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Recent changes in daily extremes of temperature and precipitation over the western Tibetan Plateau, 1973–2011

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ABSTRACT

Climate extremes in the Tibetan Plateau may cause serious regional and global consequences, but observation-based research over the western Tibetan Plateau is scarce. In this paper, recent changes in extremes of temperature and precipitation over the western Tibetan Plateau from 1973 to 2011 are investigated. A total of 24 indices that represent extreme climate events are selected and calculated by using daily maximum and minimum temperature and precipitation data. Results demonstrate that most cold-related indices of temperature extremes (frost and ice days, cool nights and cool days, and cold spell duration indicators) show a significant decrease, and that both the coldest night and coldest day have increased during the study period. Warm-related indices of temperature extremes such as summer days, the warmest night and the warmest day, warm nights and warm days, and warm spell duration indicators all have increased. The diurnal temperature ranges show a decreasing trend with statistical significance, whereas growing season lengths have increased significantly. The change trends of precipitation extremes are nonsignificant. Nonsignificant increasing trends are detected for most indices including annual total wet-day precipitation, maximum 1-day and 5-day precipitation, very wet and extremely wet day precipitation, and consecutive wet days. However, nonsignificant decreasing trends are found for the number of heavy precipitation days, consecutive dry days and simple daily intensity index.

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1. Introduction

Previous studies have detected the widespread changes in temperature and precipitation extremes during the past several decades (Alexander et al., 2006). As for the high-altitude areas with glaciers and perennial snow cover, the frequent climate extreme events may cause profound consequences (Koboltschnig et al., 2009). Investigations at European alpine glaciers indicate that cryosphere change is related to the great heat waves, because extreme temperature events may accelerate glacier shrinkage, snow melt, and runoff generation (Zappa and Kan, 2007; Hughes, 2008). Precipitation extremes in high-altitude areas can aggravate snow damage and subsequent potential fluvial flood (Fowler and Wilby, 2010).

The high-altitude Tibetan Plateau, with adjacent mountain ranges, plays an important role in regional and global environmental evolution (Immerzeel et al., 2010; Kang et al., 2010). Long-term meteorological observation evidences that the regional air temperature has increased significantly during the past half century (Liu and Chen, 2000; Niu et al., 2004), and several ice cores (Yao et al., 2006; Kang et al., 2007) and tree ring records (Xu et al., 2011) also confirm the meteorological records. According to previous studies (You et al., 2008a, 2008b), temperature indices have significantly changed at most stations over the middle and eastern Tibetan Plateau during 1961–2005.

However, due to the arctic–alpine environment and limited population, the spatial distribution of meteorological stations is uneven and sparse over the western Tibetan Plateau (Liu and Chen, 2000; Niu et al., 2004; Qin et al., 2009). Although more automatic observation stations have established in the past five years over the western Tibetan Plateau, the stations with long-term data in the national meteorological network are still sparse. Therefore, previous studies only focus on the middle and eastern Tibetan Plateau (You et al., 2008a, 2008b; Li et al., 2012) to avoid the impact of uneven spatial distribution, and the areas at the western Tibetan Plateau are usually excluded and even ignored because of the relatively short observation period (Liu et al., 2005; You et al., 2011). The weather pattern over such a wide plateau is spatially diverse, and more detailed analysis for the western Tibetan Plateau is needed.

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In order to research the changes in frequency, intensity and duration of climate extremes over the western Tibetan Plateau in the past decades, the long-term daily meteorological data available is collected. Some widely-applied climate indices are selected, and changes in temperature and precipitation extremes over the western Tibetan Plateau are presented in this paper.

2. Data and methods

2.1. Data sources

The observed meteorological data, including daily maximum temperature, minimum temperature and precipitation, was acquired from the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). The Tibetan Plateau within China's boundary covers an area of 2572.4×10^3 km^2, stretching for 2945 km from east (104°46′59″E) to west (73°18′52″E), and 1532 km from south (26°00′12″N) to north (39°46′50″N) (Zhang et al., 2002). In the meteorological observation network of China (including national reference climatological stations and national basic meteorological observing stations), there are only four stations, the altitude of which is above 3000 m in the western Tibetan Plateau (Fig. 1 and Table 1). According to the administrative division of China, most selected stations belong to the Ngari Prefecture, Tibetan Autonomous Region, with the exception of Taxkorgan in the Kashi (Kaxgar) Prefecture, Xinjiang Uygur Autonomous Region.

Table 1
List of selected stations with latitude, longitude, altitude and annual mean temperature and precipitation from 1973 to 2011.

Station name	Latitude (N)	Longitude (E)	Altitude (m)	Temperature (°C)	Precipitation (mm)
Taxkorgan	37°46′	75°14′	3090.1	3.7	76.8
Sênggêzangbo (Shiquanhe)	32°30′	80°05′	4278.6	0.8	69.7
Gêrzê	32°09′	84°25′	4414.9	0.2	173.8
Burang	30°17′	81°15′	3900	3.5	154.2

2.2. Quality control and homogeneity

Data quality control is a prerequisite for subsequent indices calculations. A series of control methods were employed and the errors were corrected by the National Meteorological Information Center of China Meteorological Administration (Li and Xiong, 2004; Wang, 2004). Subsequently a simple data quality control was operated in this study with the software RClimDex V1 (obtainable from http://cccma.seos.uvic.ca/ETCCDI/software.shtml) developed by Zhang and Yang (2004). The program can replace all the missing or unreasonable values (i.e. daily precipitation amounts below 0 mm, maximum temperature less than minimum temperature) into an internal format of NA (not available) that the software recognizes. In addition, the potential outliers for temperature (daily values outside a user-defined interval) have to be manually validated and corrected. In this study, the threshold is defined as the mean plus/minus 5 times standard deviations, according to previous studies (Rusticucci and Barrucand, 2004; Haylock et al., 2008; Croitoru and Piticar, 2012).

Data homogeneity was tested by the software RHtest V3 (obtainable from http://cccma.seos.uvic.ca/ETCCDI/software.shtml) developed by Wang (2008a, 2008b) and Feng. Possible single or multiple changepoints in a time series can be detected in the program, and confirmed step changes can be adjusted (Vincent et al., 2011). Once a possible change is identified, the metadata (including documented station relocation and instrument update) should be checked to seek any valid explanation. In this study, there is no direct relationship between the year of data inhomogeneity and metadata. The adjustment is not attempted for any stations.

2.3. Indices calculations

A total of 24 extreme climate indices are selected in this paper (Tables 2 and 3), which are considered to be core indices and recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (http://cccma.seos.uvic.ca/ETCCDI/). During the past decade, these indices were widely applied to assess the changes in daily extremes of temperature and precipitation in different regions (Klein Tank et al., 2006; New et al., 2006; Vincent et al., 2011; Revadekar et al., 2012). All the indices were calculated by RClimDex V1. Some indices, including the number of tropical nights (daily minimum temperature > 25 °C), are not relevant to this region and have not been calculated. Finally, 15 temperature indices and 9 precipitation indices were selected. According to their definitions, the temperature indices are classified into three types, that is, cold-related indices (FD0, ID0, TNn, TXn, TN10p, TX10p and CSDI), warm-related indices (SU25, TNx, TXx, TN90p, TX90p and WSDI) and variability indices (DTR and GSL).

Table 2
Definitions of the temperature indices used in this study.

Index	Descriptive name	Definitions	Units
FD0	Frost days	Annual count when TN (daily minimum temperature) < 0 °C	days
ID0	Ice days	Annual count when TX (daily maximum temperature) < 0 °C	days
SU25	Summer days	Annual count when TX > 25 °C	days
TNn	Coldest night	Annual lowest TN	°C
TXn	Coldest day	Annual lowest TX	°C
TNx	Warmest night	Annual highest TN	°C
TXx	Warmest day	Annual highest TX	°C
TN10p	Cool nights	Days when TN < 10th percentile of 1973–2011	days
TX10p	Cool days	Days when TX < 10th percentile of 1973–2011	days
TN90p	Warm nights	Days when TN > 90th percentile of 1973–2011	days
TX90p	Warm days	Days when TX > 90th percentile of 1973–2011	days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
GSL	Growing season length	Annual count between first span after 1st January of at least 6 days with TG (daily mean temperature) > 5 °C and first span after 1st July of 6 days with TG < 5 °C	days

Table 3
Definitions of the precipitation indices used in this study.

Index	Descriptive name	Definitions	Units
PRCPTOT	Annual total wet-day precipitation	Annual total precipitation of days with PR (daily precipitation) ≥ 1 mm	mm
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm
R95p	Very wet day precipitation	Annual total precipitation when PR > 95th percentile of days with PR ≥ 1 mm of 1973–2011	mm

(continued on next page)

Table 3 (*continued*)

Index	Descriptive name	Definitions	Units
R99p	Extremely wet day precipitation	Annual total precipitation when PR > 99th percentile of days with PR ≥ 1 mm of 1973–2011	mm
R10 mm	Number of heavy precipitation days	Annual count of days when PR ≥ 10 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with PR < 1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with PR ≥ 1 mm	days
SDII	Simple daily intensity index	Average daily precipitation when PR ≥ 1 mm	mm/day

The ordinary least squares regression was employed to calculate the linear trends for indices, which are widely applied in extreme temperature and precipitation studies (Rahimzadeh et al., 2009; Kruger and Sekele, 2012; Revadekar et al., 2012). A trend is considered to be statistically significant if it is significant at the 0.05 level using a two-tailed *t*-test. Regional annual series for indices were calculated as an arithmetic mean of values at four stations over the western Tibetan Plateau.

3. Results

3.1. Changes in temperature extremes

Fig. 2 shows regional annual series of cold-related indices of temperature extremes over the western Tibetan Plateau, and the linear trends for each individual station are demonstrated in Table 4 and Fig. 3. Frost days (FD0) and ice days (ID0), have decreased by 5.687 and 7.736 days/decade during the study period, respectively, and most stations have significantly decreasing trends respectively. Coldest night (TNn) and coldest day (TXn) have increased by 0.632 and 0.666 K/decade, respectively, with obvious fluctuations during the study period, and the regional trend of TXn is statistically significant. There is only one station that can pass the significant test at the 0.05 level for TNn and TXn, respectively. The linear trend for cool nights (TN10p) and cool days (TX10p) are −4.924 and −2.842 days/decade, respectively, and all stations exhibit the significantly negative trends. In most cases, the trend magnitudes of TN10p and TX10p are generally similar to those reported in the surrounding regions (Table 5). For the cold spell duration indicator (CSDI), the linear trend is −2.554 days/decade and the value fluctuation becomes more and more feeble gradually during the study period, while CSDI for each station shows different magnitudes ranging from −0.802 to −6.589 days/decade.

Table 4
Linear trends in temperature indices in different stations over the western Tibetan Plateau from 1973 to 2011.

Index		Unit of linear trend	Station name			
			Taxkorgan	Sênggêzangbo	Gêrzê	Burang
Cold-related indices	FD0	days/decade	**−4.063**	**−7.186**	**−7.291**	**−4.206**
	ID0	days/decade	−4.370	**−9.854**	**−8.079**	**−8.642**
	TNn	K/decade	−0.043	0.533	**1.407**	0.629
	TXn	K/decade	0.440	0.803	0.623	**0.797**
	TN10p	days/decade	**−2.454**	**−7.658**	**−6.190**	**−3.393**
	TX10p	days/decade	**−2.140**	**−3.479**	**−2.711**	**−3.036**
	CSDI	days/decade	−0.802	**−6.589**	−1.168	−1.658
Warm-related indices	SU25	days/decade	0.462	**0.860**	0.312	0.049
	TNx	K/decade	−0.021	**0.486**	**0.684**	**0.360**
	TXx	K/decade	−0.166	**0.530**	0.068	0.161
	TN90p	days/decade	**2.044**	**4.601**	**4.782**	**4.572**
	TX90p	days/decade	**2.694**	**4.382**	**2.929**	**3.710**
	WSDI	days/decade	**3.073**	**4.275**	**2.672**	**3.219**
Variability indices	DTR	K/decade	−0.029	**−0.305**	**−0.476**	−0.004
	GSL	days/decade	2.800	**6.134**	**3.988**	**4.478**

Note: Trends marked in bold are statistically significant at the 0.05 level.

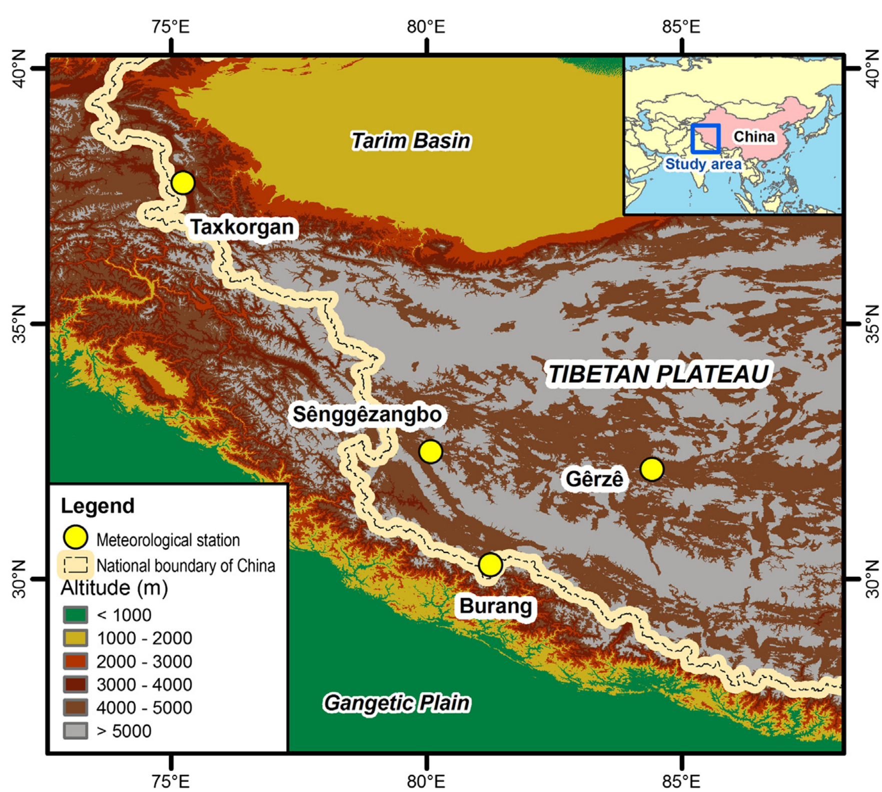

Fig. 1. Location of observation stations over the western Tibetan Plateau.

Table 5
Trends of temperature and precipitation indices around the western Tibetan Plateau.

Region and study period	Trend of temperature indices (days/decade)				Trend of precipitation indices (mm/decade)				Sources
	TN10p	TX10p	TN90p	TX90p	RX1day	RX5day	R95p	R99p	
Western Tibetan Plateau (1973–2011)	**−4.92**	**−2.84**	**4.00**	**3.43**	0.37	1.25	0.48	0.41	This study
Middle and eastern Tibetan Plateau (1961–2005)	**−2.38**	**−0.85**	**2.54**	**1.26**	0.27	−0.08	1.28	1.09	You et al., 2008a
Hengduan Mts., Eastern Tibetan Plateau (1961–2008)	**−0.37**	−0.07	**0.33**	**0.18**	0.05	−0.003	0.43	0.28	Ning et al., 2012
Sichuan Basin, SW China (1961–2008)	**−0.33**	−0.09	**0.25**	**0.22**	0.04	0.06	−0.01	0.04	Li, 2011
Yunnan-Guizhou Plateau, SW China (1961–2008)	**−0.35**	−0.08	**0.36**	**0.15**	**0.05**	0.006	0.04	**0.05**	Li, 2011
SW China (1961–2008)	**−0.37**	**−0.13**	**0.36**	**0.22**	**0.05**	0.03	0.04	**0.05**	Li et al., 2012
Xinjiang, NW China (1960–2009)	**−6.57**	**−2.6**	**6.23**	**3.59**	**0.79**	**0.85**	**6.28**	**3.26**	B. Wang et al., 2012
NW China (1960–2003)	**−0.93**	**−2.36**	**2.10**	**1.25**	0.41	–	1.64	–	H. Wang et al., 2012
Central and South Asia (1961–2000)	**−5.70**	**−2.60**	**6.86**	**4.72**	1.02	1.26	**6.46**	3.01	Klein Tank et al., 2006

Note: Trends marked in bold are statistically significant at the 0.05 level.

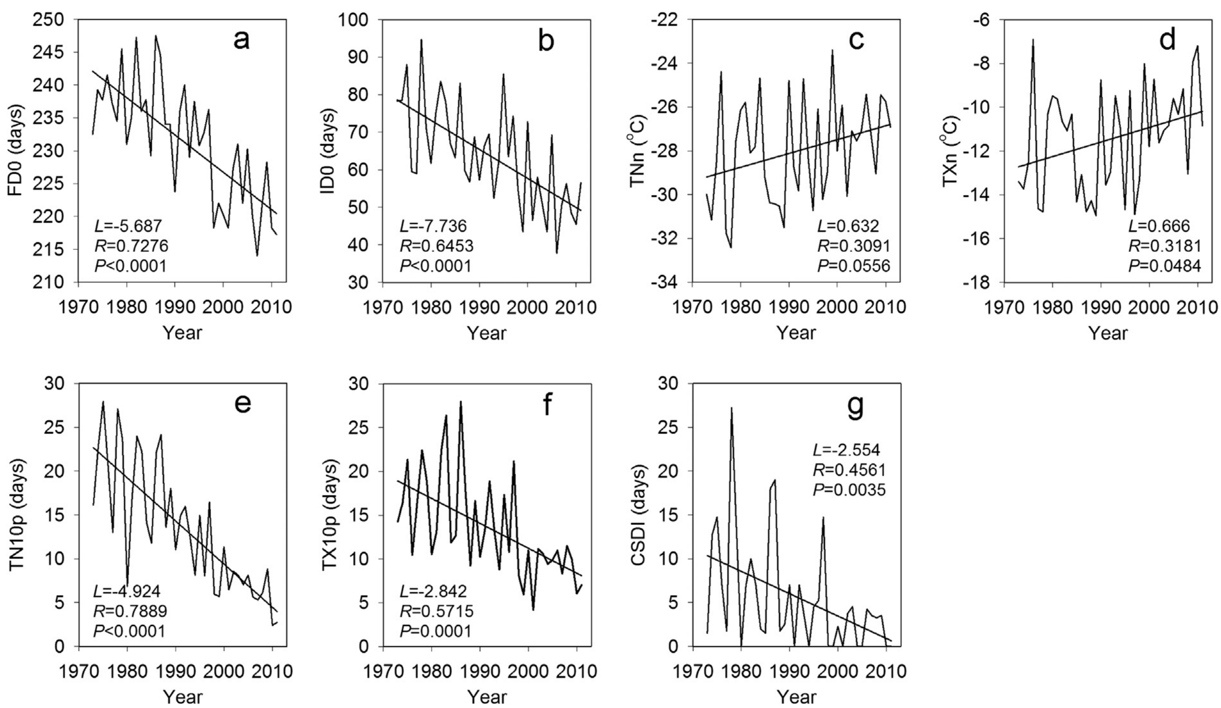

Fig. 2. Changes in cold-related indices of temperature extremes over the western Tibetan Plateau from 1973 to 2011. Linear trends are abbreviated as *L*.

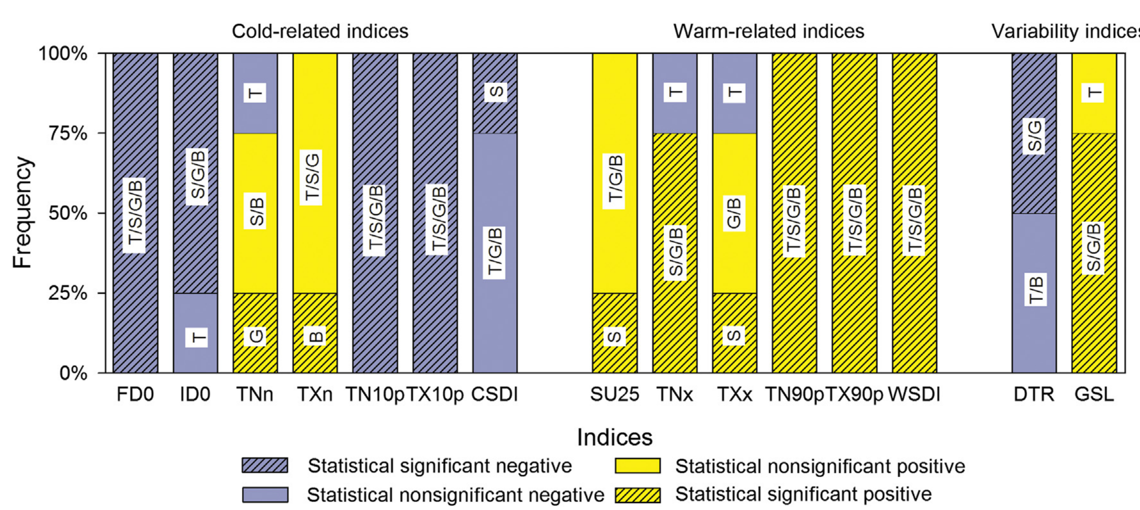

Fig. 3. Frequency of trend types for temperature indices at different stations. Abbreviated T, S, G and B in the bars mean Taxkorgan, Sênggêzangbo, Gêrzê and Burang, respectively.

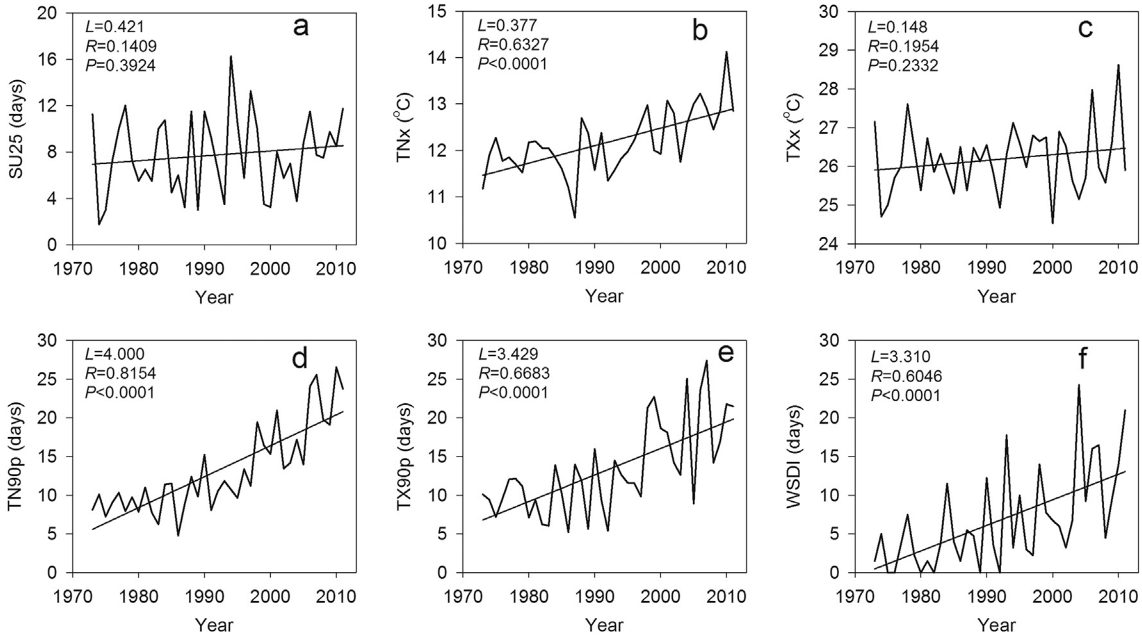

Fig. 4. Changes in warm-related indices of temperature extremes over the western Tibetan Plateau from 1973 to 2011. Linear trends are abbreviated as *L*.

Warm-related indices of temperature extremes generally show positive trends (Fig. 4). Summer days (SU25) have increased by 0.421 days/decade, and the trends at different stations range from 0.049 days/decade (Burang) to 0.860 days/decade (Sênggêzangbo) (Table 4 and Fig. 3). The warmest night (TNx) has significantly increased by 0.377 K/decade and the warmest day (TXx) shows a relatively lower trend of 0.148 K/decade. For warm nights (TN90p), warm days (TX90p) and warm spell duration indicator (WSDI), regionally averaged trends are 4.000, 3.429 and 3.310 days/decade, respectively, in the study area, and similar pattern can be found in indices for each station. These patterns of TN90p and TX90p are similar to the other researches around the study area (Table 5).

Changes in diurnal temperature range (DTR) and growing season length (GSL) are shown in Fig. 5. Linear trends for the two indices are −0.203 K/decade and 4.350 days/decade, respectively, with statistical significance at the 0.05 level. For DTR, the negative trends can be found at all stations (Table 4 and Fig. 3). On the contrary, for GSL, the trends range from 2.800 days/decade (Taxkorgan) to 6.134 days/decade (Sênggêzangbo), and the trends at 75% stations can pass the significant test ($p < 0.05$).

3.2. Changes in precipitation extremes

The regional mean series of precipitation extremes are demonstrated in Fig. 6. All the linear trends for each index are not statistically significant, and most indices fluctuate ambiguously during the study period. Annual total wet-day precipitation (PRCPTOT) has increased by 0.472 mm/decade during the study period. The maximum 1-day (RX1day) and 5-day (RX5day) precipitations show increasing trends of 0.366 and 1.249 mm/decade, respectively, and they are all statistically nonsignificant. The increments for very wet (R95p) and extremely wet (R99p) day precipitation are also limited during the past decades, and the linear trends are only 0.482 and 0.412 mm/decade, respectively. The number of heavy precipitation days (R10 mm) in the study area has decreased slightly by −0.057 days/decade. The consecutive dry (CDD) and wet (CWD) days show opposite trends of −0.521 and 0.172 days/decade, respectively. The inappreciable decrease of simple daily intensity index (SDII, −0.014 mm/day/decade) is also shown.

Linear trends for each station during the study period are in Table 6 and Fig. 7, and most of them cannot pass the significant test.

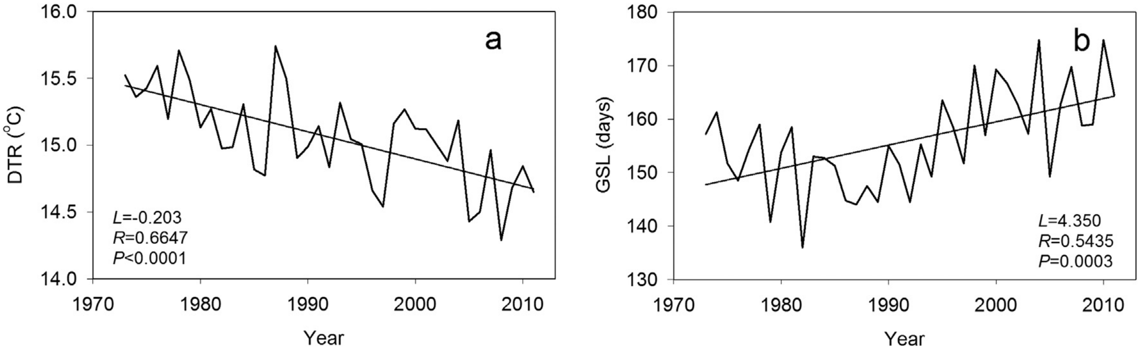

Fig. 5. Changes in variability indices of temperature extremes over western Tibetan Plateau from 1973 to 2011. Linear trends are abbreviated as *L*.

The positive and negative tendencies generally take a half proportion, respectively. For example, the annual total wet-day precipitation (PRCPTOT) at Taxkorgan and Gêrzê shows increasing trends of 7.092 mm/decade ($p < 0.05$) and 8.446 mm/decade, respectively. However, the decreasing trends at Sênggêzangbo and Burang are calculated to −4.375 and −9.275 mm/decade. The trends for other indices also show obviously internal diversity. Among all the indices at each individual station, there are only three series with significant trends: Taxkorgan for annual total wet-day precipitation (PRCPTOT), Sênggêzangbo for the number of heavy precipitation days (R10 mm) and Gêrzê for consecutive wet days (CWD).

Table 6
Linear trend in precipitation indices in different stations over the western Tibetan Plateau from 1973 to 2011.

Index	Unit of linear trend	Station name			
		Taxkorgan	Sênggêzangbo	Gêrzê	Burang
PRCPTOT	mm/decade	**7.092**	−4.375	8.446	−9.275
RX1day	mm/decade	0.384	−1.002	0.647	1.436
RX5day	mm/decade	1.493	−0.495	0.820	3.179
R95p	mm/decade	3.000	−4.427	3.593	−0.238
R99p	mm/decade	1.309	−0.024	−0.107	0.469
R10 mm	days/decade	0.186	**−0.383**	0.223	−0.255
CDD	days/decade	−4.668	−0.741	0.486	2.838
CWD	days/decade	0.156	0.239	**0.500**	−0.209
SDII	mm/days/decade	0.007	−0.273	−0.009	0.219

Note: Trends marked in bold are statistically significant at the 0.05 level.

4. Discussion and conclusions

Due to the absence of long-term observation at high-altitude inland areas, previous research in climate extremes over the western Tibetan Plateau are limited. A total of 24 climate indices, including 15 temperature and 9 precipitation indices, are selected in this study to examine the extreme events during the past decades. All the temperature indices generally show patterns consistent with a regional warming, which are also consistent with previous studies in other regions in the world (Alexander et al., 2006). Compared with related researches around the study area, the trends of temperature extremes at the western Tibetan Plateau and surroundings are similar (Table 4). However, the changes of temperature indices over the western Tibetan Plateau are generally more significant than those at the eastern junction regions such as the middle and eastern Tibetan Plateau. Compared with the above-mentioned temperature indices, trends in precipitation indices are more ambiguous during the study period, and most precipitation indices are not statistically significant. It's worth noting that, with the exception of Consecutive dry days (CDD), the other precipitation indices all exhibit increasing trends at Taxkorgan station where it is located in the northwest part of the study region, indicating that the climate transforms from drying to wetting in Northwest China. The result above is consisted with previous research (Shi et al., 2007). However, the trends of the precipitation indices at the other stations in the southern part of the study region are not the same pattern.

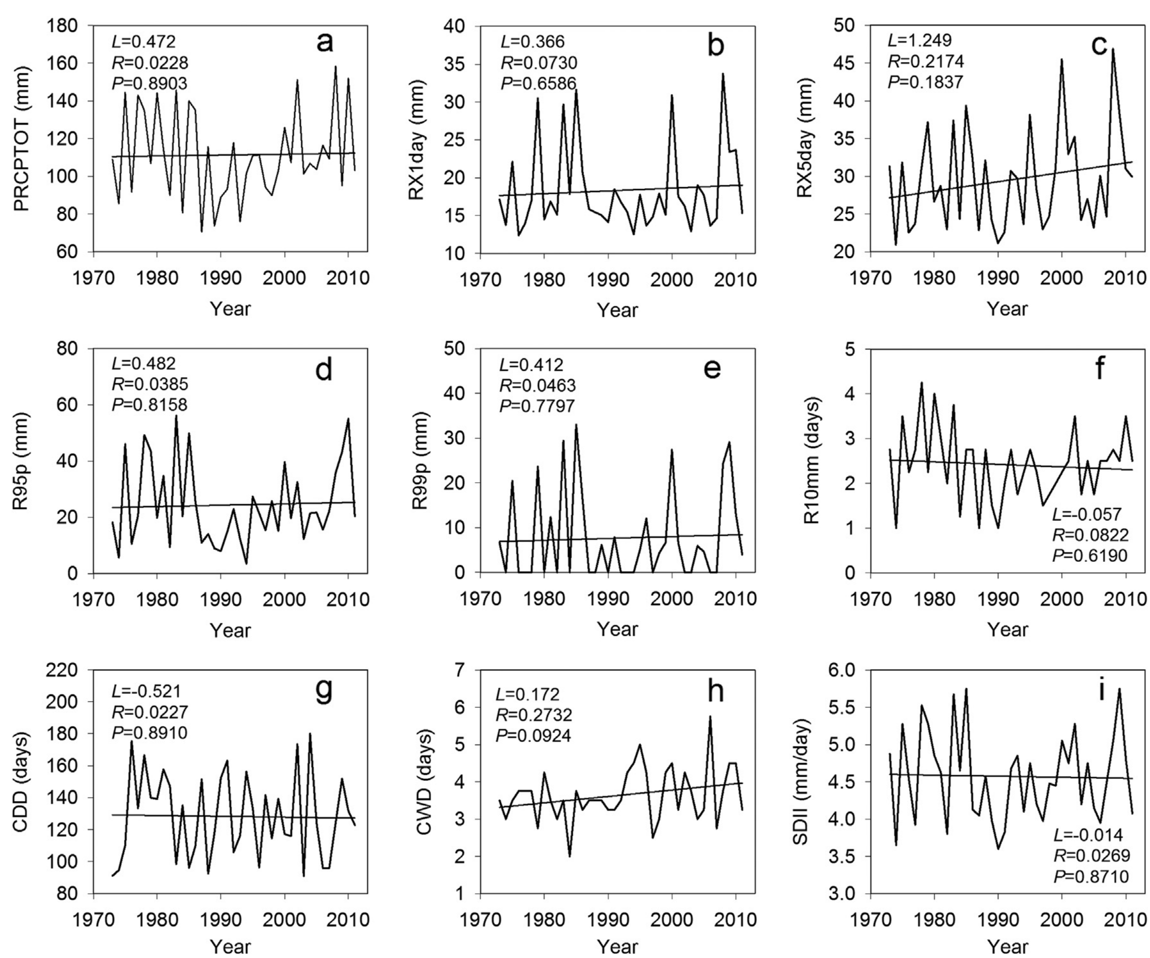

Fig. 6. Changes in precipitation indices over the western Tibetan Plateau from 1973 to 2011. Linear trends are abbreviated as *L*.

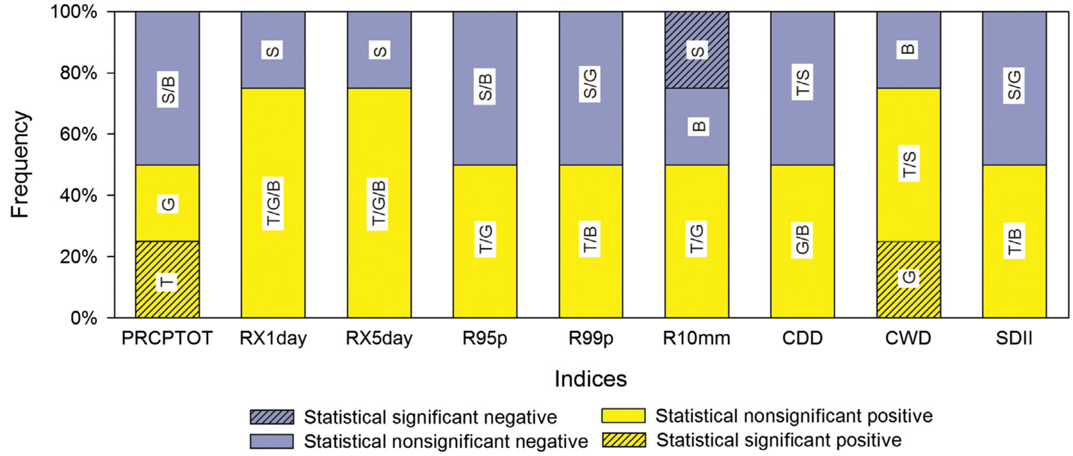

Fig. 7. Frequency of trend types for precipitation indices at different stations. Abbreviated T, S, G and B in the bars mean Taxkorgan, Sênggêzangbo, Gêrzê and Burang, respectively.

The Tibetan Plateau is considered as the water tower of Asian, and is sensitive to climate change (Immerzeel et al., 2010). Many studies demonstrate that atmospheric circulation change is an important mechanism effecting the heat and moisture transportation in this region (You et al., 2011). The extreme climate events in Tibetan Plateau are considered to be related with the summer monsoon and westerly, and the North Atlantic Oscillation is also associated with the westerly (You et al., 2008a). Other factors, such as cloud amount (Duan and Wu, 2006) and surface coverage (Wu et al., 2011), may also impact the climate extremes. Human-induced urbanization in this altitude should be very limited, due to the sparse population distributed at the arctic–alpine plateau. However, many investigations connect the recent warming and anthropogenic greenhouse gas emission (Chen et al., 2003). Therefore, more detailed studies are still needed to understand the internal regime of change in extreme climate events.

Acknowledgments

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