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

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Abstract: The variation of precipitation plays an important role in the eco-hydrological processes and water resources regimes on the Tibetan Plateau (TP). Based on the monthly mean precipitation data of 65 meteorological stations over the TP and surrounding areas from 1961 to 2015, variations, trends and temporal–spatial distribution of precipitation have been studied; furthermore, the possible reasons were also discussed preliminarily. The results show that the annual mean precipitation on the TP was 465.5 mm during 1961–2015. The precipitation in summer (June–August (JJA)) accounted for 60.1% of the whole year's precipitation, the precipitation in summer half-year (May–October) accounted for 91.0%, while the precipitation in winter half-year (November–April) only accounted for 9.0% of the whole year's precipitation. During 1961–2015, the annual precipitation trend was 3.8 mm/10a and the seasonal precipitation trends were 3.0 mm/10a, 0.0 mm/10a, −0.1 mm/10a and 0.4 mm/10a in spring, summer, autumn and winter on the TP, respectively. The precipitation has decreased from the southeastern to northwestern TP; the trend of precipitation has decreased with the increase of altitude, but the correlation was not significant. The rising of air temperature and land cover changes may cause the precipitation by changing the hydrological cycle and energy budget. Furthermore, different patterns of atmospheric circulation can also influence precipitation variation in different regions.

Keywords: precipitation; Tibetan Plateau; trends; temporal–spatial distribution; hydrological cycle

1. Introduction

According to the fifth report from Intergovernmental Panel on Climate Change (IPCC), the global surface temperature has risen 0.85 °C on average [1,2]. Significant warming led to glaciers melting [2,3], hydrological cycle accelerating [4], changes of species habitat, and even degeneration of ecosystem [5].

In recent years, under the background of global warming, precipitation around the world has been redistributed. The moist regions would be wetter, while the arid regions would become more arid [6]. 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 to increase [9,10]. As we all know, the precipitation variation is one of the main elements of climate change, as well as a key factor of economic development and environmental change. The precipitation variation can even lead to a change in ecological environment [11]. China is an agricultural country with a large population, and it is of great importance to understand the variation of precipitation in the future climate background. It is very important to study precipitation changes for guiding the allocation of water resource [12].

Since the 1990s, the total surface precipitation has risen 2% [13,14], and displayed great differences in space and time [15,16]. For example, during 1946–1999, the tendency of precipitation in Europe has increased at the rate of 11.1 mm/10a. The period could be divided into two parts: during 1946–1975, the rate was 16.1 mm/10a, while during 1975–1999, it was −2.8 mm/10a [17]. In Europe, the precipitation in central and western regions was reduced and the climate became dry in summer. However, in western 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, precipitation increased about 10% during 1910–1996, and the increases in spring and autumn were more obvious than that in winter [4]. The precipitation in Australia, Japan and India also had great regional variation [19,20]. In general, the feature of global precipitation was periodic; it increased gradually from 1901 to the mid-1950s, then stayed stable from the mid-1950s to the mid-1970s relatively, and decreased gradually from the mid-1970s to 1992. After 1992, it started to increase again [21]. In many regions, the reason for the precipitation increase was increasing disproportionate frequency of heavy precipitation events [22].

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

The Tibetan Plateau (TP) 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 area, where the precipitation variation plays an important role in the eco-hydrological processes [28]. The changes in precipitation would influence the local eco-environment's 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 variation was quite large and even decreased in some regions [29–33]. The areas where the precipitation increased were mainly located in the central, western and southern TP, while it has decreased in the eastern regions. The spatial difference of variation tendency in heavy precipitation days 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 an increasing trend in most regions, except in the Brahmaputra river basins [34]. Lu et al., found that the rate of precipitation trend has increased with altitude under 2000 m [35]. The precipitation trend in the TP could be divided into several periods and the rate in different periods differed greatly. The TP was rainy during 1985–1991 and 1998–2001, and rainless during 1962–1985 and 1991–1998 [32]. From the 1950s to the early 1990s, precipitation in the TP decreased [36]. The precipitation in the TP has increased at the rate of 6.66 mm/10a from 1961 to 2005 [37]. The trend of the annual precipitation is 12.0 mm/10a during 1971–2000, with spatial difference from −58.5 to 84.5 mm/10a [31]. The rate of precipitation trend in the TP also had great seasonal difference. The rate reached the maximum in summer, and it reached the minimum in autumn [31]. Different from the global conditions, the heavy precipitation events had no obvious increasing trend [37–39]. Some researchers have shown that land use and land cover change, CO_2 increases and aerosol, the North Atlantic Oscillation (NAO) and Sea Surface Temperature (SST) would have effects on precipitation [40–44].

At present, considerable research has been carried out about climate change in the TP, but problems also exist. (1) The homogeneity of data. Most of the research about climate change in the TP has not tested or corrected for the homogeneity. The meteorological data from stations may be influenced by location, environment, instrument and statistical method, resulting in the inhomogeneity of data series [45–47]; it would bring inevitable wrong to analysis on climate change. For this reason, the effect from non-climate factors must be eliminated when we study climate change, so that the result can reflect the real climate situations. (2) There is little study on the difference. Most of the current studies focus on climate variation in the whole plateau. There are few detailed analyses about local climate change in each region on the TP. The TP covers a great area with complex topography, and climate change here has a prominent spatial difference. Therefore, the contrast analysis of climate variation in different regions is a prerequisite for understanding the features of climate variation on the TP. 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 research may only be suitable in the central and eastern regions, rather than the whole TP [48].

In this paper, we have chosen the precipitation data from 65 stations in the TP and surrounding regions. Firstly, we tested and corrected these data for homogeneity. After correction, the quality of data improved significantly. We then used reintegration data to analyze the trend and range of precipitation variation in the TP, and analyze the precipitation data of each stations. Finally, we integrated all the results and obtained the conclusion about different precipitation variations in each station.

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 chose 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 chose 65 stations (Figure 1) and obtained their monthly precipitation data. All data are from the China Meteorological Administration. Table 1 gives 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 in the western regions. All data from these stations have experienced an initial quality test. We have interpolated and corrected the missing data or those with obvious mistakes. 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 ones. The four seasons are: spring, March–May (MAM); summer, June–August (JJA); autumn, September–November (SON); winter, December–February (DJF).

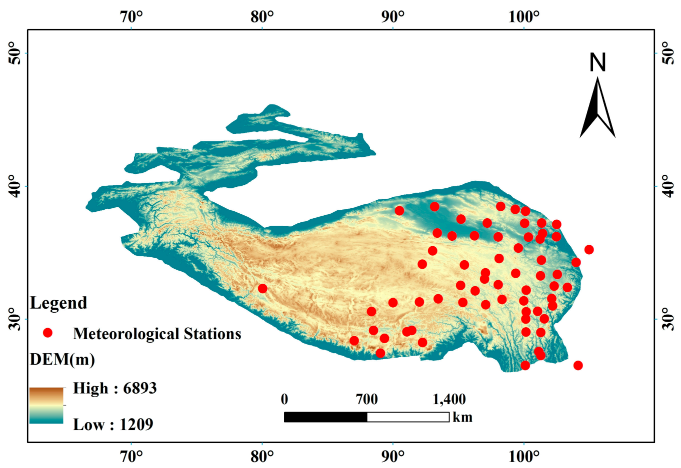

Figure 1. The location of selected meteorological stations.

Table 1. Detailed information of the selected stations.

Station Number	Name	Latitude (° N)	Longitude (° E)	Altitude (m)	Missing Period (Month)
51886	Mangya	38°15′	90°51′	2944.8	
52602	Lenghu	38°45′	93°20′	2770	
52633	Tuole	38°48′	98°25′	3367	
52645	Yeniugou	38°25′	99°35′	3320	
52657	Qilian	38°11′	100°15′	2787.4	
52707	Xiaozaohuo	36°48′	93°41′	2767	Apr.–Dec. 1974
52713	Dachaidan	37°51′	95°22′	3173.2	
52737	Delingha	37°22′	97°22′	2981.5	
52754	Gangcha	37°20′	100°08′	3302	
52765	Menyuan	37°23′	101°37′	2851	
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	
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	Apr. 1965
55299	Naqu	31°29′	92°04′	4507	
55472	Shenzha	30°57′	88°38′	4672	
55578	Rikaze	29°15′	88°53′	3836	
55591	Lasa	29°04′	91°08′	3648.9	Jun.–Oct. 1968
55598	Zedang	29°15′	91°46′	3551.7	
55664	Dingri	28°38′	87°05′	4300	Nov. 1968–Jan. 1969 Aug. 1969–Sep. 1970
55680	Jiangzi	28°55′	89°36′	4040	Jun. 1968
55696	Longzi	28°25′	92°28′	3860	Jul.–Aug. 1969
55773	Pali	27°44′	89°05′	4300	
56004	Tuotuohe	34°13′	92°26′	4533.1	
56018	Zaduo	32°54′	95°18′	4066.4	
56021	Qumalai	34°08′	95°47′	4175	Aug.–Dec. 1962
56029	Yushu	33°01′	97°01′	3681.2	
56033	Maduo	34°55′	98°13′	4272.3	
56034	Qingshuihe	33°48′	97°08′	4415.4	
56046	Dari	33°45′	99°39′	3967.5	
56065	Henan	34°44′	101°36′	3501	
56067	Jiuzhi	33°26′	101°29′	3628.5	
56079	Ruoergai	33°35′	102°58′	3439.6	
56083	Shiqu	32°59′	98°06′	4201	
56093	Minxian	34°26′	104°01′	2315	
56106	Suoxian	31°53′	93°47′	4022.8	
56116	Dingqing	31°25′	95°36′	3873.1	Jun.–Aug. 1969
56125	Nangqian	32°12′	96°29′	3643.7	
56137	Changdu	31°09′	97°10′	3306	Jun. 1969
56144	Dege	31°48′	98°35′	3199	
56146	Ganzi	31°37′	100°00′	3394	
56152	Seda	32°17′	100°20′	3896	
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	
56182	Songpan	32°39′	103°34′	2850.7	
56251	Xinlong	30°56′	100°19′	2999	
56257	Litang	30°00′	100°16′	3948.9	Sep. 1967 Jan.–Jul. 1968 May–Aug. 1969 Jan. 1970
56357	Daocheng	29°03′	100°18′	3729	May 1968
56374	Kangding	30°03′	101°58′	2615.7	Apr. 1969
56459	Muli	27°56′	101°16′	2426.5	
56462	Jiulong	29°00′	101°30′	2994	
56565	Yanyuan	27°26′	101°31′	2545	
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 (Climate Research Division, Environment Canada, Toronto, ON, Canada) 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 that 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 TP 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 $\{X_t\}$ with β as linear trend has discontinuity when $t = k$. Make the null hypothesis:

$$H_0:\ X_t = \mu + \beta t + \epsilon_t,\ t = 1, 2, \ldots, n \tag{1}$$

Make alternative hypothesis:

$$H_\alpha : \begin{cases} X_t = \mu_1 + \beta t + \epsilon_t,\ t \leq k \\ X_t = \mu_2 + \beta t + \epsilon_t, k-1\ \leq t \leq n \end{cases} \tag{2}$$

where $\mu_1 \neq \mu_2$. The time point $t = k$ would have discontinuity when H_α is true and $\Delta = |\mu_1 - \mu_2|$ is the range of mean-adjustment.

After testing for those stations with inhomogeneous data, RHtests have offered a corrected method called the 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:

$$\begin{cases} \mathrm{z_i} \in (\mu_1, \sigma),\ i \in \{1, 2, \ldots, p\} \\ \mathrm{z_i} \in (\mu_2, \sigma),\ i \in \{p+1, p+2, \ldots, n\} \end{cases} \tag{3}$$

where μ_1, μ_2 represent the mean residual of series before and after p, respectively; $\mu_2 - \mu_1$ 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.

The Mann–Kendall test statistic is given as follows,

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}}, S > 0 \\ 0\ S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}}, S < 0 \end{cases} \tag{4}$$

in which

$$S = \sum_{i=1}^{n-1} \sum_{k=\mathrm{i}+1}^{n} \mathrm{sgn}(x_k - x_i) \tag{5}$$

where the X_k, X_i are the sequential data values, n is the length of the data set, and sgn (θ) is equal to 1, 0, −1 if θ is greater than, equal to, or less than zero, respectively. The null hypothesis $\mathrm{H_0}$ is accepted if $-\mathrm{Z}_{1-\mathrm{a}/2} \leq \mathrm{Z}_c \leq \mathrm{Z}_{1-\mathrm{a}/2}$.

In the Mann–Kendall test, another very useful index is the Kendall slope, which is the magnitude of the monotonic trend and is given as

$$\beta = \text{Median}\left(\frac{x_i - x_j}{i - j}\right), \forall j < i \quad (6)$$

in which $1 < j < i < n$. The estimator β is the median overall combination of record pairs for the whole data set, and is thereby resistant to the effect of extreme values in the observations. A positive value of β indicates an "upward trend", i.e., increasing values with time, and a negative value of β indicates a "downward trend", i.e., decreasing values with time.

3. Results

This section may be divided into three 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. Trend in Annual and Seasonal 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 trend at every station (Table 2) in order to study the annual precipitation distribution and the monthly precipitation trend. The annual mean precipitation in the TP is 465.5 mm during 1961–2015. Among the four seasons, the precipitation in summer accounts for 60.1% of the annual precipitation. The precipitation in summer half-year (May–October) accounts for 91.0%, while that in winter half-year (November–April) 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% (Figure 2). Among the 12 months, the trends of precipitation in August, September and November are decreasing and that in December has no significant change. The range of precipitation trend reaches a maximum in May, which is 1.64 mm/10a, and significant at 99% confidence level (CI) (Table 2).

Table 2. The precipitation amount and trends in each month on the TP during 1961–2015.

Month	Precipitation (mm)	Ratio of Annual Precipitation (%)	Precipitation Trend (mm/10a)
Junuary	2.7	0.6	0.18
Feburary	3.9	0.8	0.17
Marrch	9.4	2.0	0.59 *
April	19.5	4.2	0.92 *
May	46.7	10.0	1.64 *
June	85.9	18.4	0.86
July	102.6	22.1	0.46
August	91.2	19.6	−0.45
September	70.6	15.2	−0.77
October	26.5	5.7	0.29
November	4.8	1.0	0.01
December	1.9	0.4	0.01
Annual	465.5	100	3.87

* Represents significance at 95% level; TP = Tibetan Plateau.

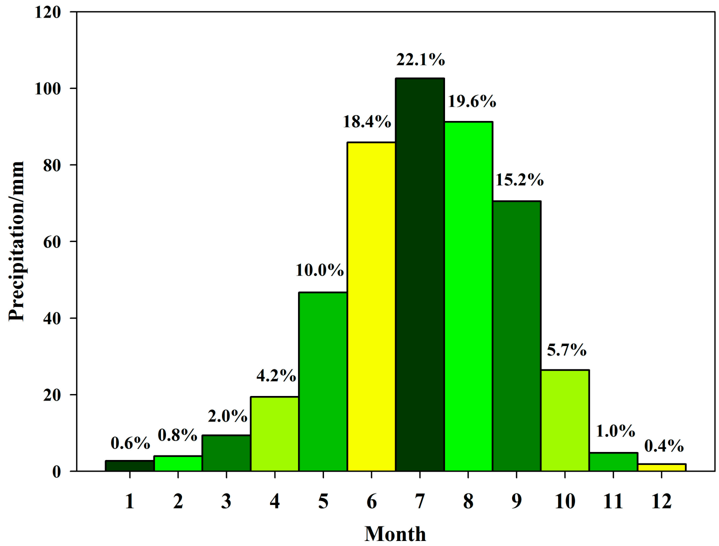

Figure 2. The precipitation distribution in each month on the TP during 1961–2015.

During 1961–2015, the annual precipitation trend is 3.8 mm/10a in the TP and the seasonal precipitation trend in spring, summer, autumn and winter is 3.0 mm/10a, 0.0 mm/10a, −0.1 mm/10a and 0.4 mm/10a, respectively (Figure 3). The spring and winter precipitation trend is significant at 95% confidence level, while those in summer and autumn are not significant at 95% confidence level. Only in autumn is the precipitation 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 shows no significant change. However, from the 1970s to the 1980s, the mean precipitation increased 10.9 mm, and comparing the first 15 years of this century with the 1990s, the precipitation also had a great increase of 10.0 mm. For each station, the precipitation trend ranged from −72.75 mm/10a (Shiqu station) to 28.45 mm/10a (Kangding station). There are 49 stations whose precipitation trend is positive among the 65 stations, 75% of the total; there are 16 stations whose precipitation trend is negative among the 65 stations, 25% of the total (Figure 4). In general, the precipitation trend 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.

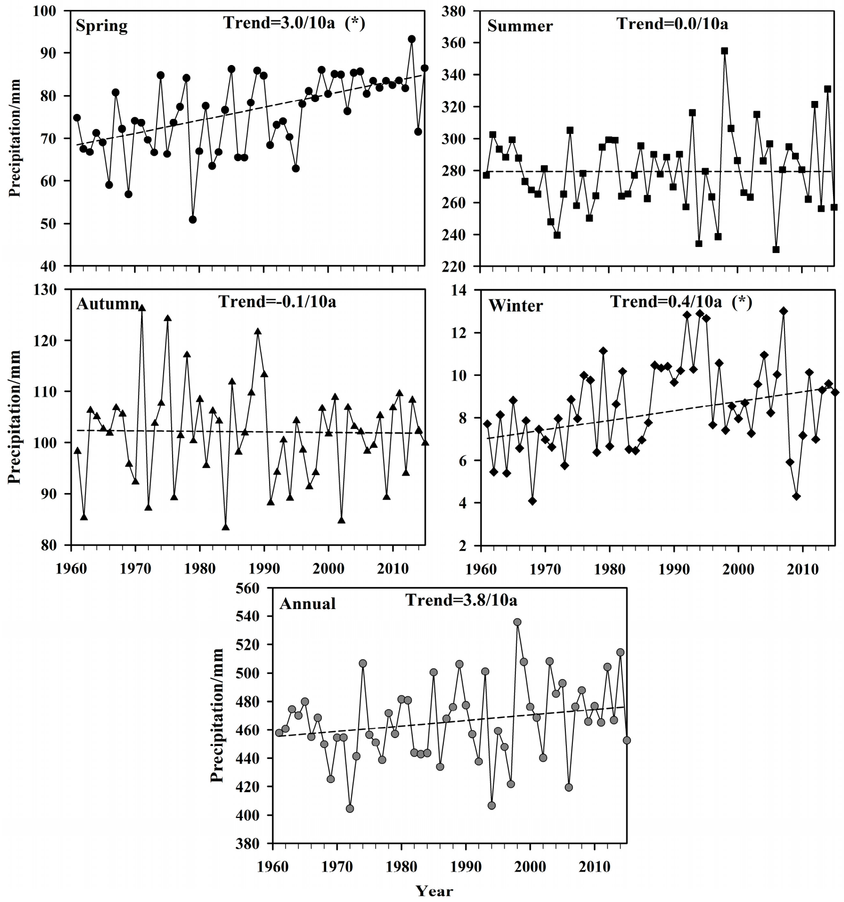

Figure 3. The trend in the annual and seasonal precipitation from 1961 to 2015 over the TP; * Represents significant at 95% level.

There is a great difference among the annual and seasonal change of precipitation in different stations. The variation range is −6.2 mm/10a to 9.6 mm/10a in spring; −46.7 mm/10a to 16.3 mm/10a in summer; −14.7 mm/10a to 7.6 mm/10a in autumn, and −2.4 mm/10a to 2.1 mm/10a in winter. Figure 5 shows the number of stations with different precipitation trends. In spring, the precipitation trend is mainly concentrated in the range 0–10 mm/10a and the number of stations is 58, 89% of the total; in summer, the precipitation trend is mainly concentrated in the range −10 mm/10a to 10 mm/10a and the number of stations is 54, 83% of the total; in autumn, the precipitation trend is mainly concentrated in the range −1 mm/a to 8 mm/10a and the number of stations is 63, 97% of the total; in winter, the precipitation trend is mainly concentrated in the range 0–10 mm/10a and the number of stations is 56, 86% of the total. The annual precipitation trend is mainly concentrated in the range 0–20 mm/10a and the number of stations is 46, 71% of the total.

Table 3. The average annual and seasonal precipitation in different periods during 1961–2015.

Period	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

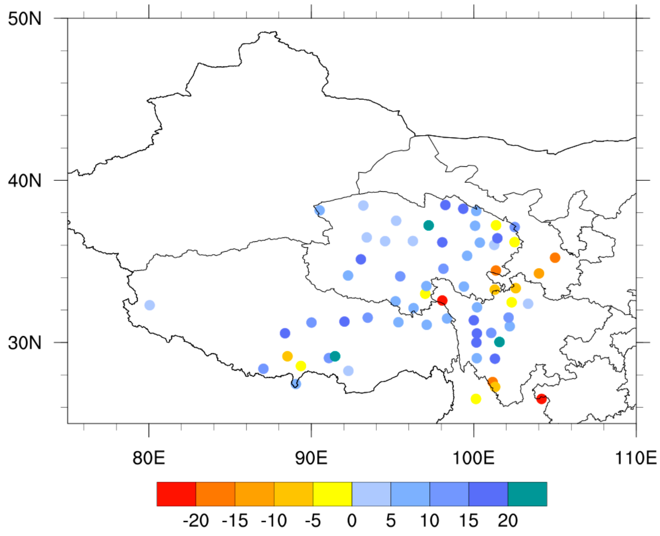

Figure 4. Spatial distribution of long-term trends in the precipitation (mm/10a) during 1961–2015.

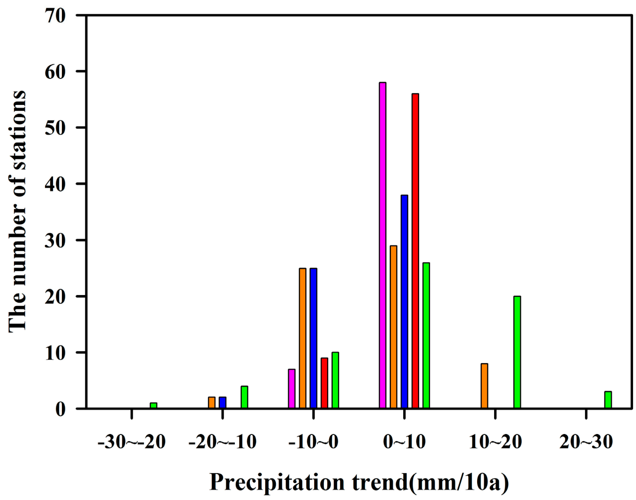

Figure 5. The number of stations with different precipitation trends during 1961–2015.

Table 4 has listed the top ten stations with the most significant increasing and decreasing in precipitation. The top ten stations with the most obvious increasing in precipitation have a precipitation trend ranging from 16.1 mm/10a to 28.5 mm/10a, and the top ten stations with the most obvious decreasing in precipitation have a precipitation trend ranging from −72.8 mm/10a to −4.8 mm/10a. The phenomena prove that the precipitation trend has great spatial difference in the TP. The station with the most obvious increasing on annual precipitation is Kangding station, whose precipitation trend is 28.5 mm/10a; the station with the most obvious decreasing on annual precipitation is Shiqu station whose precipitation trend is −72.8 mm/10a. The mean precipitation trend among all stations is 3.8 mm/10a. Some previous research has indicated that climate change has an obvious periodic characteristic [55]. The warming trend shows great difference in different period. After the 1990s, the temperature in the TP increased sharply [56], and so did the precipitation [57].

Table 4. Information of the ten stations with the largest upward (downward) trends in precipitation during 1961–2015.

10 Stations with Largest Upward Trends		10 Stations with Largest Downward Trends	
Name	**Precipitation Trend (mm/10a)**	**Name**	**Precipitation Trend (mm/10a)**
Kangding	28.48 *	Shiqu	−72.75 *
Zedang	27.45	Weining	−24.44
Delingha	22.20 *	Huajialing	−16.27 *
Dulan	18.47 *	Muli	−15.76 *
Jiulong	17.72	Henan	−12.66
Wudaoliang	17.67	Minxian	−8.50
Litang	16.56 *	Yanyuan	−6.50
Yeniugou	16.46 *	Ruoergai	−5.32 *
Xinlong	16.15	Jiuzhi	−5.08 *
Tuole	16.14	Rikaze	−4.82

* Represents significance at 95% level.

3.2. The Relationship Between Precipitation and Its Trend and Altitude, Latitude and Longitude

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 6). 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.

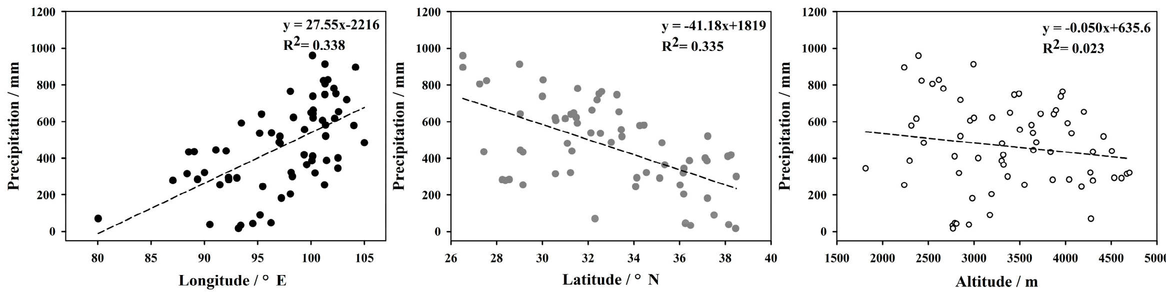

Figure 6. The relationship between precipitation and longitude, latitude and altitude.

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

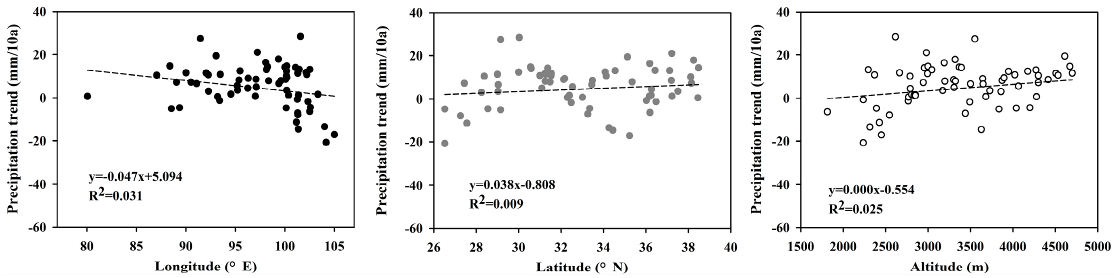

Figure 7. The relationship between the precipitation trend and longitude, latitude and altitude.

3.3. The Possible Reasons for Precipitation Variations

The precipitation has increased during the years 1961–2015 in the TP at the rate of 3.8 mm/10a. During 1901–1998, the global precipitation trend was 0.89 mm/10a [21]. However, the global precipitation began to decrease during 1951–1980 at the rate of −4 mm/10a; the precipitation trend is −13 mm/10a in the Northern Hemisphere and 14 mm/10a in the Southern Hemisphere [7]. In Asia, the summer precipitation has decreased during 1978–2002, and the summer precipitation trend is −35.6 mm/10a in southwestern Asia and −40.8 mm/10a in northeastern Asia. In China, the precipitation has increased at the rate of 3.3 mm/10a during 1955–2007, and the winter precipitation trend is 1.5 mm/10a and the summer precipitation trend is 1.6 mm/10a [24]. In the TP, the precipitation has great temporal–spatial distribution, the trends of precipitation variation have great difference in different regions or at different times. Research has shown that the frequency of extreme precipitation events changes disproportionately. In China, the frequency of extreme precipitation events has reduced by 10%. The light precipitation events have decreased and the heavy precipitation events have increased [58]. During nearly 50 years, the extreme precipitation has shown a significant spatial and temporal difference in China. However, during the same period, the precipitation intensity has no significant increase in the TP [37].

The research on climate model simulation showed that the rising surface temperature may cause the global precipitation to increase [14,59]. The land cover changes can affect the dynamic and thermodynamic power of atmosphere by changing the hydrological cycle and energy budget, and so that it can change the climate [60]. Cui et al. indicated that the variation of land use has influenced local climate in the TP [40]. The land use changes make the TP wetter, and it contributes 90 mm/10a 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 (NAO) and the El Niño also have effects on precipitation in the TP [43].

The precipitation variation shows significant differences in different places and times in the TP. The precipitation in the southeastern regions is heavier than that in the central regions from a spatial scale. Since the 1990s, the increasing precipitation has been associated with the rising temperature. It has been proven that the trend of precipitation is increasing under the background of climate warming, and the trend increases with the rising of the warming rate. The high-speed economic development has led to the increase in carbon dioxide in the TP, especially in the southeastern regions. The spatial distribution of precipitation trend is connected with the complex topography in the TP. The TP has a vast territory and varied terrain with mountains, plain and rivers cross-distributed. It has formed a 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 [35]. The research by Liu et al. pointed out an adverse feature between NAO and precipitation in the southern and northern regions [58]. Different patterns of atmospheric circulation can also lead to the spatial distribution of precipitation variation [62].

4. Discussion and Conclusions

This paper chose the precipitation data from 65 stations during 1961–2015 in the TP and surrounding regions. Variations, trends and temporal–spatial distribution of precipitation have been studied; furthermore, the possible reasons were also discussed preliminarily. During 1961–2015, the annual mean precipitation on the TP was 465.5 mm, the annual precipitation trend was 3.8 mm/10a and the seasonal precipitation trend was 3.0 mm/10a, 0.0 mm/10a, −0.1 mm/10a and 0.4 mm/10a in spring, summer, autumn and winter on the TP, respectively. The precipitation in summer (June–August (JJA)) accounted for 60.1% of the whole year's precipitation, the precipitation in summer half-year (May–October) accounted for 91.0%, while the precipitation in winter half-year (November–April) only accounted for 9.0% of the whole year's precipitation. The precipitation has decreased from the southeastern to northwestern TP. The precipitation increases with the increase of longitude, while it decreases with the increase of latitude. The trend of precipitation is decreasing with the increase of altitude, but the correlation is not significant. Due to a lack of observation data and limitation of the methods, our study results have some uncertainty, and the study also has some deficiencies.

Two prominent problems in the TP are the harsh natural environment and less observational data, especially in the wide western regions. Observational data from stations is the foundation of studying 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 on homogeneity. All test methods have their advantages and disadvantages at present, and different methods may be suitable for different meteorological factors. So, choosing suitable methods is of incredible importance to the future study on varied meteorological factors. The station historical data (metadata) play 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 exhaustively as possible in the TP.

The climate environment is special in the TP. Many studies on climate change have been carried out and include almost all climate factors, but most of them focus on precipitation and temperature only. In the future, more studies on other climate factors need to be carried out to understand the characteristics of climate change. Otherwise, because of the lack of sufficient quantitative analysis, we have no profound understanding of the physical mechanism of climate change in the TP. For these reasons, the quantitative study is essential in future study.

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References

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; pp. 1–30.
2. Shi, Y.; Shen, Y.; Kang, E.; Li, D.; Ding, Y.; Zhang, G.; Hu, R. Recent and future climate change in northwest China. *Clim. Chang.* **2007**, *80*, 379–393. [CrossRef]

3. Radić, 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. [CrossRef]
4. Sala, O.E.; Chapin, F.S.; Armesto, J.J.; Berlow, E.; Bloomfield, J.; Dirzo, R.; Huber-Sanwald, E.; Huenneke, L.E.; Jackson, R.B.; Kinzig, A.; et al. Global biodiversity scenarios for the year 2100. *Science* **2000**, *287*, 1770–1774. [CrossRef] [PubMed]
5. Chapin, F.S.; Osvaldo, E.S.; Huber-Sannwald, E. *Global Biodiversity in a Changing Environment: Scenarios for the 21st Century*; Springer: New York, NY, USA, 2013; pp. 5–22.
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. *J. Clim.* **2016**, *29*, 5205–5222. [CrossRef]
7. Yao, C.; Yang, S.; Qian, W.; Lin, Z.; Wen, M. Regional summer precipitation events in Asia and their changes in the past decades. *J. Geophys. Res. Atmos.* **2008**, *113*, 487–497. [CrossRef]
8. Roderick, M.L.; 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. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 1575–1589. [CrossRef]
9. Hirabayashi, Y.; Mahendran, R.; Koirala, S.; Konoshima, L.; Yamazaki, A.; Watanabe, S.; Kim, H.; Kanae, S. Global flood risk under climate change. *Nat. Clim. Chang.* **2013**, *3*, 816–821. [CrossRef]
10. Trenberth, K.E.; Dai, A.; van der Schrier, G.; Jones, P.D.; Barichivich, J.; Briffa, K.R.; Sheffield, J. Global warming and changes in drought. *Nat. Clim. Chang.* **2014**, *4*, 17–22. [CrossRef]
11. Weltzin, J.F.; Loik, M.E.; Schwinning, S.; Williams, D.G.; Fay, P.A.; Haddad, B.M.; Harte, J.; Huxman, T.E.; Knapp, A.K.; Lin, G.; et al. Assessing the response of terrestrial ecosystems to potential changes in precipitation. *Bioscience* **2009**, *53*, 941–952. [CrossRef]
12. Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.; Peng, S.; Li, J.; Zhou, L.; Liu, H.; Ma, Y.; Ding, Y.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [CrossRef] [PubMed]
13. Jones, P.D.; Hulme, M. Calculating regional climatic time series for temperature and precipitation: Methods and illustrations. *Int. J. Climatol.* **1996**, *16*, 361–377. [CrossRef]
14. Hulme, M.; Osborn, T.J.; Johns, T.C. Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations. *Geophys. Res. Lett.* **1998**, *25*, 3379–3382. [CrossRef]
15. Karl, T.R.; Knight, R.W. Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Am. Meteor. Soc.* **1998**, *79*, 231–241. [CrossRef]
16. Li, Y.; Li, D.; Yang, S.; Liu, C.; Zhong, A.; Li, Y. Characteristics of the precipitation over the eastern edge of the Tibetan Plateau. *Meteorol. Atmos. Phys.* **2010**, *106*, 49–56. [CrossRef]
17. Klein Tank, A.M.G.; Wijngaard, J.B.; Können, G.P.; Böhm, R.; Demarée, G.; Gocheva, A.; Pashiardis, S.; Hejkrlik, L.; Kern-Hansen, C.; Heino, R.; et al. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *Int. J. Climatol.* **2002**, *22*, 1441–1453. [CrossRef]
18. Pal, J.S.; Giorgi, F.; Bi, X. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. *Geophys. Res. Lett.* **2004**, *31*, 1–4. [CrossRef]
19. Xu, Z.; Takeuchi, K.; Ishidaira, H. Monotonic trend and step changes in Japanese precipitation. *J. Hydrol.* **2003**, *279*, 144–150. [CrossRef]
20. Sen Roy, S.; Balling, J.R.; Robert, C. Trends in extreme daily precipitation indices in India. *Int. J. Climatol.* **2004**, *24*, 457–466. [CrossRef]
21. New, M.; Todd, M.; Hulme, M.; Jones, P. Precipitation measurements and trends in the twentieth century. *Int. J. Climatol.* **2001**, *21*, 1889–1922. [CrossRef]
22. Mohammed, H.I. Climate change and changes in global precipitation patterns: What do we know? *Environ. Int.* **2005**, *31*, 1167–1181.
23. Zhai, P.; Zhang, X.; Wan, H.; Pan, X. Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Clim.* **2005**, *18*, 1096–1108. [CrossRef]
24. Choi, G.; Collins, D.; Ren, G.; Trewin, B.; Baldi, M.; Fukuda, Y.; Afzaal, M.; Pianmana, T.; Gomboluudev, P.; Huong, P.T.T.; et al. Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. *Int. J. Climatol.* **2011**, *29*, 1906–1925. [CrossRef]
25. Liu, B.; Xu, M.; Henderson, M.; Qi, Y. Observed trends of precipitation amount, frequency, and intensity in China, 1960–2000. *J. Geophys. Res. Atmos.* **2005**, *110*, 1–10. [CrossRef]
26. Xin, H. A green fervor sweeps the Qinghai-Tibetan Plateau. *Science* **2008**, *321*, 633–635. [CrossRef] [PubMed]

27. Feng, L.; Wei, F. Regional characteristics of summer precipitation on Tibetan Plateau and it's water vapor feature in neighboring areas. *Plateau Meteor.* **2008**, *27*, 491–499.
28. Cannarozzo, M.; Noto, L.V.; Viola, F. Spatial distribution of rainfall trends in Sicily (1921–2000). *Phys. Chem. Earth* **2006**, *31*, 1201–1211. [CrossRef]
29. Niu, T.; Chen, L.; Zhou, Z. The characteristics of climate change over the Tibetan Plateau in the last 40 years and the detection of climatic jumps. *Adv. Atmos. Sci.* **2004**, *21*, 193–203. [CrossRef]
30. Ma, X.; Hu, Z. Precipitation variation characteristics and abrupt change over Qinhai-Xizang Plateau in recent 40 years. *J. Desert Res.* **2005**, *25*, 137–139.
31. Wu, S.; Yin, Y.; Zheng, D.; Yang, Q. Climatic trends over the Tibetan Plateau during 1971–2000. *J. Geogr. Sci.* **2007**, *17*, 141–151. [CrossRef]
32. Xu, Z.; Gong, T.; Li, J. Decadal trend of climate in the Tibetan Plateau-regional temperature and precipitation. *Hydrol. Process.* **2008**, *22*, 3056–3065. [CrossRef]
33. Xie, H.; Ye, J.; Liu, X.; Chongyi, E. Warming and drying trends on the Tibetan Plateau (1971–2005). *Theor. Appl. Climatol.* **2010**, *101*, 241–253. [CrossRef]
34. Zhou, S.; Wang, C.; Wu, P.; Wang, M. Temporal and spatial distribution of strong precipitation days over the Tibetan Plateau. *Arid Land Geogr.* **2012**, *35*, 23–31.
35. Lu, H.; Shao, Q.; Liu, J.; Chen, Z. Temporo-spatial distribution of summer precipitation over Qinghai-Tibet Plateau during the last 44 years. *Acta Geogr. Sin.* **2007**, *62*, 946–958.
36. Lin, Z.; Zhao, X. Spatial characteristics of changes in temperature and precipitation of the Qinghai-Xizang (Tibet) Plateau. *Sci. China Earth Sci.* **1996**, *39*, 442–448.
37. You, Q.; Kang, S.; Aguilar, E.; Yan, Y. Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961–2005. *J. Geophys. Res. Atmos.* **2008**, *113*, 1639–1647. [CrossRef]
38. Easterling, D.R.; Meehl, G.A.; Parmesan, C.; Changnon, A.A.; Kar, T.R.; Mearns, L.O. Climate extremes: Observations, modeling, and impacts. *Science* **2000**, *289*, 2068–2074. [CrossRef] [PubMed]
39. Groisman, P.Y.; Knight, R.W.; Easterling, D.R.; Karl, T.R.; Hegerl, G.C. Trends in intense precipitation in the climate record. *J. Clim.* **2005**, *18*, 1326–1350. [CrossRef]
40. Cui, X.; Graf, H.F.; Langmann, B.; Chen, W.; Hhuang, R. Climate impacts of anthropogenic land use changes on the Tibetan Plateau. *Glob. Planet. Chang.* **2006**, *54*, 33–56. [CrossRef]
41. Guo, Y.; Yu, Y.; Liu, X.; Zhang, X. Simulation of climate change induced by CO_2 increasing for East Asia with IAP/LASG GOALS model. *Adv. Atmos. Sci.* **2001**, *18*, 53–66.
42. Lau, K.M.; Kim, K.M. Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophys. Res. Lett.* **2006**, *33*, 320–337. [CrossRef]
43. Liu, H.; Duan, K. Effects of north atlantic oscillation on summer precipitation over the Tibetan Plateau. *J. Glaciol. Geocryol.* **2012**, *34*, 311–318.
44. Dai, A. Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* **2013**, *3*, 52–58. [CrossRef]
45. Li, Q.; Liu, X.; Zhang, H.; Peterson, T.C.; Easterling, D.R. Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. *Adv. Atmos. Sci.* **2004**, *21*, 260–268. [CrossRef]
46. Begert, M.; Schlegel, T.; Kirchhofer, W. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *Int. J. Climatol.* **2005**, *25*, 65–80. [CrossRef]
47. Yan, Z.; Li, Z.; Xia, J. Homogenization of climate series: The basis for assessing climate changes. *Sci. China Earth Sci.* **2014**, *57*, 2891–2900. [CrossRef]
48. Qin, J.; Yang, K.; Liang, S.; Guo, X. The altitudinal dependence of recent rapid warming over the Tibetan Plateau. *Clim. Chang.* **2009**, *97*, 321–327. [CrossRef]
49. Cao, L.; Ju, X.; Liu, X. Penalized maximal F test for the homogeneity study of the annual mean wind speed over China. *Meteor. Mon.* **2010**, *36*, 52–56.
50. Zhang, X.; Aguilar, E.; Sensoy, S.; Melkonyan, H.; Tagiyeva, U.; Ahmed, N.; Kutaladze, N.; Rahimzadeh, F.; Taghipour, A.; Hantosh, T.H.; et al. Trends in Middle East climate extreme indices from 1950 to 2003. *J. Geophys. Res. Atmos.* **2005**, *110*, 3159–3172. [CrossRef]
51. Wang, X. Comments on "Detection of undocumented changepoints: A revision of the two-phase regression model". *J. Clim.* **2003**, *16*, 3383–3385. [CrossRef]
52. Wang, X. Accounting for autocorrelation in detecting mean-shifts in climate data series using the penalized maximal t or F test. *J. Appl. Meteor. Climatol.* **2008**, *47*, 2423–2444. [CrossRef]

53. Wang, X. Penalized maximal f-test for detecting undocumented mean-shifts without trend-change. *J. Atmos. Ocean. Technol.* **2008**, *25*, 368–384. [CrossRef]
54. Lu, A.; Kang, S.; Quan, Q. Spatial precipitation variation across China during 1951–2002. *Ecol. Environ. Sci.* **2010**, *19*, 205–207.
55. Cai, Y.; Li, D.; Tang, M.; Bai, C. Decadal temperature changes over Qinghai-Xizang Plateau in recent 50 years. *Plateau Meteor.* **2003**, *22*, 464–470.
56. Jiang, Y.; Li, S.; Shen, D.; Chen, W.; Jin, C. Climate change and its impact on the lake environment in the Tibetan Plateau in 1971–2008. *Sci. Geogr. Sin.* **2012**, *32*, 1503–1512.
57. Du, J.; Ma, Y. Climate trend of rainfall over Tibetan Plateau from 1971 to 2000. *Acta Geogr. Sin.* **2004**, *59*, 375–382.
58. Liu, X.; Yin, Z.; Shao, X.; Qin, N. 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. *J. Geophys. Res. Atmos.* **2006**, *111*, 4617–4632. [CrossRef]
59. Wentz, F.J.; Ricciardulli, L.; Hilburn, K.; Mears, C. How much more rain will global warming bring? *Science* **2007**, *317*, 233–235. [CrossRef] [PubMed]
60. Werth, D.; Avissar, R. The local and global effects of Amazon deforestation. *J. Geophys. Res.* **2002**, *107*, 5823–5826. [CrossRef]
61. Meehl, G.A.; Arblaster, J.M.; Collins, W.D. Effects of black carbon aerosols on the Indian monsoon. *J. Clim.* **2008**, *21*, 2869–2882. [CrossRef]
62. Yao, T.; Thompson, L.; Yang, W.; Yu, W.; Gao, Y.; Guo, X.; Yang, X.; Duan, K.; Zhao, H.; Xu, B.; et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Chang.* **2012**, *2*, 663–667. [CrossRef]