Article

The Precipitation Variations in the Qinghai-Xizang (Tibetan) Plateau during 1961-2015

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Abstract: The Tibetan Plateau(TP) is known as 'the water tower of Asian', its precipitation variation play an important role in the eco-hydrological processes and water resources regimes. based on the monthly mean precipitation data of 65 meteorological stations over the Tibetan Plateau and the surrounding areas from 1961-2015,variations, trends and temporal-spatial distribution were analyzed, furthermore, the possible reasons were also discussed preliminarily. The main results are summarized as follows: the annual mean precipitation in the TP is 465.54mm during 1961-2015, among four seasons, the precipitation in summer accounts for 60.1% of the annual precipitation, the precipitation in summer half year (May.- Oct.) accounts for 91.0% while that in winter half year (Nov.- Apr.) only accounts for 9.0%; During 1961-2015, the annual precipitation variability is 0.45mm/a and the seasonal precipitation variability is 0.31mm/a, 0.13mm/a, -0.04mm/a and 0.04mm/a in spring, summer, autumn and winter respectively on the TP; The spatial distribution of precipitation can be summarized as decreasing from southeast to northwest in the TP, the trend of precipitation is decreasing with the increase of altitude, but the correlation is not significant. The rising of air temperature and land cover changes may cause the precipitation by changing the hydrologic cycle and energy budget, furthermore, different pattern of atmospheric circulation can also influence on precipitation variability in different regions.

Keywords: Precipitation; Tibetan Plateau; trends; temporal-spatial distribution; hydrological cycle;

1. Introduction

According to the fifth report from IPCC, the global surface temperature has risen 0.85℃ on average[1,3]. Remarkable warming led to glaciers melting[2,3] and hydrological cycle process accelerating[4],the change of species growth area, even the change of ecosystem[5].

In recent years, under the background of global warming, the precipitation around the world has redistributed. The moist regions would be wetter, while the arid regions would become more arid[6]. The global warming has also changed regional atmospheric circulation and water circulation[7,8]. It has caused the number of extreme precipitation events and flood disasters increasing[9,10]. As we all known, the precipitation variability is one of the main elements of climate change, as well as a key factor of economic development and environmental change. The change of precipitation can even lead to the change of ecological environment[11]. China is a agricultural country with a large population, It is of great importance to command the variation of precipitation in the future climate background. It plays an important role in guiding the allocation of water resource[12].

Since the 1990s, the total surface precipitation has risen 2%[13,14] and with great difference in space, time and season[15,16]. For example, during 1946-1999, the tendency of precipitation in Europe was increasing and the rate was 1.11mm/a. The period could be divided into two parts: during 1946-1975, the rate was 1.61mm/a, while during 1975-1999 it was -0.28/mm/a[17]; In Europe, the precipitation in central and western regions was reduced and the climate became drying in summer, while in the west of Russia, the climate became wetter[18]; In Africa, the precipitation in three regions (the eastern region, the southeast region and the Sahara region) was obviously differential; In America, during 1910-1996 the precipitation has increased about 10%, and the increasing in spring and autumn were more obvious while in winter was little[4] ; The precipitation Australia, Japan and India were also with great regional variability[19,20]. In general, the feature of global precipitation was periodic: it was gradually increased from 1901 to the middle of 1950s, relatively stable from the middle of 1950s to the middle of 1970s, and gradually decreased from the middle of 1970s to 1992. After 1992, it started to increase again[21]. In many regions, the reason of precipitation increasing was disproportionate frequency of heavy precipitation events[22].

Nearly 50 years, the total precipitation in China was slightly increasing, and it fluctuated at a certain periodicity. In different regions, the periodicity performs different as well. The precipitation have great spatial difference in China. In Southwest China, the precipitation in summer and winter were both increasing. However, in eastern regions, the precipitation showed an obvious seasonal difference. The number of precipitation days noticeably decreased in most parts of China (except in northwest region), but the precipitation intensity was increased[23]. Similar to the global change, the precipitation in China showed a periodic feature as well[24,25].

The Tibetan Plateau is known as 'the water tower of Asia', it is the source of many great rivers[26,27]. Meanwhile, the Tibetan Plateau is also an ecologically fragile areas, where the precipitation variability play an important role in the eco hydrological process[28]. The change of precipitation would influence the local eco-environment stability and the development of agriculture and industry directly. The precipitation of the TP has increased totally in nearly half a century. However, the spatial difference of precipitation variability was quite large and a reverse trend even happened in some regions[29,30,31,32,33]. The area where the precipitation increased were mainly located in the west, south and middle of the TP, while the trend of precipitation was decreased in the eastern regions and Qinghai province. The spatial difference of heavy precipitation days variation tendency was large as well: The heavy precipitation days in summer half year had an increasing (decreasing) trend in the northern(southern) regions, while in winter half year it became increasing trend in most regions, except in the Brahmaputra River Basins[34]. Lu et al. found the rate of precipitation variability increased with altitude under 2000m[35]. The precipitation variability in the TP could be divided into several periods and the rate in different periods had great difference. The Tibetan Plateau was rainy during 1985-1991 and 1998-2001, and rainless during 1962-1985 and 1991-1998[32]. From the 1950s to the early 1990s, the trend of precipitation in TP was decreased[36]. The precipitation in TP was increased with the rate of 0.666mm/a[37]. The rate became into 1.2mm/a during 1971-2000 and the extend of variation was from -5.85mm/a to 8.45mm/a[31]. The rate of precipitation variability in the TP also had great seasonal difference: in summer the rate reached the maximum, and in autumn it reached the minimum[31]. Different from the global conditions, the number of heavy precipitation events had no obvious increasing trend[37,38,39]. Some research have showed the land use and land cover change, the increasing CO_2 content, aerosol, the NAO and SST would have effects on the precipitation[40,41,42,43,44].

At present, many research have been carried out about the climate change in the TP, but issues also exist : (1) The homogeneity of data. Most of the research about climate change in the TP have not tested or corrected for the homogeneity. The meteorological data from stations may be influenced by the changes of location, environment, instrument and statistical method, resulting in the inhomogeneity of data series[45,46,47]. It would bring inevitable wrong to analysis about climate change. For this reason, when we study on the climate change, the effect from non-climate factors must be eliminated, so that the result can reflect the real climate situations. (2) There is less study on the difference: Most of current studies focus on climate variation in the whole plateau. To each region on the great plateau, there is few analysis about local climate change in detail. The Tibetan Plateau , which cover a great area, with complex topography. The climate change here have prominent spatial difference. Therefore, the contrast analysis of climate variation in different regions is a prerequisite for understanding the features of climate variability on the Tibetan Plateau. Besides, most of stations on the TP are located on the eastern part and the central part. There are few stations in the western regions. For this reason, the conclusion from researches may only suitable in the central and eastern regions, rather than the whole Tibetan Plateau[48].

In this paper, we have chosen the precipitation data from 65 stations in the Tibetan Plateau and the surrounding regions. Firstly, test and correct these data for the homogeneity. After correction, the quality of data improved significantly. Then use reintegration data to analyze the trend and range of precipitation variation in the whole plateau, analyze the station data of each. Finally, integrate all the results and obtain the conclusion about the difference of precipitation variation in each region.

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2. Data and methods

For most stations in the TP, the setting time was the mid 1950s. Considering that the length of research time must be consistent, we choose 1961 as the beginning year in the research, and 2015 as the ending year. The length of research time is 55 years. Also, to guarantee the quality of data, we have eliminated several stations whose missing observation lasts for a year. Finally we choose 65 stations (Figure 1) and obtain their monthly precipitation data. All data are from the China Meteorological Administration. Table.1 gives the details of the 65 stations. The stations we have chosen are spread out over the study area unevenly. They are mainly concentrated in the central and eastern regions and a few are in the western regions. All the data from these stations have experienced an initial quality test. For missing data or data with obvious mistake, we have done the interpolation and modification. In order to discuss the annual variation and seasonal difference of precipitation in the TP, we have processed monthly precipitation data into total annual and seasonal precipitation data. The four seasons are: Spring (Mar.- May), Summer (Jun.- Aug.), Autumn (Sep.- Nov.), Winter (Dec.- next Feb.).

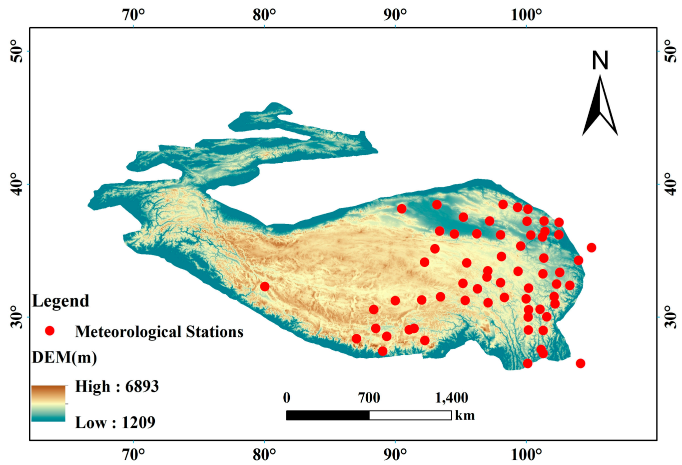

Figure 1. The location of selected meteorological stations

Table 1. Detailed information on the selected stations

Station Number	Name	Latitude (°N)	Longitude (°E)	Altitude(m)	Missing time(Mon)
51886	Mangya	38°15′	90°51'	2944.8	
52602	Lenghu	38°45'	93°20'	2770.0	
52633	Tuole	38°48'	98°25'	3367.0	
52645	Yeniugou	38°25'	99°35'	3320.0	
52657	Qilian	38°11'	100°15'	2787.4	
52707	Xiaozaohuo	36°48'	93°41'	2767.0	1974.4-12
52713	Dachaidan	37°51'	95°22'	3173.2	
52737	Delingha	37°22'	97°22'	2981.5	
52754	Gangcha	37°20'	100°08'	3302.0	
52765	Menyuan	37°23'	101°37'	2851.0	
52787	Wushaoling	37°12'	102°52'	3045.1	
52818	Geermu	36°25'	94°54'	2807.6	
52825	Nuomuhong	36°26'	96°25'	2790.4	
52836	Dulan	36°18'	98°06'	3191.1	

52856	Gonghe	36°16'	100°37'	2835.0	
52866	Xining	36°43'	101°45'	2295.2	
52868	Guide	36°02'	101°26'	2237.1	
52876	Minhe	36°19'	102°51'	1813.9	
52908	Wudaoliang	35°13'	93°05'	4612.2	
52943	Xinghai	35°35'	99°59'	3323.2	
52996	Huajialing	35°23'	105°00'	2450.6	
55228	Shiquanhe	32°30'	80°05'	4278.6	
55279	Bange	31°23'	90°01'	4700.0	1965.4
55299	Naqu	31°29'	92°04'	4507.0	
55472	Shenzha	30°57'	88°38'	4672.0	
55578	Rikaze	29°15'	88°53'	3836.0	
55591	Lasa	29°04'	91°08'	3648.9	1968.6-10
55598	Zedang	29°15'	91°46'	3551.7	
55664	Dingri	28°38'	87°05'	4300.0	1968.11-1969.1
55680	Jiangzi	28°55'	89°36'	4040.0	1969.8-1970.9
55696	Longzi	28°25'	92°28'	3860.0	1968.6
55773	Pali	27°44'	89°05'	4300.0	1969.7-
56004	Tuotuohe	34°13'	92°26'	4533.1	1969.8
56018	Zaduo	32°54'	95°18'	4066.4	
56021	Qumalai	34°08'	95°47'	4175.0	
56029	Yushu	33°01'	97°01'	3681.2	
56033	Maduo	34°55'	98°13'	4272.3	
56034	Qingshuihe	33°48'	97°08'	4415.4	1962.8-12
56046	Dari	33°45'	99°39'	3967.5	
56065	Henan	34°44'	101°36'	3501.0	
56067	Jiuzhi	33°26'	101°29'	3628.5	
56079	Ruoergai	33°35'	102°58'	3439.6	
56083	Shiqu	32°59'	98°06'	4201.0	
56093	Minxian	34°26'	104°01'	2315.0	
56106	Suoxian	31°53'	93°47'	4022.8	
56116	Dingqing	31°25'	95°36'	3873.1	
56125	Nangqian	32°12'	96°29'	3643.7	
56137	Changdu	31°09'	97°10'	3306.0	
56144	Dege	31°48'	98°35'	3199.0	1969.6-8
56146	Ganzi	31°37'	100°00'	3394.0	
56152	Seda	32°17'	100°20'	3896.0	1969.6
56167	Daofu	30°59'	101°07'	2957.2	
56172	Maerkang	31°54'	102°14'	2664.4	
56173	Hongyuan	32°48'	102°33'	3491.6	
56178	Xiaojin	31°00'	102°21'	2369.2	

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56182	Songpan	32°39'	103°34'	2850.7	
56251	Xinlong	30°56'	100°19'	2999.0	
56257	Litang	30°00'	100°16'	3948.9	
					1967.9
56357	Daocheng	29°03'	100°18'	3729.0	1968.1-7
56374	Kangding	30°03'	101°58'	2615.7	1969.5-8
56459	Muli	27°56'	101°16'	2426.5	1970.1
56462	Jiulong	29°00'	101°30'	2994.0	1968.5
56565	Yanyuan	27°26'	101°31'	2545.0	1969.4
56651	Lijiang	26°52'	100°13'	2392.4	
56691	Weining	26°52'	104°17'	2237.5	

The precipitation data from stations may be influenced by non-climate factors, causing precipitation data series inhomogeneity. We use the software package RHtestsV4 to test the homogenization of data and correct the inhomogeneous data[37,49,50]. Normally the distribution of monthly precipitation is non-normal; thus we use cube roots of data to test homogenization. The methods of RHtests are based on binomial regression testing methods and improved by Wang et al.from Environment Canada[51]. It has provided two testing methods: the penalized maximal T test (PMT)[52] and the penalized maximal F test (PMFT)[53]. They both can be run under R language by using RHtests software package. Their difference is PMT needs a homogenous time series as reference series, while for PMFT the reference is not necessary. While testing the homogenization by using PMT or PMFT, RHtests can correct the data series. The stations in the TP are few and widely spaced. In addition, the topography of Tibetan Plateau is complex and the altitude differences among stations are large. Therefore, the reference series have little effect on testing data series. For inhomogeneous series, we use the mean-adjusted base series to replace the original data.

Set εt as a Gaussian variable with zero-mean to test whether a time series {Xt} with β as linear trend has discontinuity when t=k. Make the null hypothesis:

$$H_0:\ X_t = \mu + \beta t + \varepsilon_t\ ,\quad t=1,2,\dots,N \qquad (1)$$

Make alternative hypothesis:

$$H_a:\begin{cases} X_t = \mu_1 + \beta t + \varepsilon_t\ ,\ t \le k \\ X_t = \mu_2 + \beta t + \varepsilon_t\ ,\ k-1 \le t \le N \end{cases} \qquad (2)$$

where μ1 ≠ μ2 .The time point t=k would have discontinuity when Ha is true and Δ=|μ1 - μ2| is the range of mean-adjustment.

After testing for those stations with inhomogeneous data, RHtests have offered a corrected method called mean-adjusted method. It regards the mean residual between the trend of last homogeneous series and inhomogeneous series as correction to correct data. Assuming p is the tested inhomogeneous point, under these conditions:

$$\begin{cases} Z_i \in (\mu_1,\sigma),\ i \in \{1,2,\dots,p\} \\ Z_i \in (\mu_2,\sigma),\ i \in \{p+1,p+2,\dots,N\} \end{cases} \qquad (3)$$

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where μ_1、μ_2 represent the mean residual of series before and after p respectively. μ_2-μ_1 is the mentioned difference between homogeneous series and inhomogeneous series. The generated new series are the corrected series. In this paper, all data used are the corrected data.

Here we use the linear regression method to analyze the change characteristics of precipitation:

$$y_x = a + bx + e_x \quad (4)$$

where b represents the variation trend. b>0 means increasing, b<0 means decreasing and b=0 means no significant variation. |b| indicates the variation range of precipitation. We use the student t-test to estimate the statistical significance between x and y_x. α<0.05 means the linear trend has over 95% confidence level and x and y_x have significant correlation; α<0.01 means the linear trend has over 99% confidence level and the correlation is even more significant.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

3.1. The temporal-spatial distribution characteristics of precipitation

The annual precipitation distribution in the Tibetan Plateau is very uneven and the rainfall is mainly concentrated in summer[54]. We have calculated the monthly mean precipitation and the precipitation variability at every station (see in Table 2) in order to study the annual precipitation distribution and the trend of monthly precipitation. The annual mean precipitation in the TP is 465.54mm during 1961-2015. Among four seasons, the precipitation in summer accounts for 60.1% of the annual precipitation. The precipitation in summer half year (May.- Oct.) accounts for 91.0% while that in winter half year (Nov.- Apr.) only accounts for 9.0%. Therefore the precipitation in the TP is mainly concentrated in the summer half year. July has the most precipitation with the ratio of 22.1% in the annual precipitation and December has the least precipitation with the ratio of 0.4% (see in Figure 2). Among the 12 months, the trends of precipitation variability in Aug., Sep. and Nov. are decreasing and that in Dec has no significant change. The range of precipitation variability reaches maximum in May, which is 0.162mm/a, and significant at 99% confidence level.

Table 2. The precipitation amount and trends in each month on the TP

	Precipitation (m)	**Ratio of annual precipitation(%)**	**Precipitaiton variability（mm/a）**
Jun.	2.71	0.6	0.021*
Feb.	3.93	0.8	0.019
Mar.	9.39	2.0	0.054**
Apr.	19.45	4.2	0.097**
May.	46.71	10.0	0.162**
Jun.	85.89	18.4	0.125
Jul.	102.56	22.1	0.034
Aug.	91.23	19.6	-0.027
Sep.	70.55	15.2	-0.068
Oct.	26.45	5.7	0.033
Nov.	4.79	1.0	-0.001

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Dec.	1.88	0.4	0
Annual	465.54	100	0.545*

“*”represents significant at 95% level, “**”represents significant at 99% level, the same below.

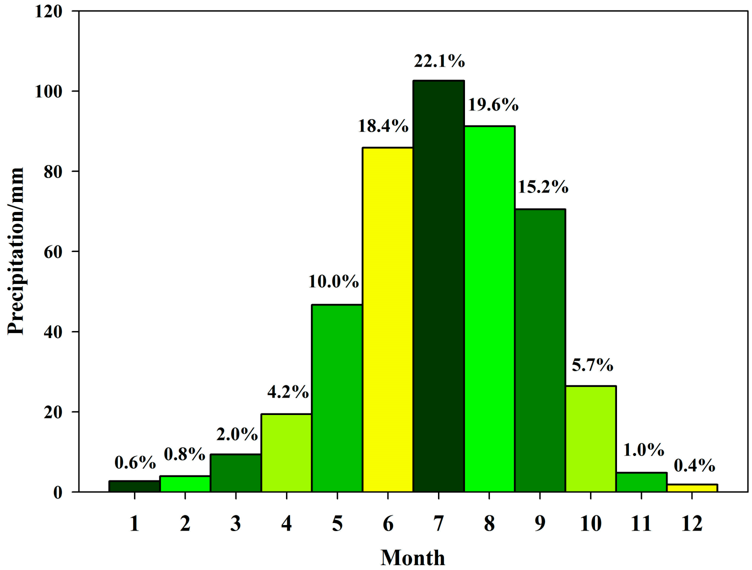

Figure 2. The precipitation distribution in each month on the TP

The spatial distribution of precipitation in the TP also varies greatly and the precipitation is correlated to latitude, longitude and altitude to a certain extent (Figure 3). The precipitation increases with the increase of longitude, while it decreases with the increase of latitude. The spatial distribution of precipitation can be summarized as decreasing from southeast to northwest in the Tibetan Plateau. The trend of precipitation is decreasing with the increase of altitude, but the correlation is not significant. In general, the distribution of precipitation has great longitudinal zonality and altitudinal zonality, but has no significant relationship with altitude.

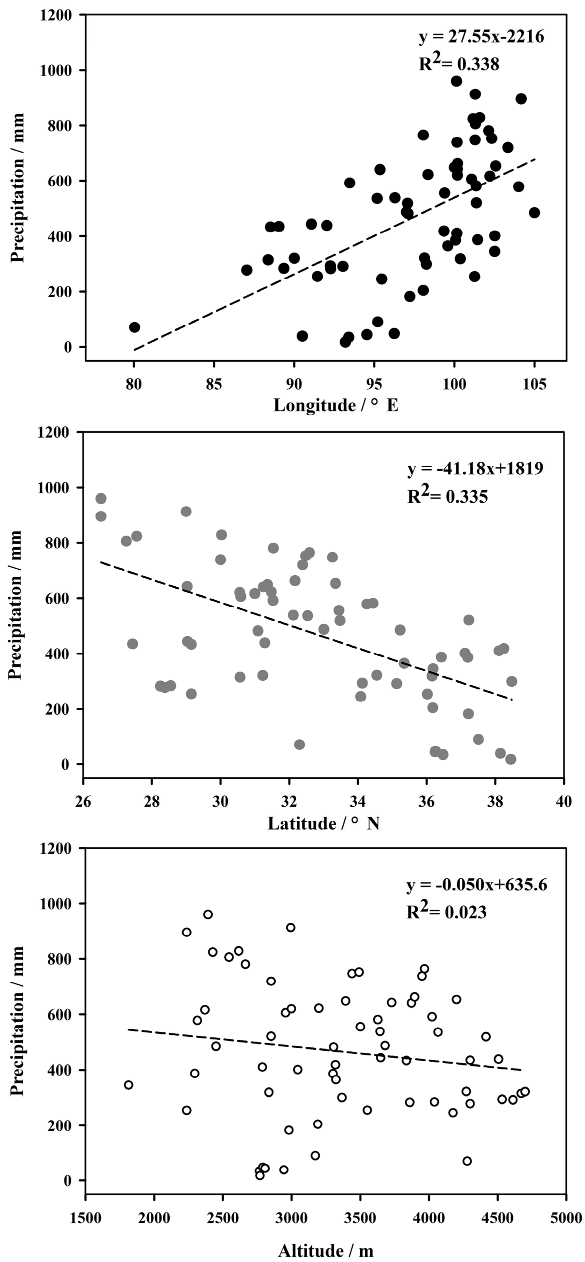

Figure 3. The relationship between precipitation and longitude, latitude and altitude

3.2. The annual and seasonal variation characteristics of precipitation

During 1961-2015, the annual precipitation variability is 0.451mm/a in the TP and the seasonal precipitation variability in spring, summer, autumn and winter is 0.314mm/a, 0.131mm/a, -0.036mm/a and 0.041mm/a respectively (Figure 4). The annual precipitation variability is significant at 95% confidence level. For the seasonal precipitation variability, those in spring and winter are significant at 99% level, while those in summer and autumn are not significant at 95% level. Only in autumn the precipitation is decreasing and those in other seasons are all increasing. The increase of precipitation in spring, summer and winter decrease in turn which means that the precipitation increase in spring makes the biggest contribution to the annual precipitation increase. We divide the 55 years into five periods and the results can be seen in Table.3. The results show that the mean annual precipitation during 1971-1980 is basically the same as that during 1961-1970, and compared with that during 1981-1990, the mean annual precipitation during 1991-2000 also have no significant

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change. However, from the 1970s to the 1980s, the mean precipitation increased 10.9mm, and comparing the first 15 years of this century with the 1990s, the precipitation also had a great increase of 10.0mm. For each station, the precipitation variability ranged from -6.969mm/a (Shiqu station) to 2.830mm/a (Kangding station). There are 49 stations whose precipitation variability are positive among the 65 stations, 75% of the total; There are 16 stations whose precipitation variability are negative among the 65 stations, 25% of the total (Figure.5). In general, the precipitation variability in the southeastern Tibetan Plateau is larger than that in the central Tibetan Plateau, and the stations with decreasing trend are mainly distributed in the northern and southeastern Tibetan Plateau.

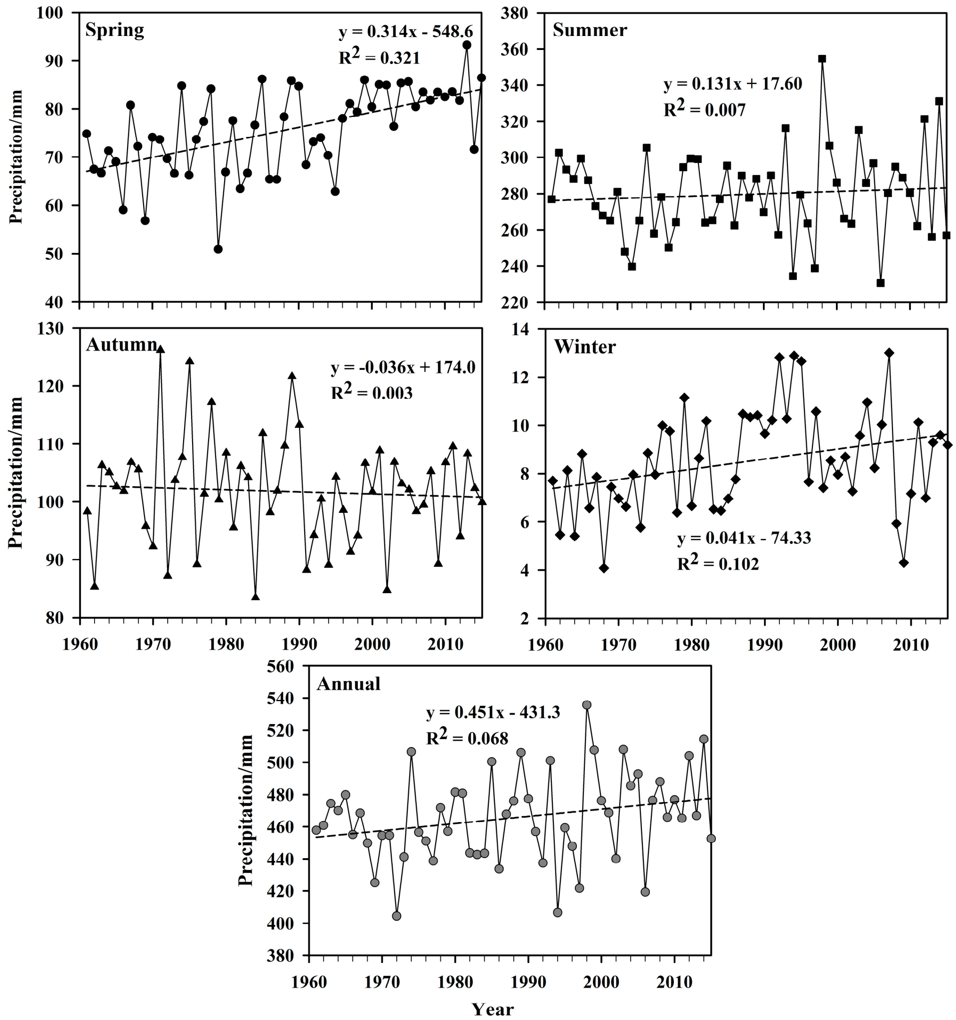

Figure 4. The variation in the annual and seasonal precipitation in the 1961-2015 over the TP

Table 3. The average annual and seasonal precipitation in different periods

	Annual(mm)	Spring(mm)	Summer(mm)	Autumn(mm)	Winter(mm)
1961-1970	459.6	69.2	283.5	100.0	6.8
1971-1980	456.3	71.4	270.3	106.5	8.1
1981-1990	467.2	75.0	278.9	104.6	7.0
1991-2000	465.0	75.4	282.7	96.9	10.1
2001-2015	475.0	83.0	282.0	101.2	8.7

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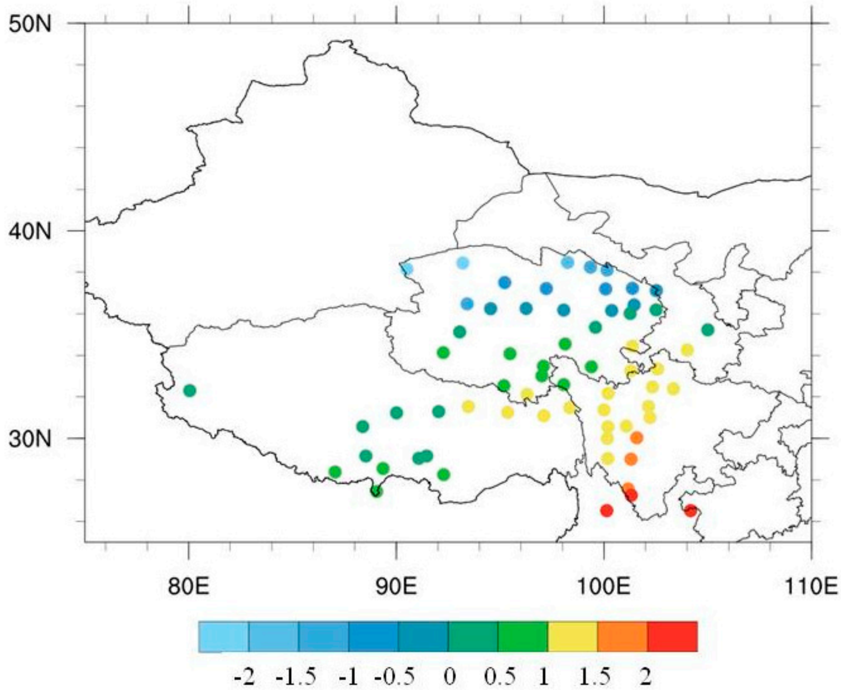

Figure 5. Spatial distribution of long-term trends in the annual precipitation (mm /a)

There is great difference among the annual and seasonal change of precipitation in different stations: the variation range is -0.694mm/a-0.969mm/a in spring; -4.537mm/a-1.496mm/a in summer; -1.553mm/a-0.726mm/a in autumn and -1.553mm/a-0.726mm/a in winter. Figure 6 shows the number of stations with different precipitation variability. In spring, the precipitation variability is mainly concentrated in the range 0-1mm/a and the number of stations is 56, 86% of the total; in summer, the precipitation variability is mainly concentrated in -1mm/a-1mm/a and the number of stations is 54.83% of the total; in autumn, the precipitation variability is mainly concentrated in -1mm/a-0.8mm/a and the number of stations is 63.97% of the total; in winter, the precipitation variability is mainly concentrated in 0-1mm/a and the number of stations is 52.80% of the total. The annual precipitation variability is mainly concentrated in the range 0-0.5mm/a and the number of stations is 42.65% of the total.

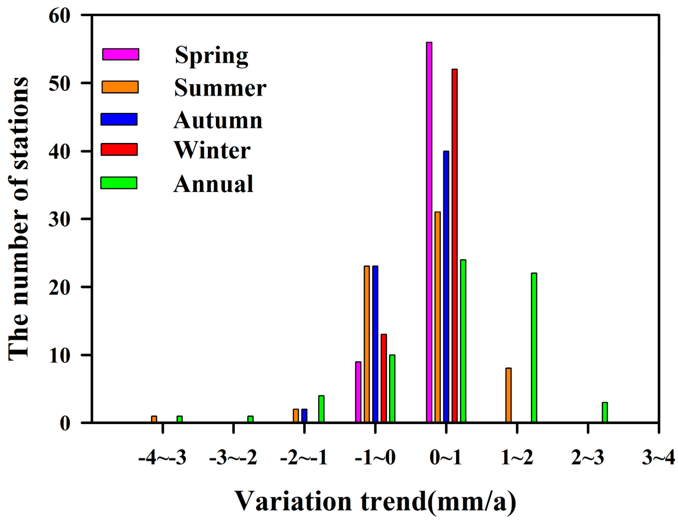

Figure 6. The number of stations with different precipitation trends

Table.4 has listed the top ten stations with the most significant increasing and decreasing in precipitation. From the Table, the top ten stations with the most obvious increasing in precipitation have precipitation variability ranging from 2.83mm/a to 1.413mm/a, and the top ten stations with the most obvious decreasing in precipitation have precipitation variability ranging from -6.969mm/a to -0.517mm/a. The phenomena prove that the precipitation variability has great spatial difference in the TP. The station with the most obvious increasing on annual precipitation is Kangding station, whose precipitation variability is 2.83mm/a; the station with the most obvious decreasing on annual precipitation is Shiqu station, whose precipitation variability is -6.969mm/a. The mean precipitation variability among all stations is 0.451mm/a.

Table 4. Information of the ten stations with the largest upward(downward)trends in precipitation

10 stations with largest upward trends		**10 stations with largest downward trends**	
Name	Precipitation variability（mm/a）	Name	Precipitation variability（mm/a）
Kangding	2.83**	Shiqu	-6.969**
Zedang	2.73**	Weining	-2.076
Delingha	2.10**	Huajialing	-1.713*
Wudaoliang	1.937**	Henan	-1.464
Yeniugou	1.786**	Minxian	-1.35
Dulan	1.634**	Muli	-1.14
Xinlong	1.469	Yamyuan	-0.8
Shenzha	1.468*	Jiuzhi	-0.717
Tuole	1.432**	Minhe	-0.646
Ganzi	1.413	Rikaze	-0.517

"*"represents significant at 95% level, "**" represents significant at 99% level, the same below.

Some previous researches indicated that the climate change has an obvious periodic characteristic[55]. The warming trend has great difference in different period. After the 1990s, the temperature in the TP increased sharply[56], and so did the precipitation[57]. We divide the precipitation data into two time periods (1961-1990 and 1991-2015) to understand the precipitation response to different warming trends. Table 5 has listed the precipitation variability difference between the two periods. The annual precipitation variability is 0.495mm/a during 1961-1990, which is far less than 1.081mm/a during 1991-2015. The precipitation variability during 1991-2015 is larger as well in spring, summer and autumn. However, only in winter the precipitation changed from increasing during 1961-1990 to decreasing during 1991-2015. The results show the increasing variability of precipitation in the TP under the accelerated global warming during nearly 20 years.

Table 5. Comparisons of the precipitation variability in 1961-1990 and 1991-2015

	Annual (mm/a)	**Spring (mm/a)**	**Summer (mm/a)**	**Autumn (mm/a)**	**Winter (mm/a)**
1961-1990	0.495	0.273	-0.148	0.271	0.098**
1991-2015	1.081	0.544**	0.299	0.354**	-0.117**
1960-2015	0.451*	0.314**	0.131	-0.036	0.041**

"*" represents significant at 95% level, "**" represents significant at 99% level, the same below.

3.3. The relationship between precipitation variability and altitude, latitude and longitude

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Some previous researches indicated that the precipitation variability is related with altitude in the Tibetan Plateau[35]. We have analyzed the relationship between precipitation variability and altitude in 65 stations to ascertain whether the variability has elevation dependency or not (Figure 7). As can be seen from Figure 7, the correlation coefficient square (R^2) is 0.025 and it is not significant at 95% level. It has proved that there is no obvious linear relationship between them. From above we know that the precipitation has great longitudinal zonality and altitudinal zonality in the Tibetan Plateau, but the correlation coefficient between the precipitation variability and neither latitude nor longitude is significant at 95% level. Therefore, there is no obvious linear relationship between the precipitation variability and altitude, latitude and longitude.

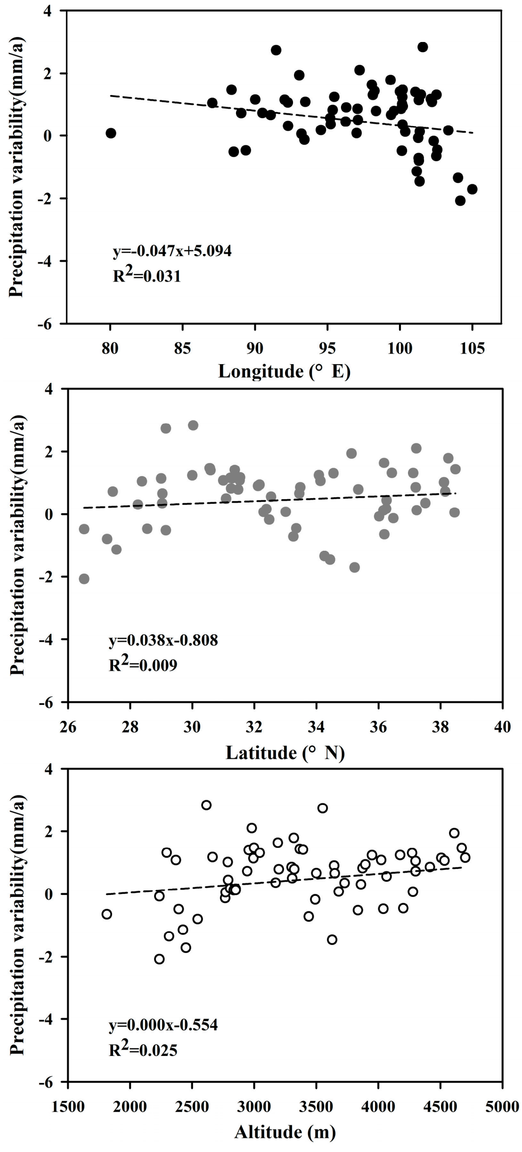

Figure 7. The relationship between the precipitation variability and longitude, latitude and altitude

3.4. The possible reasons for precipitation variations

The precipitation has increased during the 1961-2015 in the TP with the rate of 0.451mm/a and during 1991-2015 that is 1.081mm/a . During 1901-1998 the global precipitation variability is 0.089mm/a[21]. However, the global precipitation become into decrease during 1951-1980 with the rate of -0.4mm/a, the precipitation variability is -1.3mm/a in the Northern Hemisphere and 1.4mm/a in the Southern Hemisphere[7]. In Asia, the summer precipitation decrease during 1978-2002, the summer precipitation variability is -3.56mm/a in southwest Asia and -4.08mm/a in northeast Asia. In China, the precipitation increase during 1955-2007 with the rate of 0.33mm/a, the winter precipitation variability is 0.15mm/a and the summer precipitation variability is 0.16mm/a[24]. In the Tibetan Plateau, the precipitation has great temporal-spatial distribution, the trends of precipitation variation may have great difference in different regions or at different time. Research has shown the frequency of extreme precipitation events change disproportionately. In China, the frequency of extreme precipitation events has reduced by 10%. The light precipitation events are decreasing and the heavy precipitation events are increasing[58]. During nearly 50 years, the extreme precipitation has showed a significant spatial and temporal difference in China. However, at the same period, the precipitation intensity has no significant increase nearly 50 years in the Tibetan Plateau[37].

The researches on climate model simulation show that the rising surface temperature may cause the global precipitation to increase[14,59]. The land over changes can affect the dynamic and thermodynamic power of atmosphere by changing the hydrologic cycle and energy budget, and so that it can change the climate[60]. Cui et al. indicate the variation of land use has influenced local climate in the Tibetan Plateau[40]. The land use changes make the Tibetan Plateau wetter and it contributes 9mm/a to the precipitation. Normally, the aerosols can make the regional precipitation decrease[42], but the absorbency black carbon aerosols may make the precipitation increase in the TP[61]. Otherwise, the increasing content of CO_2, the North Atlantic oscillation and the El Niño also have effects on the precipitation in the TP[62].

The precipitation variation have significant difference in different regions and periods in the Tibetan Plateau. The increasing range of precipitation during 1991-2015 is larger than that during 1961-1990 from time scale; The precipitation in southeastern regions is heavier than that in central regions from spatial scale. Since the 1990s, the increasing precipitation is associated with the rising temperature. It has proved the trend of precipitation is increasing under the warming climate background and the variability increases with the rising of warming rate. The high-speed economic development has led to the increase carbon dioxide in the Tibetan Plateau, especially in the southeast regions. The spatial distribution of precipitation variability is connected with the complex topography in the TP. The Tibetan Plateau has vast territory and varied terrain, with mountains, plain and rivers cross distributed. It has formed relatively independent local climate under the complex topography. The topographic influence on precipitation in the TP is more significant than that in other regions of China because of the specific location and topography[35]. The research by Liu et al. show an adverse feature between NAO and precipitation in southern and northern regions[58]. Different pattern of atmospheric circulation can also lead to the spatial distribution of precipitation variability[63].

4. Summary and Discussion

Two prominent problems in the Tibetan Plateau are the harsh natural environment and less observational data, especially in the wide western regions. Observational data from stations is foundation of studying on climate change. Therefore, it is still imperative to enhance the meteorological observation on the climate study in the TP. For the existing data, appropriate methods should be chosen to test and correct them on homogeneity. All the test methods has their advantages and disadvantages at present, and different methods maybe suitable for different meteorological factors. So choosing suitable methods is of incredible importance to the future study on varied

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meteorological factors. The station historical data (metadata) plays an important role in testing and correcting the homogeneity of climatic data. It includes all information which is likely to influence the homogeneity of meteorological data series such as the variation of station sites, time, calculating methods and instrument, and it can provide valuable reference and objective support for analyzing, testing and correcting the climate data series. Therefore, it is a basic work on homogeneity study to collect the metadata from stations as exhaustive as possible in the Tibetan Plateau.

The climate environment is special in the Tibetan Plateau. A great number of study on climate change have been carried out and almost include all climate factors, but quite a number of study focus on precipitation and temperature only. In the future, more study on other climate factors need to be carried out to understand the characteristics of climate change. Otherwise, because of the lack of enough quantitative analysis, we have no profound understanding on the physical mechanism of climate change in the Tibetan Plateau. For that reason, the quantitative study is essential in the future study.

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References

1. IPCC. Working Group I Contribution to the IPCC Fifth Assessment Report. Climate Change 2013:The Physical Science Basis: Summary for Policymakers.
2. Radic V, Bliss A, Beedlow A C, Hock R, Miles E, Cogley J G. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Clim Dyn, 2014, 42: 37-58.
3. Shi Yafeng, Shen Yongping, Kang Ersi, Li Dongliang, Ding Yongjian, Zhang Guowei, Hu Ruji. Recent and Future Climate Change in Northwest China. Climatic Change, 2007, 3: 379-393 .
4. Sala OE , Chapin FS , Armesto JJ, et al. Biodiversity - Global biodiversity scenarios for the year 2100. Science, 2000, 5459: 1770 -1774.
5. Chapin, F. Stuart, Osvaldo E. Sala, and Elisabeth Huber-Sannwald, eds. Global biodiversity in a changing environment: scenarios for the 21st century. Vol. 152. Springer Science & Business Media, 2013.
6. Wang J, Dai A, Mears C. Global Water Vapor Trend from 1988 to 2011 and Its Diurnal Asymmetry Based on GPS, Radiosonde and Microwave Satellite Measurements. Journal of Climate, 2016, 29(14): 5205-5222.
7. Yao C, Yang S, Qian W, et al. Regional summer precipitation events in Asia and their changes in the past decades. Journal of Geophysical Research-Atmospheres, 2008, 113(D17):487-497.
8. Roderick ML, Sun F, Lim W H, Farquhar G D. A general framework for understanding the response of the water cycle to global warming over land and ocean. Hydrology and Earth System Sciences, 2014, 18(5): 1575-1589.
9. Hirabayashi Y, Mahendran R, Koirala S, et al. Global flood risk under climate change. Nature Climate Change, 2013, 3(9): 816-821.
10. Trenberth K E, Dai A, Van Der Schrier G, et al. Global warming and changes in drought. Nature Climate Change, 2014, 4(1): 17-22.
11. Weltzin J F, Loik M E, Schwinning S, et al. Assessing the Response of Terrestrial Ecosystems to Potential Changes in Precipitation. Bioscience, 2009, 53: 941-952.
12. Piao S, Ciais P, Huang Y, et al. The impacts of climate change on water resources and agriculture in China. Nature, 2010, 467(7311): 43-51.

13. Jones P D, Hulme M. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. International Journal of Climatology, 1996, 16(4): 361-377.
14. Hulme M, Osborn T J, Johns T C. Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations. Geophysical Research Letters, 1998, 25(17):3379-3382.
15. Karl T R, Knight R W. Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. Bulletin of the American Meteorological Society, 1998, 79(2): 231-241.
16. Li Y, Li D, Yang S, et al. Characteristics of the precipitation over the eastern edge of the Tibetan Plateau. Meteorology & Atmospheric Physics, 2010, 106(1): 49-56.
17. Klein Tank A M G, Wijngaard J B, Können G P, et al. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. International Journal of Climatology, 2002, 22(12):1441-1453.
18. Pal J S, Filippo G, Bi X. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophysical Research Letters, 2004, 31(13):137-151.
19. Xu Z X, Takeuchi K, Ishidaira H. Monotonic trend and step changes in Japanese precipitation. Journal of Hydrology, 2003, 279(1-4):144-150.
20. Shouraseni S R, Balling R C. Trends in extreme daily precipitation indices in India. International Journal of Climatology, 2004, 24(2): 19-24.
21. New M, Todd M, Hulme M, et al. Precipitation measurements and trends in the twentieth century. International Journal of Climatology, 2001, 21(15): 1889-1922.
22. Mohammed H.I. Climate change and changes in global precipitation patterns: What do we know? Environment International, 2005 ,8 : 1167-1181.
23. Zhai P, Zhang X, Wan H, et al. Trends in Total Precipitation and Frequency of Daily Precipitation Extremes over China. Journal of Climate, 2005, 18(7): 1096-1108.
24. Choi G, Collins D, Ren G, et al. Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955-2007. International Journal of Climatology, 2011, 113(29):1906-1925.
25. Liu B, Xu M, Henderson M, et al. Observed trends of precipitation amount, frequency, and intensity in China, 1960-2000. Journal of Geophysical Research-Atmospheres, 2005, 110(D8): 211-211.
26. Xin H. China's environmental challenges. A green fervor sweeps the Qinghai-Tibetan Plateau. Science, 2008, 321(5889): 633-635.
27. Feng Lei, Wei Fengying, Regional Characteristics of Summer Precipitation on Tibetan Plateau and It's Water Vapor Feature in Neighboring Areas. Plateau Meteorology, 2008, 27(3): 491-499.
28. Cannarozzo M, Noto L V, Viola F. Spatial distribution of rainfall trends in Sicily (1921-2000). Physics & Chemistry of the Earth Parts A/b/c, 2006, 31(18):1201-1211.
29. Niu T, Yin Y H , Zhou Z J . The Characteristics of Climate Change over the Tibetan Plateau in the Last 40 Years and the Detection of Climatic Jumps. Advances in Atmospheric Sciences, 2004, 21(2):193-203.
30. Ma Xiaobo, Hu Zeyong. Precipitation Variation Characteristics and Abrupt Change over Qinhai-Xizang Plateau in Recent 40 Years. Journal of Desert Research, 2005, 25(1):137-139.
31. Wu S, Yin Y, Du Z, et al. Climatic trends over the Tibetan Plateau during 1971-2000. Journal of Geographical Sciences, 2007, 17(2):141-151.
32. Xu Z X, Gong T L, Li J Y. Decadal trend of climate in the Tibetan Plateau-regional temperature and precipitation. Hydrological Processes, 2008, 22(16): 3056-3065.
33. Xie H, Ye J, Liu X, et al. Warming and drying trends on the Tibetan Plateau (1971-2005). Theoretical & Applied Climatology, 2010, 101(3): 241-253.
34. Zhou Shunwu, Wang Chuanhui, Wu Ping, et al. Temporal and spatial distribution of strong precipitation days over the Tibetan Plateau. Arid Land Geography, 2012, 35(01):23-31.
35. Lu Heli, Shao Quanqin, Liu Jiyuan, et al. Temporo-spatial Distribution of Summer Precipitation over Qinghai- Tibet Plateau during the Last 44 Years. Act Geographica Sinica, 2007, 62(9):946-958.
36. Lin Z Y , Zhao X Y. Spatial characteristics of changes in temperature and precipitation of the Qinghai-Xizang (Tibet) Plateau. Science in China Ser D, 1996, 39(4): 442-448.
37. You Q, Kang S, Enric A, et al. Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961-2005.Journal of Geophysical Research -Atmospheres, 2008, 113(D7):1639-1647.
38. Easterling D R, Meehl G A, Parmesan C, et al. Climate Extremes: Observations, Modeling, and Impacts. Science, 2000, 289(5487):2068-2074.

39. Groisman P Y, Knight R W, Easterling D R, et al. Trends in Intense Precipitation in the Climate Record. Journal of Climate, 2010, 18(9):1326-1350.
40. Cui X, Graf H F, Langmann B, et al. Climate impacts of anthropogenic land use changes on the Tibetan Plateau. Global & Planetary Change, 2006, 54(1-2):33-56.
41. Guo Y, Yu Y, Liu X, et al. Simulation of climate change induced by CO 2, increasing for East Asia with IAP/LASG GOALS model. Advances in Atmospheric Sciences, 2001, 18(18): 53-66.
42. Lau K M, Kim K M. Observational relationships between aerosol and Asian monsoon rainfall, and circulation. Geophysical Research Letters, 2006, 332(21): 320-337.
43. Liu Hunacai, Duan Keqin. Effects of North Atlantic Oscillation on Summer Precipitation over the Tibetan Plateau. Journal of Glaciology and Geocryology, 2012, 34(2): 311-318.
44. Dai A. Increasing drought under global warming in observations and models. Nature Climate Change, 2013, 3(1): 52-58.
45. Li Q, Liu X, Zhang H, et al. Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. Advances in Atmospheric Sciences, 2004, 21(2): 260-268.
46. Begert M, Schlegel T, Kirchhofer W. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. International Journal of Climatology, 2005, 25(1):65-80.
47. Yan Z W, Li Z, Xia J J. Homogenization of climate series: The basis for assessing climate changes. Science China Earth Sciences, 2014, 57(12): 2891-2900.
48. Qin J, Yang K, Liang S, et al. The altitudinal dependence of recent rapid warming over the Tibetan Plateau. Climatic Change, 2009, 97(1): 321-327.
49. Cao Lijuan, Ju Xiaohui, Liu Xiaoning. Penalized Maximal F Test for the Homogeneity Study of the Annual Mean Wind Speed over China. Meteorological Monthly, 2010, 36(10): 52-56.
50. Zhang X, Aguilar E, Sensoy S, et al. Trends in Middle East climate extreme indices from 1950 to 2003. Journal of Geophysical Research-Atmospheres, 2005, 110(D22):3159-3172.
51. Wang X L. Comments on 'Detection of Undocumented Changepoints: A Revision of the Two-Phase Regression Model'. Journal of Climate, 2002, 15(17): 2547-2554.
52. Wang XL. 2008a: Accounting for autocorrelation in detecting mean-shifts in climate data series using the penalized maximal t or F test. J. Appl.Meteor. Climatol., 2008a, 47: 2423-2444.
53. Wang X L. Penalized maximal F-test for detecting undocumented mean-shifts without trend-change. J. Atmos. Oceanic Tech., 2008b, 25 (3): 368-384.
54. Lu Aigang. Spatial precipitation variation across China during 1951-2002. Ecology and Environmental Sciences, 2009,01: 46-50.
55. Cai Ying, Li Dongliang, Tang Maocang, et al. Decadal Temperature Changes over Qinghai-Xizang Plateau in Recent 50 Years. Plateau Meteorology, 2003, 22(5): 464-470.
56. Jiang Yongjian, Li Shijie, Shen Defu, et al. Climate Change and Its Impact on the Lake Environment in the Tibetan Plateau in 1971-2008. Scientia Geographica Sinica, 2012, 32(12):1503-1512.
57. Du Jun, Ma Yucai. Climate Trend of Rainfall over Tibetan Plateau from 1971 to 2000. Act Geographica Sinica, 2004, 59(3): 375-382.
58. Liu X, Yin Z Y, Shao X, et al. 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 Atmospheres, 2006, 111(D19): 4617-4632.
59. Wentz F J, Ricciardulli L, Hilburn K, et al. How much more rain will global warming bring? Science, 2007, 317(5835): 233-5.
60. Werth D, Avissar R. The local and global effects of Amazon deforestation. Journal of Geophysical Research, 2002, 107(8087): 5823-5826.
61. Meehl G A, Arblaster J M, Collins W D. Effects of Black Carbon Aerosols on the Indian Monsoon. Journal of Climate, 2008, 21(12): 2869-2882.
62. Liu Huancai, Duan Keqin. Effects of North Atlantic Oscillation on Summer Precipitation over the Tibetan Plateau. Journal of Glaciology and Geocryology, 2012, 34(2): 311-318.
63. Yao T, Thompson L, Yang W, et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nature Climate Change, 2012, 2(9):663-667.

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