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Changes of Temperature and Precipitation Extremes in Hengduan Mountains, Qinghai-Tibet Plateau in 1961–2008

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Abstract: Variations and trends in extreme climate events are more sensitive to climate change than the mean values, and so have received much attention. In this study, twelve indices of temperature extremes and 11 indices of precipitation extremes at 32 meteorological stations in Hengduan Mountains were examined for the period 1961–2008. The results reveal statistically significant increases in the temperature of the warmest and coldest nights and in the frequencies of extreme warm days and nights. Decreases of the diurnal temperature range and the numbers of frost days and ice days are statistically significant. Regional averages of growing season length also display the trends consistent and significant with warming. At a large proportion of the stations, patterns of temperature extremes are consistent with warming since 1961: warming trends in minimum temperature indices are greater than those relating to maximum temperature. As the center of the Shaluli Mountain, the warming magnitudes decrease from inner to outer. Changes in precipitation extremes is low: trends are difficult to detect against the larger inter-annual and decadal-scale variability of precipitation, and only the wet day precipitation and the regional trend in consecutive dry days are significant at the 0.05 level. It can be concluded that the variation of extreme precipitation events is not obvious in the Hengduan Mountains, however, the regional trends generally decrease from the south to the north. Overall, the spatial distribution of temporal changes of all extreme climate indices in the Hengduan Mountains illustrated here reflects the climatic complexity in mountainous regions.

Keywords: precipitation; temperature; climate extremes; global warming; Hengduan Mountains, Qinghai-Tibet Plateau

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) (2007) report demonstrated that global warming has had an accelerating tendency since the 1910s. Global mean annual temperature increased by 0.74℃ during the last century, and it is predicted to increase by 1.1–6.4℃ by 2100 (IPCC, 2007). In China, the temperature increased by 0.4–0.5℃ from 1860 to 2005, and the temperature rise in winter has been higher, especially since 1951. Nineteen ′green winters′ have been experienced since 1986/1987 (China Meteorological Administration, 2006). In the context of global warming, variations and trends in extreme climate events have received much attention because they are more sensitive to climate change than mean values (Katz and Brown, 1992), and they have a considerable impact on the global hydrological cycle, economy, human health and sustainable development

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(Kunkel *et al.*, 1999; Easterling *et al.*, 2000).

Precipitation and temperature extremes have been studied in South America (Haylock *et al.*, 2006), central and southern Asia (Klein Tank *et al.*, 2006), South and West Africa (New *et al.*, 2006), the Middle East (Zhang *et al.*, 2005), central America and northern South American (Aguilar *et al.*, 2005), the Asia-Pacific region (Manton *et al.*, 2001; Griffiths *et al.*, 2005), and the Caribbean region (Peterson *et al.*, 2002). The results of those studies showed that significant widespread changes in temperature extremes are associated with warming. Changes in precipitation extremes exhibit much less spatial coherence than those of temperature extremes, making it difficult to detect regional trends. In China, Zhai *et al.* (1999) and Zhai and Pan (2003) found that mean minimum temperature increased significantly between 1951 and 1995, especially in winter in the northern China. However, the number of annual rainy days has decreased dramatically throughout China, except for the northwest (Zhai *et al.*, 2005). You *et al.* (2010) reported the consistent warming of temperature extremes. In respect of precipitation indices, the stations in the Changjiang (Yangtze) River Basin, the southeastern China and the northwestern China had the strongest positive trends, while the stations in the Huanghe (Yellow) River Basin and in the northern China had the strongest negative trends. Patterns of temperature extremes on the eastern and central Tibetan Plateau during 1961–2005 were consistent with warming, and most precipitation indices exhibited increasing trends on the southern and northern Tibetan Plateau and decreasing trends on the central Tibetan Plateau but, unlike the temperature trends, these were not statistically significant (You *et al.*, 2008). Liu *et al.* (2006; 2009) also verified the asymmetric pattern of greater warming trends in nighttime temperature as compared to daytime temperature, especially during winter and spring over the eastern and central Tibetan Plateau during 1961–2003. Li *et al.* (2012a) have also confirmred the significant warming of daily temperature extremes. Generally speaking, because of the influence of moisture sources, transport directions, macroclimate background and topography, precipitation variations are more complexly related to regional features than those of temperature (Du and Ma, 2004; Zhou *et al.*, 2005; 2009; Ge *et al.*, 2008).

At present, there have been few studies of temperature and precipitation extremes variations in the Qinghai-Tibet Plateau, primarily owing to the lack of easily available data. The aim of this paper is to investigate the changes in temperature and precipitation extremes during the period 1961–2008 in the Hengduan Mountains, and the spatial and temporal variability of the changes in temperature and precipitation extremes are also discussed, with the intent of a better understanding of the variability and changes in frequency, intensity and duration of extreme climate events.

2 Study Area

The Hengduan Mountains, in the southeastern part of the Qinghai-Tibet Plateau (24°40′–34°00′N, 96°20′–104°30′E), are the easternmost and southernmost glacial region in mainland Eurasia, with an area of 500 000 km^2 in the counties of Changdou (Tibet Autonomous Region), Aba, Ganzi, Panzhihua and Liangshan (Sichuan Province), and Lijiang, Diqing, Nujiang, Zhaotong and Dali (Yunnan Province) (Li and Su, 1996) (Fig. 1). They consist of a series of north-south oriented mountain ranges and rivers from east to west. Except for the Nujiang River, which drains into the Indian Ocean, the rivers drain into the Pacific Ocean. There are 1929 glaciers, with a total area of 1912 km^2 and a volume of 117.64 km^3 (Pu, 1994; Li *et al.*, 2009a; 2009b; 2010a; 2010b; 2011; 2012b; Yang *et al.*, 2012).

The Hengduan Mountains are located in a typical monsoonal climate region, controlled by the South Asia monsoon but also influenced by the East Asia monsoon. In addition, they are influenced by the Qinghai-Tibet Plateau monsoon and the westerlies. Correspondingly, moisture transfer is characterized by the marked seasonal changes, mainly from the westerly winds in winter and spring to the monsoonal moisture originating from the Bay of Bengal and the South China Sea in summer, and the moisture mainly obtained from the western Pacific Ocean in autumn. The monsoonal circulation in the Hengduan Mountains expands to 40°N in the beginning of August, but withdraws to 30°N in the middle ten days of October; the strength or weakness, and advance or retreat, of the monsoon often result in drought or flood extremes (Zhou *et al.*, 2005; 2009). The winter monsoon period is from December to April. May to October is the summer monsoon period, with precipitation accounting for 75%–90% of the annual precipitation. The division of the rainy and dry seasons has an important rela-

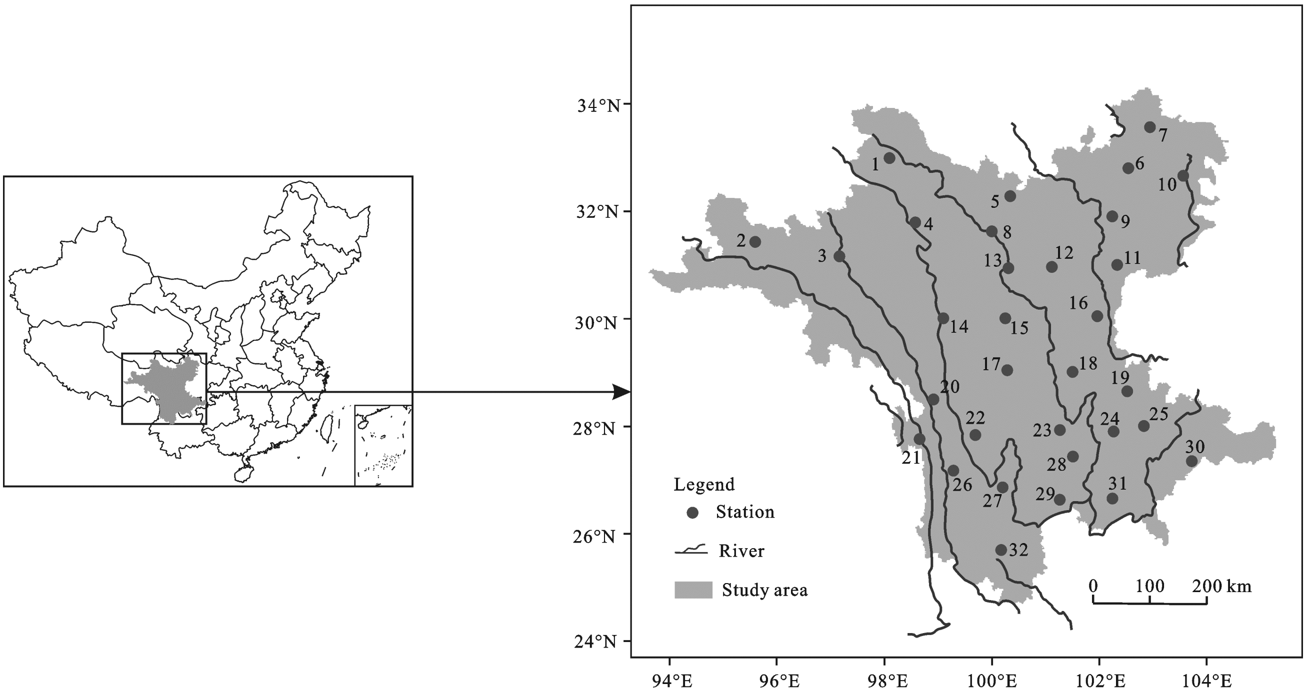


Fig. 1 Location of study area and meteorological stations

tionship with the evolution of the ecological environment.

3 Data and Methods

The study was based on meteorological data from 32 stations (Fig. 1) and analysis of indices generated by RClimDex (http://cccma.seos.uvic.ca/ETCCDI/software.shtml). The data of daily precipitation, maximum temperature and minimum temperature were provided by the National Climate Center, China Meteorological Administration (CMA) (http://www.nmic.gov.cn/). Against a background of rapid development of meteorological observations, the modern nation-wide network of weather observing stations in China began operation in the 1950s. The 32 selected stations all have data available for at least 48 years. Although most have longer records, only the period from January 1, 1961 to December 31, 2008 was analyzed, because seven stations began recording in 1960. Detailed information about the stations, which are located at altitudes between 1242 m and 4200 m, is shown in Table 1.

Data quality control is a necessary step before analysis of variations of temperature and precipitation because erroneous outliers can seriously influence trends. In this study, data quality control was performed by using the computer program RClimDex, developed and maintained by Zhang Xuebin and Yang Feng at the Climate Research Branch of the Meteorological Service of Canada. Software and documentation are available online for downloading (http://cccma.seos.uvic.ca/ETCCDI/software.shtml). In this case, three standard deviations were chosen as the threshold for a finer quality control of the data. Both for precipitation and temperature, data plots are available for visual inspections to reveal more outliers as well as a variety of problems that cause changes in the seasonal cycle or variance of the data (Aguilar *et al.*, 2005; New *et al.*, 2006). Homogeneity assessment and adjustment can be quite complex, and often requires close neighboring stations, detailed station history, and a long time series (Vincent *et al.*, 2005). Data homogeneity was assessed with the Rhtest software (http://cccma.seos.uvic.ca/ETCCDI/software.shtml), which uses a two-phase regression model to check for multiple step change points that could exit in a time series (Wang and Zhou, 2005; Zhang *et al.*, 2005).

After data quality control and homogeneity assessment, RClimDex was used to calculate climate indices from the daily data. Expert Team for Climate Change Detection and Indices (ETCCDI) has been coordinating a suite of 11 precipitation and 16 temperature indices.

Table 1 Selected 32 meteorological stations in Hengduan Mountains

Number	Station name	Longtitude	Latitude	Altitude (m)	Number	Station name	Longtitude	Latitude	Altitude (m)
1	Shiqu	98°06′E	32°59′N	4200.0	17	Daocheng	100°18′E	29°03′N	3727.7
2	Dingqing	95°36′E	31°25′N	3873.1	18	Jiulong	101°03′E	29°00′N	2987.3
3	Changdou	97°01′E	31°09′N	3306.0	19	Yuexi	102°31′E	28°39′N	1659.5
4	Dege	98°35′E	31°48′N	3184.0	20	Deqin	98°55′E	28°29′N	3319.0
5	Seda	100°20′E	30°59′N	3893.9	21	Gongshan	98°40′E	27°45′N	1583.3
6	Hongyuan	102°33′E	32°48′N	3491.6	22	Xianggelila	99°42′E	27°05′N	3276.1
7	Ruoergai	102°58′E	33°35′N	3439.6	23	Muli	101°16′E	27°56′N	2426.5
8	Ganzi	100°00′E	31°37′N	3393.5	24	Xichang	102°16′E	27°54′N	1590.9
9	Maerkang	102°14′E	31°54′N	3491.6	25	Zhaojue	102°51′E	28°00′N	2132.4
10	Songpan	103°34′E	32°39′N	2850.7	26	Weixi	99°17′E	27°01′N	2325.6
11	Xiaojin	102°21′E	31°00′N	2369.2	27	Lijiang	100°13′E	26°52′N	2392.4
12	Daofu	101°04′E	30°59′N	2957.2	28	Yanyuan	101°31′E	27°26′N	2545.0
13	Xinlong	100°19′E	30°56′N	3000.0	29	Huaping	101°16′E	26°38′N	1244.8
14	Batang	99°06′E	30°00′N	2589.2	30	Zhaotong	103°43′E	27°21′N	1949.5
15	Litang	100°16′E	30°00′N	3948.9	31	Huili	102°15′E	26°39′N	1787.3
16	Kangding	101°58′E	30°03′N	2615.7	32	Dali	100°11'E	25°42′N	1990.5

For percentile indices, a bootstrap procedure has been implemented to ensure that the percentile-based temperature indices do not have artificial jumps at the boundaries of the in-base and out-of-base period (Zhang *et al*., 2004). Some of the indices, such as the number of tropical nights, are not relevant to the studied region and were not used, leading to a final selection of 12 temperature indices (Table 2) and 11 precipitation indices (Table 3). They were calculated over the quality controlled data of the stations that passed the homogeneity assessment.

Linear trends for temperature and precipitation were calculated by using a nonparametric approach. Sen′s robust slope estimator based on Kendall′s t (Sen, 1968) was adapted and applied in a study on annual temperature and precipitation change over Canada (Zhang *et al*., 2000) and for extreme wave heights over Northern Hemisphere oceans (Wang and Swail, 2001). The regional series were converted into trends per year when describing linear regression trends, and a trend was

Table 2 Definitions of 12 temperature indices used in this study[a]

Index	Descriptive name	Definition	Unit
TXx	Warmest day	Annual highest TX	℃
TNx	Warmest night	Annual highest TN	℃
TXn	Coldest day	Annual lowest TX	℃
TNn	Coldest night	Annual lowest TN	℃
TN10	Cold night frequency	Percentage of days when TN < 10th percentile of 1961–1990	%
TX10	Cold day frequency	Percentage of days when TX < 10th percentile of 1961–1990	%
TN90	Warm night frequency	Percentage of days when TN > 90th percentile of 1961–1990	%
TX90	Warm day frequency	Percentage of days when TX > 90th percentile of 1961–1990	%
DTR	Diurnal temperature range	Annual mean difference between TX and TN	℃
ID	Ice days	Annual count when TX < 0℃	d
FD	Frost days	Annual count when TN < 0℃	d
GSL	Growing season length	Annual count between first span of at least 6 days with TG > 5℃ after winter and first span after summer of 6 days with TG <℃	d

Notes: a, all the indices are calculated by RClimDEX; TX, daily maximum temperature; TN, daily minimum temperature; TG, daily mean temperature. Indices are included for completeness but are not analyzed further in this study

Table 3 Definitions of 11 precipitation indices used in this study[a]

Index	Descriptive name	Definition	Unit
PRCPTOT	Wet day precipitation	Annual total precipitation from wet days	mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/d
CDD	Consecutive dry days	Maximum number of consecutive dry days	d
CWD	Consecutive wet days	Maximum number of consecutive wet days	d
R10mm	Number of heavy precipitation days	Annual count of days when RR ≥ 10 mm	d
R20mm	Number of heavier precipitation days	Annual count of days when RR ≥ 20 mm	d
R25mm	Number of heaviest precipitation days	Annual count of days when RR ≥ 25 mm	d
R95	Very wet day precipitation	Annual total precipitation when RR > 95th percentile of 1961–1990 daily precipitation	mm
R99	Extremely wet day precipitation	Annual total precipitation when RR > 99th percentile of 1961–1990 daily precipitation	mm
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm

Notes: a, all the indices are calculated by RClimDEX; RR, daily precipitation; a wet day is defined when RR ≥ 1 mm, and a dry day is defined when RR < 1 mm

considered to be statistically significant if it was significant at the 5% level. In order to avoid average series being dominated by those stations with higher values, the simple anomalies were standardized through division by the station standard deviation during the studied period.

In order to study the spatial distribution of linear tendency rate in daily climate extremes during 1961–2008, we employed the spline method, which has been used in many studies (Hutchinson, 1991; Hutchinson and Gessler, 1994; Thornton *et al*., 1997; Price *et al*., 2000; Yan *et al*., 2005). This method is best for varying surfaces such as elevation, water table heights, or pollution concentrations. The regularized method used with the ArcGIS software yields a smooth surface. The formula of the spline interpolator is as follows:

$$Z = \sum_{i=1}^{n} a_i R(b_i) + T(x, y) \quad (1)$$

where Z is the value of the climate constituent to be forecasted; n is the number of climate stations; a_i is a coefficient fixed by a series of linear equations; b_i is the distance from the forecasting point to the i-th point; and $R(b_i)$ and $T(x, y)$ are knot span and internal control point for non-uniform spline function, and they are calculated by:

$$R(b_i) = \frac{\frac{b^2}{4}\left\{\ln\left[\left(\frac{b}{2\pi}\right)+c-1\right]+d_2\left[k_0\left(\frac{b}{d}\right)+c+\ln\left(\frac{b}{2\pi}\right)\right]\right\}}{2\pi} \quad (2)$$

$$T(x, y) = f_1 + f_2x + f_3y \quad (3)$$

where d^2 is the weighing coefficient; b is the distance between the observation and forecasting points; k_0 is the Bessel function after revision; c is a constant; and f is the coefficient of linear equations.

4 Results and Analyses

4.1 Temperature extremes

4.1.1 Cold extremes

Except for the cold days (TX10) and the coldest day temperature (TXn), the data of other cold extremes showed the statistically warming during 1961–2008, and the regional trends for the cold nights (TN10), the coldest night temperature (TNn), the ice days (ID) and the frost days (FD) were 0.369 d/yr, 0.055℃/yr, –0.064 d/yr and –0.42 d/yr, respectively, but for TXn and TX10 are not significant at the 0.05 level (Table 4). As Fig. 2 shown, there was a slow decrease of the cold days between 1961 and 1970, an increase from 1971 to 1985 and then a drastic decline with a non-significant trend of –0.073 d/yr, while there was a continually decreasing trend for the cold nights during 1961–2008. As a non-statistically trend of 0.019℃/yr, TXn increased in the early 1960s, slowly decreased between 1965 and 1985, and increased again after 1985, whereas an increasing trend of TNn indicated rising temperature. The number of the ice days changed with fluctuations from decline in the 1960s to increase during 1970–1985 and subsequent drastic decrease, but the frost days also generally decreased through the study period.

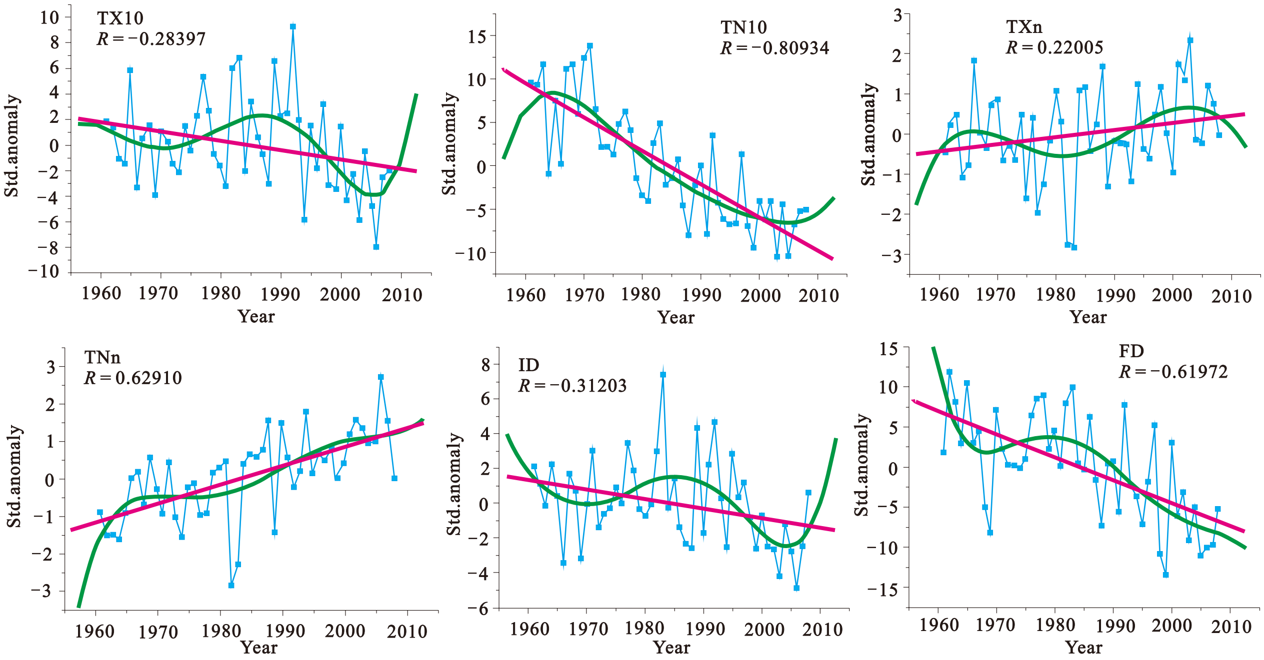
Table 4 Linear tendency rate for regional indices of temperature extremes

Index	Mean value	Range
ID (d/yr)	**–0. 064**	–0.040–0.010
FD (d/yr)	**–0.420**	–2.122–0.002
GSL (d/yr)	**0.400**	–0.002–1.181
TXx (℃/yr)	0.013	–0.042–0.075
TXn (℃/yr)	0.019	–0.033–0.062
TNx (℃/yr)	**0.016**	–0.170–0.062
TNn (℃/yr)	**0.055**	–0.140–0.128
TX10 (d/yr)	–0.073	–0.394–0.255
TX90 (d/yr)	**0.180**	–0.404–0.875
TN10 (d/yr)	**–0.369**	–0.844–0.084
TN90 (d/yr)	**0.325**	–0.033–1.036
DTR (℃/yr)	**–0.017**	–0.059–0.019

Note: Values for trends significant at the 5% level are set in bold

For TN10, about 97% of the stations have statistically significant decreasing trends, but the value is only 28% for TX10 and 50% of the stations had non-significant decreasing trends (Table 5). As shown in Fig. 3, cold nights statistically decreased more markedly in the zone roughly centered on the central-southern area between the Jinsha River and the Yalongjiang River (around the southern part of Shaluli Mountain) than in the southern part of the Hengduan Mountains, especially in the southern valleys of the Nujiang River and the Lancangjiang River and around Daliang Mountain. There was a weak decreasing trend in the southwestern and far southeastern areas of the Hengduan Mountains. The regional trend of cold days increased with smaller and nonsiginificant magnitudes particularly in the east of middle and the northeastern parts of the region, and it was a decrease in the southern Hengduan Mountains.

About 72% and 94% of the stations showed increasing trends for coldest day (TXn) and coldest night (TNn) temperature, but only 13% and 78% were statistically significant (Table 5). The significant increasing trend of coldest day temperature was roughly centered on the central section of the Lancang River and the central area between the Yalongjiang River and the Daduhe River, whereas there was a decreasing trend in the southwestern margin of the Hengduan Mountains and the southern area between the Nujiang River and the Jinsha River (Fig. 3). An statistically increasing trend of the temperature of the coldest nights characterised the Hengduan Mountains, with only four smaller areas in the western and eastern margins indicating a decreasing trend. Owing to the low latitude, 11 stations in the study area have no ice days, and only three stations showed statistically decrease (Table 5). An increasing trend of the decline of ice days from south to north in the Heng-



Line is the linear trend, and smoother line is the 5-year smoothing average

Fig. 2 Regional annual anomalies series during 1961–2008 for indices of cold extremes

Table 5 Number of stations with positive or negative trends for regional indices of temperature extremes

Index	Negative trend		Positive trend	
	Significant	Non-significant	Significant	Non-significant
ID	3 (20)	17	0 (12)	12
FD	30 (32)	2	0	0
GSL	0 (1)	1	19 (31)	12
TXx	2 (8)	6	8 (24)	16
TXn	0 (9)	9	4 (23)	19
TNx	0 (4)	4	19 (28)	9
TNn	0 (2)	2	25 (30)	5
TX10	9 (25)	16	1 (7)	6
TX90	1 (3)	2	17 (29)	12
TN10	31 (31)	0	0 (1)	0
TN90	0 (1)	1	29 (31)	2
DTR	20 (26)	6	1 (6)	5

Notes: Numbers of stations with negative and positive trends are also known in parentheses, and significant at the 0.05 level is out parentheses

duan Mountains is evident (Fig. 3). For frost days, all the stations experienced a decreasing trend, which was statistically significant at about 94% of them. The area with the greatest decrease of the number of FD was centred roughly between the Jinsha River and the Yalongjiang River in the south.

4.1.2 *Diurnal temperature range*

The results of previous studies showed that there were the increasing trends for maximum and minimum temperature, but the minimum has increased more rapidly than the maximum in recent decades (Manton *et al.*, 2001; Peterson *et al.*, 2002; Aguilar *et al.*, 2005; Griffiths *et al.*, 2005; Zhang *et al.*, 2005; Klein Tank *et al.*, 2006; New *et al.*, 2006; You *et al.*, 2008). The regional trend is –0.017℃/yr for DTR during 1961–2008 in the Hengduan Mountains, and is significant at the 0.05 level (Table 2, Fig. 4). The DTR changed from a marked increase in the 1960s to decline during 1970–1990, before increasing again after 1990 (Fig. 4). About 81% of the stations experienced a decreasing trend, with 53% of them having a statistically significant pattern (Table 5). The statistically significant decrease mainly occurred at the zone between the Jinsha River and the Yalongjiang River, and at the northeastern margin of the Hengduan Mountains, whereas there was an increasing trend in the central part of the western margin (Fig. 5).

4.1.3 *Warm extremes*

Regional averages of warm night frequency (TN90), warm day frequency (TX90), warmest night temperature

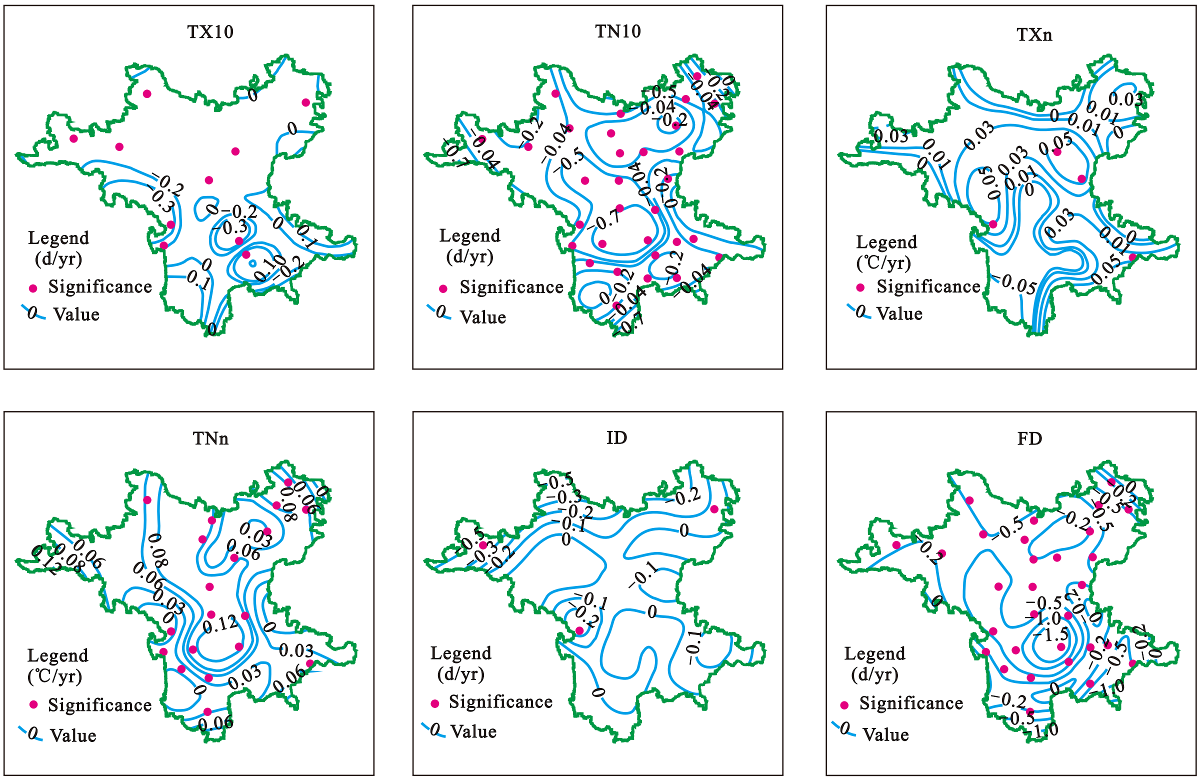
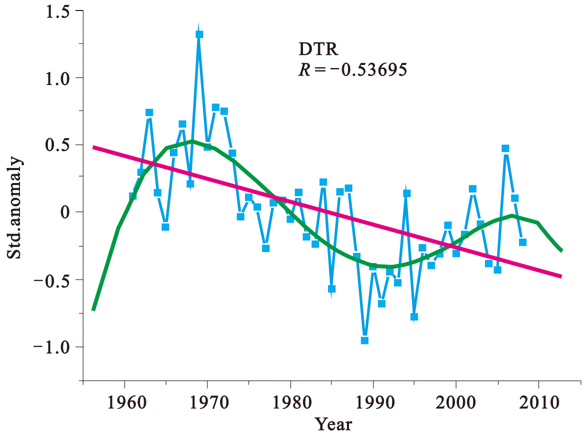


Fig. 3 Spatial distribution of linear tendency rate for indices of cold extremes



Smoother line is the 5-year smoothing average

Fig. 4 Regional annual anomalies series during 1961–2008 for DTR

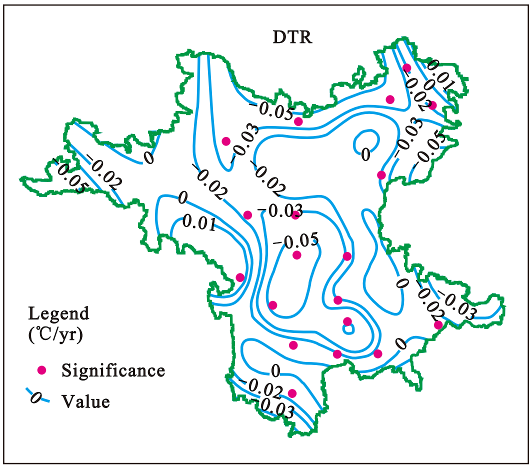
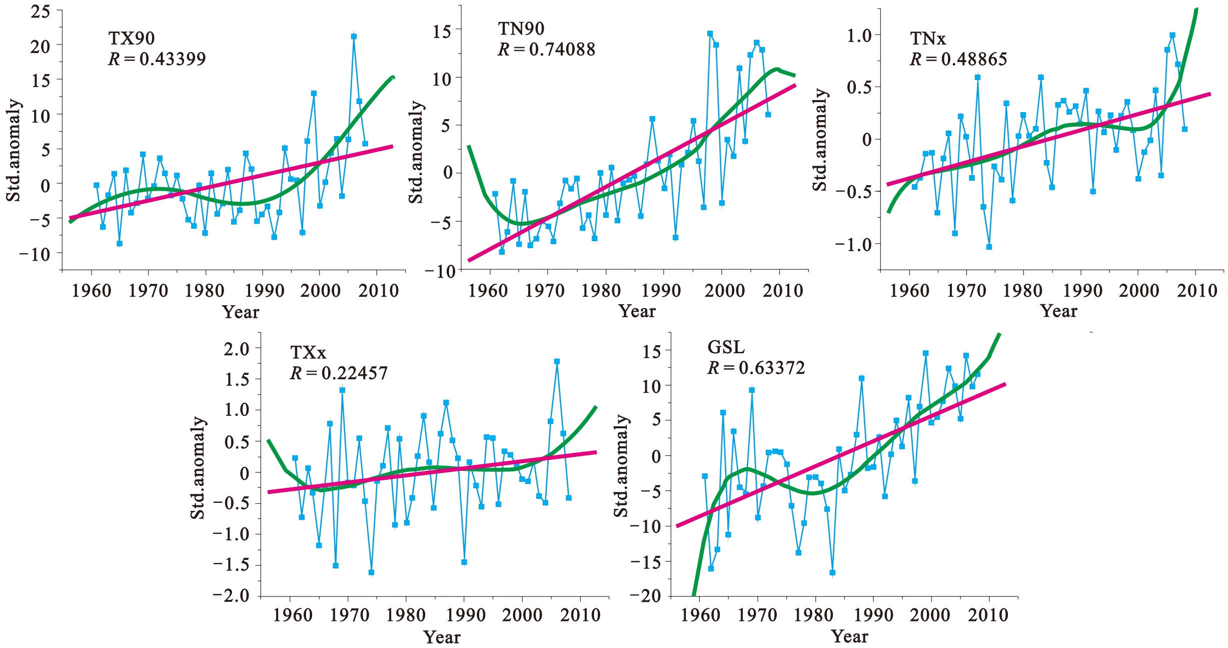


Fig. 5 Spatial distribution of linear tendency rate for DTR

(TNx) and growing season length (GSL) also display the trends consistent with warming during 1961–2008, and the regional trends were 0.325 d/yr, 0.180 d/yr, 0.016℃/yr and 0.410 d/yr significant at the 0.05 level, respectively (Table 3). TX90 increased slightly in the 1960s, decreased slightly between 1970 and 1990 and then intensified, while TN90 retained the clear increasing trend throughout the period. Although both warmest day temperature (TXx) and TNx displayed the increasing trend during 1961–2008, that of TNx was greater and intensified after 2000, and the regional trend for TXx is not significant (Fig. 6). For GSL, a considerable increase in the 1960s was followed by a slight decrease in the 1980s and then an intensification after 1990 in response to the stronger climatic warming in recent years.

About 91% (TX90) and 97% (TN90) of the stations show a statistically significant increasing trend in the percentage of days exceeding the 90th percentiles, and the statistically significant value are 53% and 91% (Table 5). Except for the southwestern and eastern margins, there is an significant increasing trend of TX90, with greater magnitudes roughly centered on the southern part of Shaluli Mountain, but at most areas of the north margin displays a decreasing trend (Fig. 7). The spatial distribution pattern of TN90 is characterized by significant increase, especially in the southern part of the Shaluli Mountain, with the most marked increases (Fig. 7). About 72% and 88% of the stations showed an increas-



Line is the linear trend and R is its correlation coefficient; smoother line is the 5-year smoothing average

Fig. 6 Regional annual anomalies series during 1961–2008 for indices of warm extremes

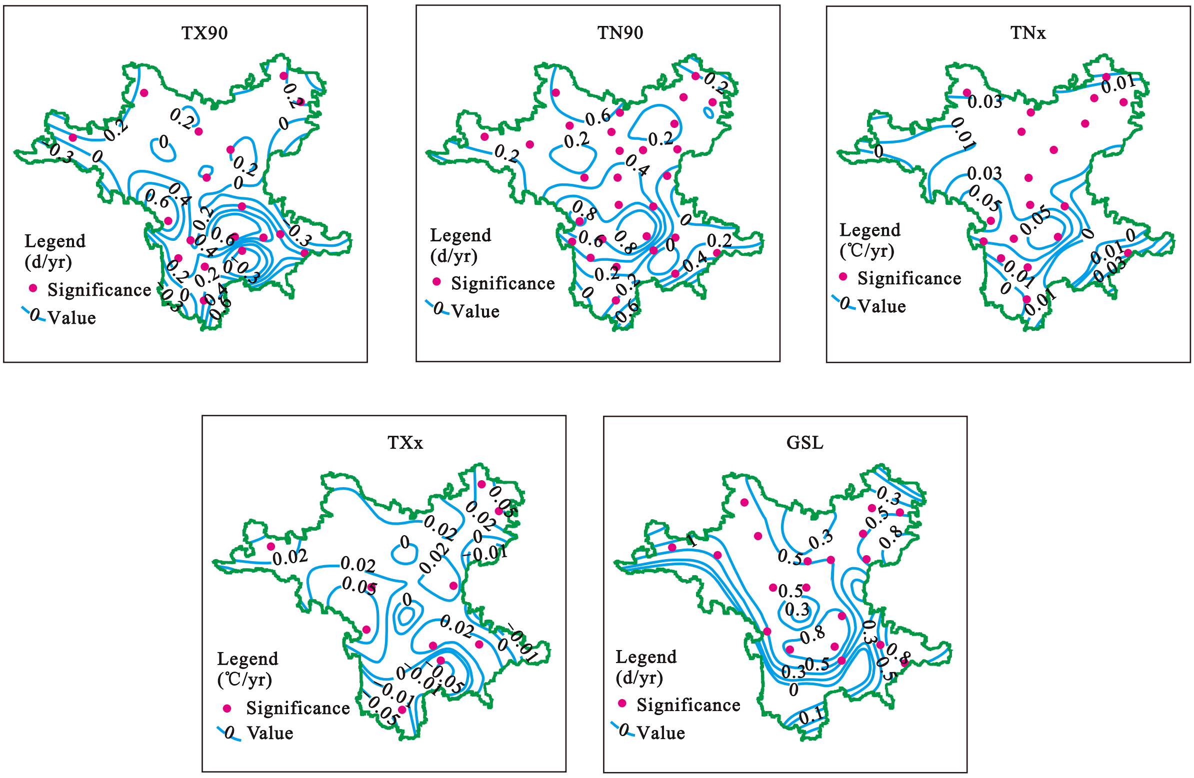


Fig. 7 Spatial distribution of linear tendency rate for indices of warm extremes

ing trend of extreme temperature (TXx and TNx), but only 25% and 60% had a statistically significant trend (Table 5). On the whole, the increasing trend of TXx increased away from the central part of the region, between the Jinsha River and the Yalongjiang River, and the significant warming manly occurred in the middle of the Hengduan Mountains (Fig. 7). The spatial pattern of TNx can be chracterized by 'two centers, two zones'. The centers are the southern area of the Shaluli Mountain and the western part of the central area of the Hengduan Mountains, around three parallel rivers (Fig. 7). The two zones with the significant increases are the northeastern margin and the middle of the Hengduan Mountains.

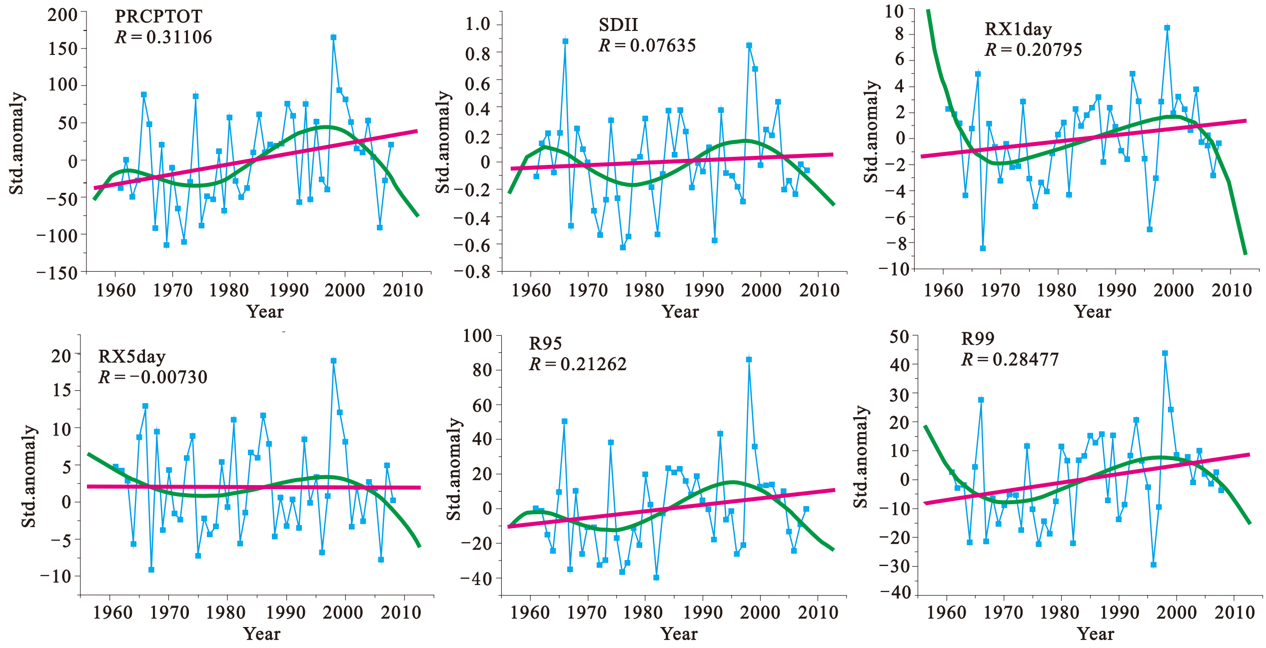
About 97% of the stations had an increasing trend, which was statistically significant at about 59% of the stations (Table 5). Four zones had significant GSL increases: the northern area between the Lancangjiang River and the Yalongjiang River, the southern part of the Shaluli Mountain, the area between the Daduhe River and the Minjiang River, and the southeastern part of the Hengduan Mountains (Fig. 7). There were two zones with relatively lower increasing trends, in the southern part of the Hengduan Mountains and the western margin of study region.

4.2 Precipitation extremes

4.2.1 PRCPTOT, SDII, RX1day, RX5day, R95 and R99

Compared with temperature extremes, the significance of changes in precipitation extremes during 1961–2008 is lower. Accordingly, the changes are difficult to detect against the larger inter-annual and decadal-scale variability of precipitation. Wet day precipitation (PRCPTOT) had a statistically significant increasing trend (1.309 mm increase per year) during 1961–2008. A slight decrease in 1961–1980 changed to an increase from 1980 to the end of the 1990s; thereafter, there was a fluctuating decrease (Fig. 8). The average precipitation on wet days (SDII) had a non-significant increasing trend (0.02 mm/yr), with similar annual variations as the wet day precipitation. Maximum 1-day precipitation (RX1day), very wet day precipitation (R95) and extremely wet day precipitation (R99) displayed non-significant increasing trends, with the changes from a decrease in the 1960s to an increase during 1970–2000 and a subsequent decrease (Fig. 8). The maximum 5-day precipitation (RX 5day) maintained a relative equilibrium, with a weak decrease over the period.

Although about 84% of the stations displayed in-



Smoother line is the 5-year smoothing average

Fig. 8 Regional annual anomalies series during 1961–2008 for PRCPTOT, SDII, RX1day, RX5day, R95 and R99

creasing trends, only 16% of them were significant at the 0.05 level (Table 6, Table 7). The spatial distribution of PRCPTOT had a regional trend, decreasing from west to east. There were two zones with a significant increasing trend, one is the west, the other is in the centre of the Hengduan Mountains. In addition, four smaller areas had decreasing trends: the northeastern, southeastern and southwestern margins, and the central border area of the northern part of the region (Fig. 9). For SDII, about half of the stations had an increasing trend and the other half a decreasing trend, but only two stations showed statistically significant increase (Table 7). The spatial distribution of SDII displayed the same characteristics (Fig. 9), but there were three centers with lower regional trends: the central zone of the Ningjing Mountain, the Jinping Mountain and the middle part of the Daduhe River.

Table 6 Linear tendency rate for regional indices of precipitation extremes

Index	Mean value	Range
RX1day (mm/yr)	0.048	–0.159–0.369
RX5day (mm/yr)	–0.003	–0.465–0.489
SDII (mm/yr)	0.002	–0.034–0.029
R10mm (d/yr)	0.032	–0.120–0.202
R20mm (d/yr)	0.013	–0.031–0.081
R25mm (d/yr)	0.013	–0.022–0.073
CDD (d/yr)	**–0.668**	–4.564–0.207
CWD (d/yr)	–0.013	–0.071–0.041
R95 (mm/yr)	0.431	–0.874–2.890
R99 (mm/yr)	0.281	–0.949–1.769
PRCPTOT (mm/yr)	**1.309**	–1.676–5.271

Note: Values for trends significant at the 5% level are set in bold

Table 7 Number of stations with positive or negative trends for regional indices of precipitation extremes

Index	Negative trend		Positive trend	
	Signifiant	Non-signifiant	Signifiant	Non-signifiant
RX1day	0 (15)	15	1 (17)	16
RX5day	0 (15)	15	1 (17)	16
SDII	0 (16)	16	2 (16)	14
R10mm	0 (8)	8	1 (24)	23
R20mm	0 (11)	11	2 (21)	19
R25mm	0 (10)	10	1 (22)	21
CDD	5 (30)	25	0 (2)	2
CWD	5 (23)	18	0 (9)	9
R95	0 (13)	13	1 (19)	18
R99	0 (11)	11	3 (21)	18
PRCPTOT	0 (5)	5	5 (27)	22

Notes: Numbers of stations with negative and positive trends are also known in parentheses, and significant at the 0.05 level is out parentheses

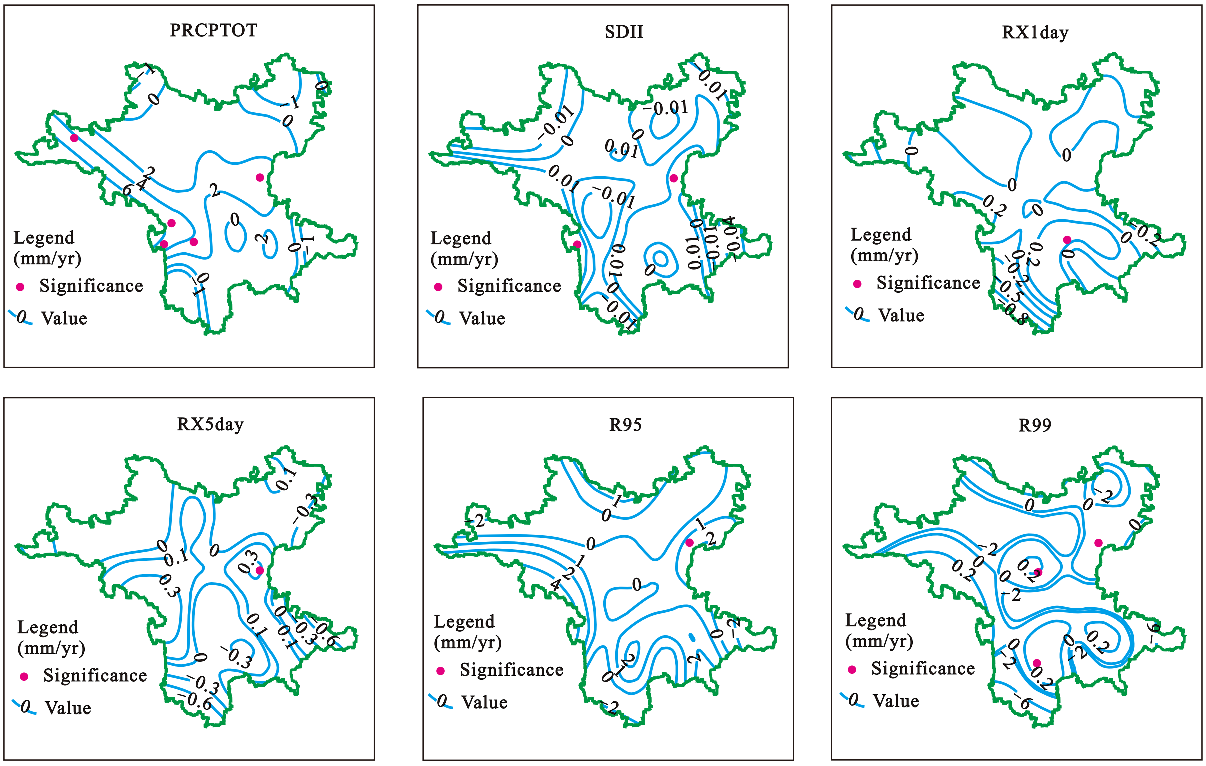


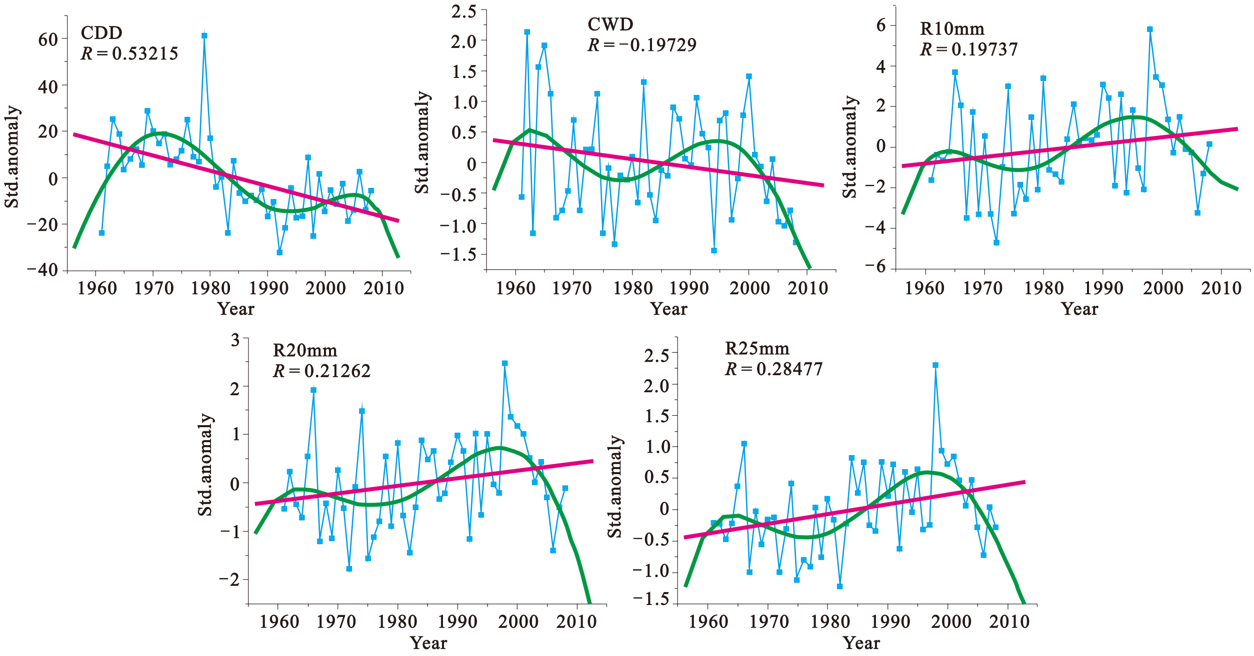
Fig. 9 Spatial distribution of linear tendency rate for PRCPTOT, SDII, RX1day, RX5day, R95 and R99

Around 53%, 59%, 66% and 53% of the stations had increasing trends RX1day, R95, R99, RX5day, respectively, but the significant increase is very few (Table 7). Except for the southwestern margin of the area, RX1day had an increasing trend centered on the southern area between the Jinsha River and the Yalongjiang River (Fig. 9). The regional trend decreased from the south to the north. The regional trend of RX5day, roughly centered on the southern area between the Jinsha River and the Yalongjiang River, increased outwards, especially in the central zone of the Hengduan Mountains, the southern area between the Yalongjiang Rvier and the Daduhe River (Fig. 9), whereas it decreased in the southwestern and eastern marginal zones. For R95, the regional trend decreased from the south to the north and from the west to the east. The southeastern, northwestern and southwestern margins had a decreasing trend, whereas there was an increasing trend in the middle and northern marginal zones of the western part of the region, and in the southern area between the Jinsha River and the Daduhe River. The spatial distribution of the regional trend of R99 also included a decrease from the south to the north, similar to that of R95, with larger increases in the southern, western and northeastern parts of the Hengduan Mountains.

4.2.2 CDD, CWD, R10mm, R20mm and R25mm

As Fig. 10 shown, consecutive dry days (CDD) had a statistically significant decrease with –0.668 d/yr in 1961–2008, although there was an increase in the 1960s and 1990s. The maximum number of consecutive wet days (CWD) in each year also exhibited decreasing trends, but of non-significant and smaller magnitude (–0.013 d/yr). The R10mm, R20mm and R25mm had a non-significant increasing trend experienced by a slightly decrease during 1960–1975 and a more marked increase from 1975 to 2000, after which there was a further decrease; the regional trends were 0.032 d/yr, 0.013 d/yr and 0.013 d/yr for R10mm, R20mm and R25mm, respectively.

Some 94% of the stations had a decreasing trend of CDD, but only five stations located at the northwest of the Hengduan Mountains and the west of middle Hengduan Mountains displayed statistically significant decrease (Table 7). The regional variations of CDD included a decreasing trend with relatively large magnitude in most of the areas west of the Yalongjiang River, east of the Minjiang River and in the southeastern margin of the Hengduan Mountains (Fig. 11). There was an increasing trend of smaller magnitude between the Yalongjiang River and the Minjiang River. At 72% of the stations, the CWD exhibited a decreasing trend, but only 16% of the stations had a statistically significant trend (Table 7). An increasing trend of CWD centered around the Yulong Mountain-Jingping Mountain, but this was not



Smoother line is the 5-year smoothing average

Fig. 10 Regional annual anomalies series during 1961–2008 for CDD, CWD, R10mm, R20mm and R25mm

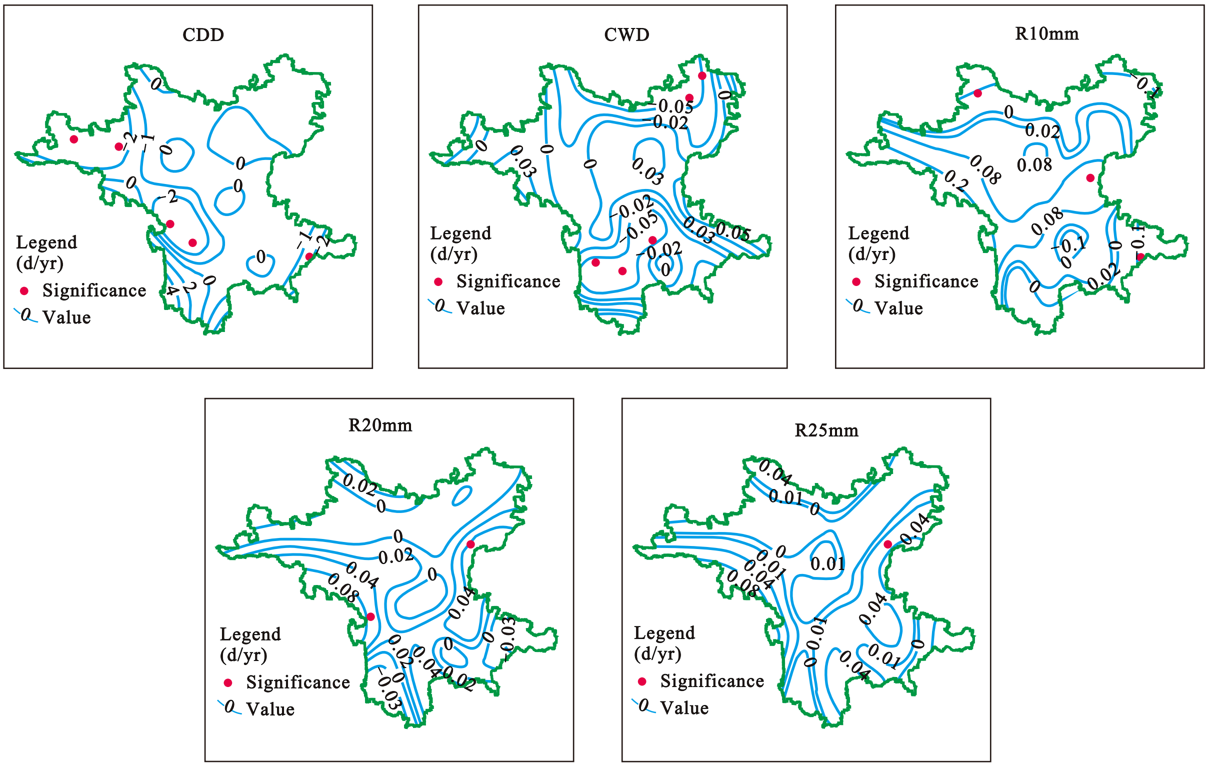


Fig. 11 Spatial distribution of linear tendency rates for CDD, CWD, R10mm, R20mm and R25mm

evident in the central area between the Yalongjiang River and the Daduhe River, in the eastern and southwestern margins, and in the northern of the Nujiang River valley (Fig. 11). About 75%, 66% and 69% of the stations had increasing trends for R10mm, R20mm and R25mm, respectively (Table 7). With the exceptions of the eastern and northern margins, R10mm in the Hengduan Mountains had an increasing trend, the magnitudes decreasing from the west to the east. The spatial distribution of R20mm and R25mm trends was characterized by the increase in the western margin and the southeastern part of the Hengduan Mountains.

5 Conclusions

Between 1961 and 2008, the temperature of the warmest and coldest nights in the Hengduan Mountains increased by 0.016℃/yr and 0.055℃/yr, respectively, significant at the 0.05 level. However, the increases for the warmest and coldest days (0.013℃/yr and 0.019℃/yr) were not significant at this level. The frequency of extreme warm days and nights increased by 1.80 d/yr and 3.25 d/yr, respectively, whereas those of extreme cold days and nights decreased by 0.073 d/yr and 0.369 d/yr. The diurnal temperature range decreased at a rate of –0.017℃/yr. The number of frost days and ice days decreased in a statistically significant pattern, at respective rates of –0.064 d/yr and –0.42 d/yr. The length of the growing season increased 0.401 d/yr during the past half-century. In the Hengduna Mountains, the warming magnitudes decreased from inner to outer as the center of the Shaluli Mountain, and the significant warming mainly occurred in the north and middle.

The significance of the changes in precipitation extremes between 1961 and 2008 is low, and it was difficult to detect against the larger inter-annual and decadal-scale variability of precipitation. Only the regional trends in consecutive dry days (–0.668 d/yr) and in the wet day precipitation (1.309 mm/yr) are significant at the 0.05 level, which reflected the precipitation increase mainly contributed by the increased rain days. Increases of the maximum 1-day precipitation, very wet day precipitation and extremely wet day precipitation are not statistically significant, and it is also true of trends in the numbers of days with heavy, heavier and heaviest precipitation. The maximum 5-day precipitation and the number of consecutive wet days decreased. It can be concluded that the variation of extreme precipitation events is not obvious in the Hengduan Mountains, however, the regional trends generally decreased from the south to the north. Overall, the spatial distribution of temporal changes of all extreme climate indices in the Hengduan Mountains illustrated here reflects the climatic complexity in mountainous regions.

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