (Zone 3) exhibits the greatest and

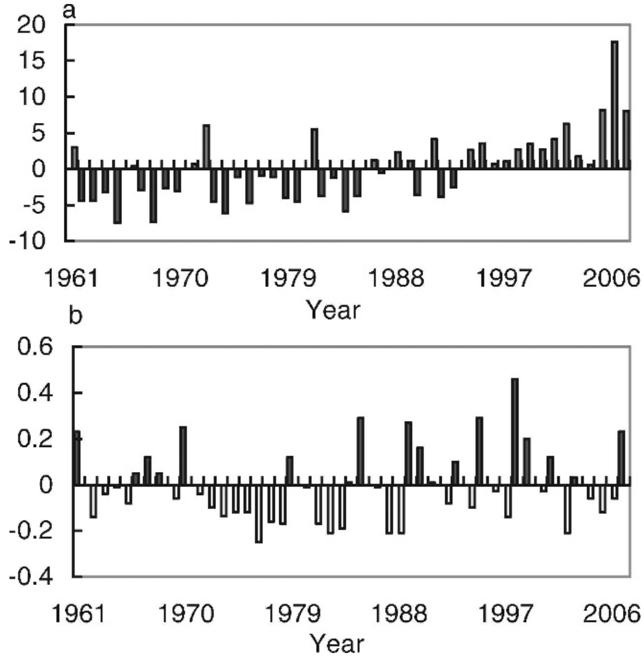

FIGURE 6. Anomalies of the frequencies (in number of occurrence) of extremely high temperature events (a) and extreme heavy rain events (b) over the Qinghai-Tibet Plateau from 1961 to 2007.

most significant decrease. The frequency of severely dry events also decreases in all the climate zones analyzed (Fig. 9), with the largest decrease over southeastern Tibet and western Sichuan (Zone 2). Relatively more apparent features are found in the decreases in extremely low temperature events than in the decreases in severely dry events.

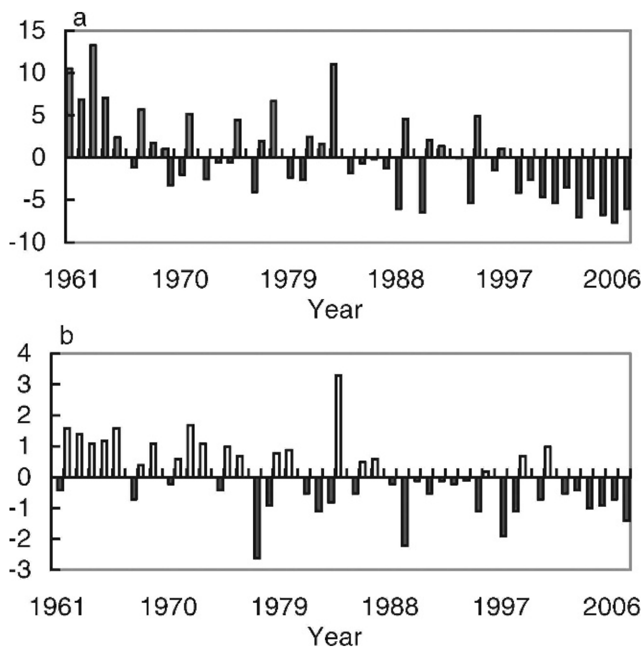

FIGURE 7. Anomalies of the frequencies (in number of occurrence) of extremely low temperature events (a) and severely dry events (b) over the Qinghai-Tibet Plateau from 1961 to 2007.

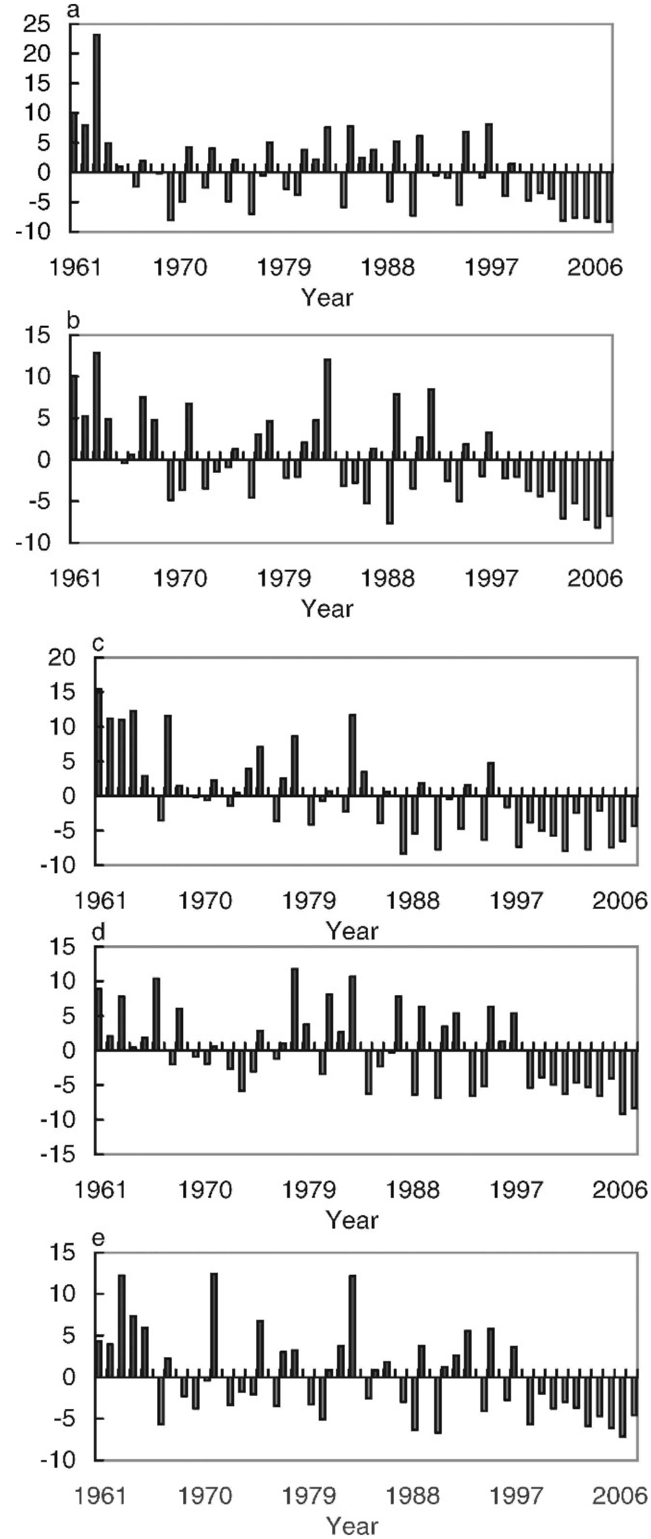

FIGURE 8. Same as in Figure 7a (for extremely low temperature events), but for Zone 1 (a), Zone 2 (b), Zone 3 (c), Zone 4 (d), and Zone 5 (e).

Conclusions

In this study, we have analyzed the meteorological data over 66 stations in the Qinghai-Tibet Plateau region for 1961–2007. Analysis of the temperature, precipitation, and aridity over various stations and averaged over various climate zones and the plateau reveals several important features about the changes in

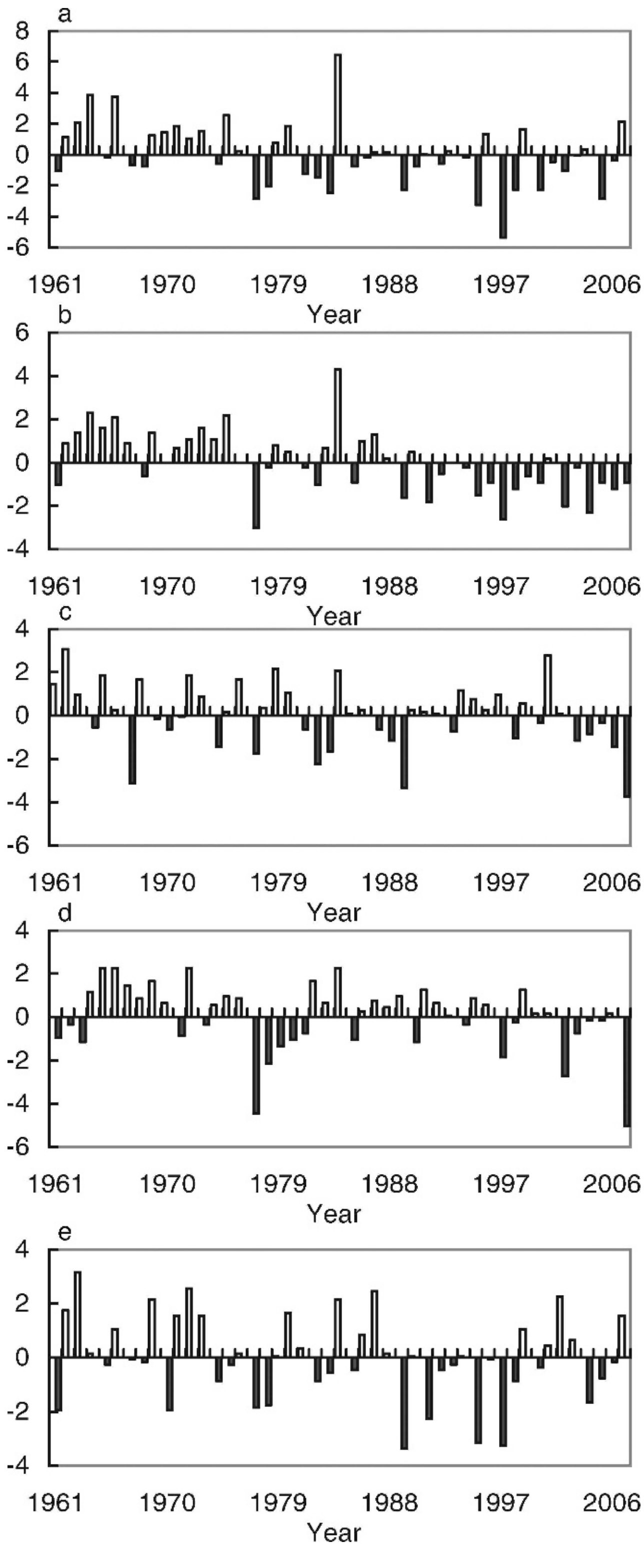

FIGURE 9. Same as in Figure 7b (for severely dry events), but for Zone 1 (a), Zone 2 (b), Zone 3 (c), Zone 4 (d), and Zone 5 (e).

mean climate and extreme climate events. Main conclusions are provided as follows.

(1) A rotational EOF analysis of aridity computed from both temperature and precipitation, with considerations of other geographical factors including land cover and terrains, shows that the QTP region can be divided into five climate zones: the alpine grassland area in northern Tibet and the Yangtze River source region, the alpine meadow area in southeastern Tibet and western Sichuan, the alpine desert area in northern Qinghai, the alpine meadow area in southern Tibet, and the alpine meadow area in the upper Yellow River basin. This classification of climate zones is consistent with the distributions of geographical and grassland features.

(2) The QTP has experienced significant warming and wetting trends. Both precipitation amount and the number of precipitation days have increased significantly. Compared to the increases in annual mean temperature and in maximum and minimum temperatures, the increases in precipitation amount and the number of precipitation days are characterized by larger seasonal and regional heterogeneousness. While the trends in precipitation amount and the number of precipitation days are positive in all climate zones for winter and spring, both positive and insignificant negative trends appear in summer and autumn.

(3) The QTP plateau has exhibited increases in extreme high temperature events and heavy precipitation events. Decreases in extreme low temperature events, especially in northern Qinghai, and serious dry events, especially over southeastern Tibet and western Sichuan, have also been found. That is, warm and wet events have increased but cold and dry events have decreased over the QTP region.

Acknowledgments

The authors are thankful for the comments by two anonymous reviewers that are helpful for improving the overall quality of the paper. This study was supported by a meteorological research project of the China Meteorological Administration (Grant GYHY200906019).

References Cited

Bao, Q., Liu, Y. M., Shi, J. C., and Wu, G. X., 2010: Comparisons of soil moisture datasets over the Tibetan Plateau and application to the simulation of Asian summer monsoon onset. *Advances in Atmospheric Sciences*, 27: 303–314.

Bianduo, Bianbaciren, Li, L., Wang, W., and Zhaxiyangzong., 2009: The response of lake change to climate fluctuation in northern Qinghai-Tibet Plateau in last 30 years. *Journal of Geographical Sciences*, 19: 131–142, DOI:10.1007/s11442-009-0131-z.

Broccoli, A. J., and Manabe, S., 1992: The effects of orography on mid-latitude northern hemisphere dry climates. *Journal of Climate*, 5: 1181–1201.

Cui, X. F., Graf, H. F., Langmann, B., Chen, W., and Huang, R. H., 2007: Hydrological impacts of deforestation on the southeast Tibetan Plateau. *Earth Interactions*, 11: article no. 15.

Dong, W., Jiang, Y., and Yang, S., 2010: Response of the starting dates and the length of seasons in China to global warming. *Climatic Change*, 99: 81–91.

Duan, A. M., Wu, G. X., and Zhang, Q., 2006: New proofs of the recent climate warming over the Tibetan Plateau as a result of the increasing greenhouse gases emissions. *Chinese Science Bulletin*, 51: 989–992.

Feng, S., Hu, Q., and Qian, W., 2004: Quality control of daily meteorological data in China, 1951–2000: a new dataset. *International Journal of Climatology*, 24: 853–870.

Gao, H., and Yang, S., 2009: A severe drought event in northern China in winter 2008–09 and the possible influences of La Niña and Tibetan Plateau. *Journal of Geophysical Research*, 114: article D24104, doi:10.1029/2009JD012430.

Gutzler, D. S., Rosen, R. D., Salstein, D. A., and Peixoto, J. P., 1988: Patterns of interannual variability in the northern hemisphere wintertime 850 mb temperature field. *Journal of Climate*, 1: 949–964.

Han, H., and Gong, D. Y., 2003: Extreme climate events over northern China during the last 50 years. *Journal of Geographical Sciences*, 13: 469–479.

He, H. Y., McGinnis, J. W., Song, Z. S., and Yanai, M., 1987: Onset of the Asian summer monsoon in 1979 and the effect of the Tibetan Plateau. *Monthly Weather Review*, 115: 1966–1995.

Jiang, Y., Dong, W., Yang, S., and Ma, J., 2008a: Long-term changes in ice phenology of the Yellow River in the past decades. *Journal of Climate*, 21: 4879–4886.

Jiang, Y., Wang, S., Yang, S., Dong, W., Fu, C., and Zhao, T., 2008b: Future trends of climatic belts and seasons in China. *International Journal of Climatology*, 28: 1483–1491.

Kendall, M. G., and Gibbons, J. D., 1981: *Rank Correlation Methods.* Fifth edition. London: Edward Arnold.

Liu, X. D., and Chen, B. D., 2000: Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, 20: 1729–1742.

Li, S. C., and Tang, H. Y., 2000: Analyses of monthly mean temperature and anomalous distribution over the Qinghai-Xizang Plateau in winter and summer. *Plateau Meteorology*, 19: 520–539.

Li, L., Zhu, X. D., Qin, N. S., Wang, Z. Y., Wang, Q. C., and Zhou, L. S., 2003: Temperature variations and temperature anomaly patterns in the Tibetan Plateau. *Plateau Meteorology*, 22: 524–531.

Li, L., Li, F. X., Zhu, X. D., and Zhang, H. D., 2007: Study of the evolution rule of extreme climatic events over the source of the Three Rivers. *Journal of Natural Resources*, 24: 656–663.

Li, Y., Li, D., Yang, S., Liu, C., Zhong, A., and Li, Y., 2010: Characteristics of the precipitation over the eastern edge of the Tibetan Plateau. *Meteorology and Atmospheric Physics*, 106: 49–56.

Liu, X. D., Yin, Z. Y., Shao, X. M., and Qin, N. S., 2006: 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. *Journal of Geophysical Research*, 111: article D19109.

Liu, Y. M., Bao, Q., Duan, A. M., Qian, Z. A., and Wu, G. X., 2007: Recent progress in the impact of the Tibetan Plateau on climate in China. *Advances in Atmospheric Sciences*, 24: 1060–1076.

Meng, M., Ni, J., and Zhang, Z., 2004: Geographical and ecological aridity of and assessment of its applications. *Botanical Ecology*, 28: 853–861.

Murakami, T., 1987: Effects of Tibetan Plateau. *In* Chang, C.-P., and Krishnamurti, T. (eds.), *Monsoon Meteorology*. New York: Oxford University Press, 235–270.

Nan, S., Zhao, P., Yang, S., and Chen, J., 2009: Springtime tropospheric temperature over the Tibetan Plateau and evolutions of the tropical Pacific SST. *Journal of Geophysical Research*, 114: article D10104, doi:10.1029/2008JD011559.

Niu, T., Liu, H. L., Song, Y., and Chen, L. X., 2005: Study of the decade change of climate shift from warm-dry to warm-wet period over the Tibetan Plateau. *Journal of Applied Meteorological Science*, 16: 763–771.

Qian, W., and Qin, A., 2008: Precipitation division and climate shift in China from 1960 to 2000. *Theoretical and Applied Climatology*, 93: 1–17.

Qian, W., Lin, X., Zhu, Y., Xu, Y., and Fu, J., 2007: Climatic regime shift and decadal anomalous events in China. *Climatic Change*, 84: 167–189.

Quality and Technology Administration in Qinghai Province, 2001: *Local Meteorological Disaster Standard in Qinghai*. Xining, Qinghai, China: 9–10.

Sato, M., Kato, T., and Tang, Y., 2009: Temperature controls ecosystem CO_2 exchange of an alpine meadow on the northern Tibetan Plateau. *Global Change Biology*, 15: 221–228.

Sato, T., and Kimura, F., 2007: How does the Tibetan Plateau affect the transition of Indian monsoon rainfall? *Monthly Weather Review*, 135: 2006–2015.

Shi, Y. F., 1995: *Impact of Climate Change on Water Resource over Northwest China*. Jinan, China: Shandong Scientific Press, 127–141.

Tang, M. C., Cheng, G. D., and Lin, Z. Y., 1998: *Contemporary Climatic Variations over the Qinghai-Xizang Plateau and Their Influences on Environments*. Guangzhou, China: Guangdong Science & Technology Press.

Terao, T., 1999: Relationships between the quasi-stationary Rossby waves in the subtropical jet and the mass and heat transport in the northern periphery of the Tibetan High. *Journal of Meteorological Society of Japan*, 77: 1271–1286.

Trenberth, K. E., and Chen, S. C., 1988: Planetary-waves kinematically forced by Himalayan orography. *Journal of Atmospheric Sciences*, 45: 2934–2948.

Wang, L. N., Zheng, Q. L., and Song, Q. L., 2002: Influences of surface conditions over the Tibetan Plateau on China summer circulation. *Journal of Nanjing Institute of Meteorology*, 25: 186–191.

Wu, G. X., Liu, Y. M., Wang, T. M., and coauthors., 2007: The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *Journal of Hydrometeorology*, 4: 770–789.

Xiao, X. C., and Li, T. D., 2000: *Tectonic Evolution and Uplift of the Qinghai-Xizang Plateau*. Guangzhou, China: Guangdong Science & Technology Press, 77–80.

Xu, Y., Zhao, Z. C., and Li, D. L., 2005: The simulated result analyses of climate changes over the Qinghai-Xizang Plateau and along the railway in the coming 50 years. *Plateau Meteorology*, 24: 700–707.

Yanai, M., and Wu, G. Q., 2006: Effects of the Tibetan Plateau. *In* Wang, B. (ed.), *The Asian Monsoon*. Chichester, U.K.: Praxis Publishing, 513–549.

Yang, S., Lau, K.-M., Yoo, S.-H., Kinter, J. L., Miyakoda, K., and Ho, C.-H., 2004: Upstream subtropical signals preceding the Asian summer monsoon circulation. *Journal of Climate*, 17: 4213–4229.

Yao, T. D., Liu, X. D., Wang, N. L., and Liu, Q. M., 2000: Amplitude of climatic changes in the Qinghai-Tibetan Plateau. *Chinese Science Bulletin*, 45: 98–105.

You, Q. L., Kang, S. C., Aguilar, E., and Yan, Y. P., 2008: Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961–2005. *Journal of Geophysical Research*, 113: article D07101.

Zhai, P. M., and Pan, X. H., 2003: Change in extreme temperature and precipitation over northern China during the second half of the 20th century. *Acta Geographica Sinica*, 58(Suppl.): 1–10.

Zhang, J. C., Zhang, X. G., and Xu, X. J., 1983: The drought and flood in recent 500 years in China. *Meteorological Science and Technology*, 4: 23–28.

Zhang, P. Q., Yang, S., and Kousky, V. E., 2005: South Asian High and Asian-Pacific-American climate teleconnection. *Advances in Atmospheric Sciences*, 22: 915–923.

Zhao, P., Yang, S., and Yu, R., 2010: Long-term changes in the rainfall over eastern China and associated atmospheric circulation under the global warming scenario. *Journal of Climate*, 23: 1544–1562.

Zhou, H. K., Zhou, L., Zhao, X. Q., Liu, W., Li, Y. N., Gu, S., and Zhou, X. M., 2006: Stability of alpine meadow ecosystem on the Qinghai-Tibetan Plateau. *Chinese Science Bulletin*, 51: 320–327.

MS accepted June 2010