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Temporal and spatial variability in precipitation trends in the Southeast Tibetan Plateau during 1961–2012

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Abstract

Using the monthly precipitation data at 14 stations from 1961 to 2012, the precipitation trends at the seasonal and annual scales are analyzed using the Mann–Kendall test in the Southeast Tibetan Plateau (STP). The area-averaged precipitation shows an increasing trend in the STP with strong temporal and spatial variations. The seasonal and annual precipitation increased, except in the summer; the annual precipitation increased by about one millimeter pre year over the last 52 years. The spring precipitation significantly increased at the 99 % confidence level, while the mean summer precipitation insignificantly decreased at the 95 % confidence level. The extreme precipitation, including the maxima and minima, also experienced overall increases. More than 78 % of the stations exhibited increases in the annual precipitation (93 % in spring). The precipitation variation with elevation was not obvious, but the variation with complex topography was obvious in the STP. The largest precipitation increases and decreases occurred in high-precipitation areas, while the increasing precipitation was dominant in or near the main area of the Tibetan Plateau (TP). The results of this study reveal the spatio-temporal variability in the precipitation trends in the STP for the first time. The results are beneficial for understanding the local climate characteristics in the STP and in the entire TP.

1 Introduction

Global warming is one of the most apparent climate changes that has occurred in recent decades and is gaining attention (Schaefer and Domroes, 2009). In addition to the increase in the surface temperature, the change in precipitation is notable (Chou and Lan, 2011). Information on the temporal and spatial distributions of precipitation is important for a variety of applications in hydrology and water resources management (Campling et al., 2001). Related to global warming, changing precipitation patterns and their effect on surface water resources are currently important climatic problems

(Maragatham, 2011). Under the background of global warming, the globally averaged mean precipitation exhibits an increase with a strong spatial variation based on observations and model simulations (Allen and Ingram, 2002; Meehl et al., 2007; Trenberth et al., 2007), in which different areas show different patterns of change in precipitation (Huang et al., 2013; Wang et al., 2011). For example, trends in the precipitation amount from 1900 to 2005 have been observed in many large regions. Over this period, the precipitation increased significantly in eastern parts of northern and southern America, northern Europe and northern and central Asia, whereas precipitation decreased in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (IPCC, 2007). Confidence in the average precipitation change over global land areas was low between 1901 and 1951 and moderate afterwards. According to the average over the midlatitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (moderate confidence before 1951 and high confidence afterward). For the longest common period of record (1901–2008), all of the datasets exhibit increases in the globally averaged precipitation. The precipitation over tropical land areas (30° S to 30° N) has increased over the last decade, reversing the drying trend that occurred from the mid-1970s to the mid-1990s. Therefore, the period of 1951–2008 shows no significant overall trend in tropical land precipitation. Long-term trends (1901–2008) in the tropics are also insignificant. The midlatitudes of the Northern Hemisphere (30–60° N) experienced an overall increase in precipitation from 1901 to 2008, with statistically significant trends (IPCC, 2013).

Several studies have attempted to determine the precipitation trend in China as a whole and on a regional scale. Although no significant trend has been found in country-averaged annual precipitation, interdecadal variability and trends on regional scales have been detected (Ding et al., 2007). Wang and Zhou (2005) have indicated that the mean annual precipitation in Southwest, Northwest, and East China has significantly increased; in Central, North and Northeast China, the value has significantly decreased (1961 to 2001). Studies have also shown that after the abrupt climate shift near the end of the 1970s (Chen and Wu, 2000; Ho et al., 2005; Hu, 1997; Wang, 2001; Weng et al., 1999; D. Q. Zhang et al., 2004, Y. S. Zhang et al., 2004), precipitation patterns over eastern China experienced a significant adjustment. North and Northeast China have suffered from severe and persistent droughts, while the Yangtze River Basin and South China have experienced heavier precipitation and more flood events (Ding et al., 2007; Hu et al., 2003; Lau and Weng, 2001; Weng et al., 1999; Yang and Lau, 2004; Zhou et al., 2009).

Previous studies have shown that the temporal and spatial distributions of precipitation changes were extremely uneven and variable between regions (Manish, 2014). Hence, many investigations have been conducted to explore whether precipitation records exhibit trends at the local scale in China. For example, Wang et al. (2013) have shown a slight and insignificant increase in precipitation during 1961–2008 in the Jinshajiang River Basin in China. Zhong and Li (2009) have found that the annual precipitation in Mianyang of Sichuan Province, China, displayed a decreasing tendency. Xu et al. (2010) have found that the mean annual precipitation increased in the Tarim River Basin from 1960 to 2007. In addition, many studies have analyzed the regional changes in precipitation for the Yangtze River Basin (Gong and He, 2006; Su and Jiang, 2008; Su et al., 2007; J. J. Xu et al., 2007; Zhang et al., 2006; Zeng et al., 2008).

The Tibetan Plateau (TP) is appropriately known as “the roof of the world”. The large area’s abnormal thermodynamic and dynamic effects and other land–air physical processes obviously affect climate variations and disastrous weather in China, eastern Asia and the entire world. For example, the TP exerts an important influence on the regional and global climate because of its thermal and mechanical forcings (Cuo et al., 2013; Lin and Wu, 2011; Liu et al., 2007; Manabe and Broccoli, 1990; Nan et al., 2009; Sun and Ding, 2011; Yanai et al., 1992). The thermal forcing over the TP during the winter and spring plays a considerable role in regulating the East Asian summer monsoon and corresponding precipitation patterns (Chen and Wu, 2000; Duan et al., 2003, 2013; Wu and Qian, 2003; Wu et al., 1997; Zhao and Chen, 2001; Zhao and Qian, 2007; Zhao et al., 2007). Furthermore, the TP is the source region of major Asian river systems, e.g., the Tarim, Amu Darya, Indus, Ganges, Yarlung Zangbo (Brahmaputra in India), Irrawaddy, Nujiang (Salween in Burma), Lancangjiang (Mekong in Vietnam), Yellow and Yangtze Rivers. Therefore, the TP is considered the water tower of Asia (Immerzeel et al., 2010). The role of the TP in the global water cycle and its response to climate change have become topics of significant scientific interest (e.g., Biermann et al., 2014; Immerzeel et al., 2010; Ni, 2011). The precipitation characteristics of the TP are important to understand because the convection, precipitation and associated release of latent heat above 4000 m influence variations in the Asian monsoons (Shimizu, 2002).

The TP is located in southwestern China, occupying nearly one-fourth of the total land area of China; the area has obvious effects on the precipitation variations in the Yangtze River Basin and in China. In addition, the TP remains an area that is sensitive to global changes. Significant research has been focused on the analysis of precipitation characteristics in the TP under global warming. Li et al. (2010) have found that precipitation tended to increase 9.1 mm every ten years; however, regional differences were apparent. The western area of Sichuan Province, which lies in the southeast portion of the Tibet Autonomous Region, showed the most significant increase in precipitation. Research by Lu et al. (2008) has shown that the summer precipitation tendencies at stations differed from 1961 to 2004 over the TP. Most of the stations with increases were located in the southern and northeastern plateau. Most of the stations with decreases were located in the central-eastern plateau. However, the summer precipitation tendencies were small and generally insignificant during the study period. Tan et al. (2010) have shown that the annual precipitation displayed a slight increase, with a significant regional difference in the southern TP from 1971 to 2007. Li et al. (2007) have found that the precipitation in the TP had an overall increasing trend from 1971 to 2004. The precipitation increased most remarkably in the southern parts of the Tibet Autonomous Region and Sichuan Province, followed by the Qaidam Basin, Qinghai Lake, and the Hexi Corridor. The decreasing precipitation trend primarily occurred in eastern Qinghai Province, the source region of three rivers

(Lancangjiang, Yellow and Yangtze Rivers), the Qilian Mountains, and northwestern Sichuan Province. Duan et al. (2008) have found that precipitation also varies differently in the southern and northern TP at a secular time scale. Wu et al. (2005) have shown that the primary trends in climate change are a temperature rise and a precipitation increase in the TP based on observational data. Li (2011) has found that the annual precipitation in the northern TP showed a decreasing trend, but the southern TP showed an increasing trend. In addition, the distribution of precipitation in the TP from the Brahmaputra Valley to the northwest showed a gradual decreasing trend, with the highest level of precipitation in the lower reaches of the Brahmaputra River; the lowest average annual precipitation of the northwestern Qaidam Basin is only 17.6 mm. Cuo et al. (2013) have found that the precipitation trend showed significant spatial variations over the northern TP from 1957 to 2009.

Generally, most studies have determined the changes in precipitation in the TP as a whole, but there are obvious regional disparities in the precipitation distribution because of the special topography features in this region. To date, no research on spatio-temporal variations in precipitation trends in the Southeast Tibetan Plateau (STP) have been conducted. In this study, the temporal and spatial variability in precipitation trends over the STP are researched for the first time using observational data from 1961 to 2012 on the seasonal and annual time scales. The results can enhance our understanding of the regional climate changes in the study area, particularly in the TP. Additionally, annual and seasonal precipitation is important to the hydrological cycle. A non-uniform distribution of precipitation trends has reportedly influenced the river flow system (Stahl et al., 2010; Wilson et al., 2010), and a precipitation change analysis is beneficial for regional water resources management (Cheng et al., 2002, 2008; Chau et al., 2005; Wang et al., 2009). The results of this study should provide additional information for water resources planning and flood protection in the STP (Lin et al., 2006; Wu et al., 2009).

2 Study area

The STP does not have a recognizable border. According to previous studies (Gao, 2007; Li et al., 2008), shown in Fig. 1, the study area of the STP is located between 92°30′–99°30′ E and 26°30′–32°30′ N in southwestern China, which covers three provinces: the Tibet Autonomous Region, Yunnan Province and Sichuan Province.

The STP, namely, the southeastern edge of the TP, experiences the interaction between the south Asian climatic system and the TP. The STP is located in the Gangrigabu Mountains in the southeastern TP, which is a joint section among the Himalayas, the Nyainqentanglha Mountains and the Hengduan Mountains. Four well-known rivers flow through the STP: the Yarlung Zangbo, Nujiang, Lancangjiang and Jinshajiang Rivers. This region has prominent multi-scale terrain, with intersecting high mountain ranges, deep valleys and extremely complicated surface features. The peaks reach over 6000 m in elevation, and valleys are as deep as approximately 2000–3000 m. Glaciers, rivers, lakes, grasslands and forests co-exist with diverse local microclimates. The STP is also the key area that influences the water-heat balance in the TP and weather processes. Across the STP, the underlying surfaces have strong non-uniformity, the land–atmosphere exchange is complicated, and the existing numerical mode and parameterization solutions are not applicable in this area. Therefore, observational research on the precipitation changes in the STP is significant to reveal the water-heat exchange processes in the complicated terrain of the TP.

In addition, the STP is the primary area of water vapor transfer from the Bay of Bengal to China. Moist air masses from the Indian Ocean bring abundant precipitation to this region through the valleys of the Lancangjiang, Nujiang and Yarlung Zangbo Rivers. The STP is also the central rainfall area of the TP because of its special topography. The water vapor convergence in the STP and its surrounding areas indicate the occurrence of subsequent precipitation in the STP and in southern China, particularly in the Yangtze River Basin (Shi et al., 2009; Xu et al., 2002).

Therefore, located in the key area of water-heat balance and water vapor transfer, the STP plays an important role in weather processes. Climate anomalies in the STP exert strong effects in that region, in the Yangtze River Basin, and even in southern China. Analyses of the climate variability in the STP, particularly of precipitation trends, are important. Specifically, the analysis of precipitation variability in the STP is critically important for managing water resources.

3 Data

In this study, precipitation observations were obtained by the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA), which completed the primary quality control measures. Currently, 23 meteorological stations are located in the STP; the 14 stations that have more than 30 years of continuous data from the station installation to 2012 were selected. Precipitation records from individual stations, except for the Zuogong and Chayu stations, were used to construct the regional mean seasonal and annual precipitation time series from 1961 to 2012. For the seasonal analysis, each year was divided into four seasons: spring (March to May), summer (June to August), autumn (September to November) and winter (December through February of the following year).

The information on the meteorological stations over the STP is listed in Table 1, and the locations are shown in Fig. 2.

4 Methodology

The Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945) is a rank-based non-parametric trend test method, which has many advantages in trend analysis (Fu et al., 2004, 2009; Gan, 1998; Xu et al., 2010; Wang et al., 2013). The MK test has been widely used to detect monotonic trends in hydrological and meteorological time series (Kendall, 1975; Mann, 1945; Vijay and Sharad, 2010), such as temperature, precipitation and streamflow, in various regions around the world (Casanueva et al., 2014; Cuo et al., 2013; Donald, 2008; Fu et al., 2004; Gan, 1998; Hirsch et al., 1982; Hong et al., 2008; Jaagus, 2006; Karlsson et al., 2014; Lettenmaier et al., 1994; Lins and Slack, 1999; Manfred and Attia, 2005; Manihs, 2014; Wang, 2009; Wang and Zhang, 2012; Wang et al., 2013; Z. X. Xu et al., 2007; Zhang and Du, 2008).

The MK test includes two test statistics (Gan, 1998; Hirsch et al., 1982; Sen, 1968): the trend estimator (Z) and the magnitude of the trend slope (β). A positive (negative) value of Z indicates an upward (downward) monotonic trend in the test time series. The time series shows a significant trend at a particular significance level α if the absolute value of Z is greater than $Z_{1-\alpha/2}$. $Z_{1-\alpha/2}$ is obtained from standard normal cumulative distribution tables (Fu et al., 2009; Gan, 1998; Wang et al., 2013; Xu et al., 2010).

In this study, the MK test was used to detect the long-term trend in precipitation in the STP.

5 Results

5.1 General characteristics of precipitation in the STP

The general statistics of the precipitation time series on the seasonal and annual scales over 1961–2012 in the STP are shown in Table 2 in which range means maxima minus minima. The mean annual precipitation was 556.9 mm, but the precipitation was not uniformly distributed over time. A precipitation regime from June to September, with a peak in July, and 71 % of the total annual precipitation were recorded in this period. Very little to no precipitation occurred from November to the following March. The annual precipitation was concentrated in summer (Fig. 3), and 56 % of the total annual precipitation occurred in this season. However, only less than 3 % of the total annual precipitation occurred in winter. Particularly, the precipitation variation (222.6 mm) was greatest in summer, when the mean precipitation (314.7 mm) was the highest. In contrast, winter had the lowest mean precipitation (14.9 mm) and the smallest range

(15.3 mm). Additionally, the large values of the variance or SD for summer and the annual series indicate a significant fluctuation in precipitation during these periods. The plots of the mean seasonal and annual precipitation are shown in Fig. 4. The 5 year moving-average time series are superimposed in Fig. 4, too. Evidently, the mean annual precipitation increased unsteadily and peaked in 1998. The 1998 flood is known as the greatest flood in the Yangtze River Basin since 1954. The mean spring precipitation has shown an upward tendency since the 1980s, whereas the mean summer precipitation has shown an overall downward tendency. Table 3 shows the mean seasonal and annual precipitation in each decade.

5.2 Spatial variations in precipitation in the STP

According to the STP precipitation observations over 1961–2012, the annual precipitation maximum was 1204.1 mm in Chayu in 2010, and the annual precipitation minimum was 121.0 mm in Longzi in 1982. Seasonally, the spring precipitation maximum was 819.7 mm in Chayu in 2010, and the spring precipitation minimum was 9.5 mm in Longzi in 2009. The summer precipitation maximum was 707.0 mm in Linzhi in 1998, and the summer precipitation minimum was 54.6 mm in Gongshan in 1962. The autumn precipitation maximum was 397.5 mm in Bomi in 1998, and the autumn precipitation minimum was 19.1 mm in Longzi in 1982. The winter precipitation maximum was 130.3 mm in Chayu in 1992, and the winter precipitation minimum was 0 mm at two stations in different years: Longzi (1963, 1964, 1966, 1968, 1971, 1983, 1985, 1987, 1989, 1995, 2001 and 2011) and Batang (1962, 1969, 1970, 1973, 1974, 1978, 1979, 1983, 1987, 1989, 1993, 1996, 2001, 2007, 2011 and 2012). Strong precipitation was primarily concentrated in Chayu, Linzhi and Bomi, whereas low precipitation occurred in Longzi, Gongshan and Batang. The maxima occurred primarily in the 1990s and 2010s.

The spatial distribution of the mean seasonal and annual precipitation in the STP is shown in Fig. 5. On the seasonal scale, ten of the 14 stations had an average precipitation of 50–200 mm in spring; however, only two of the 14 stations had an average precipitation of 200–300 mm; two of the 14 stations had less than 50 mm of precipitation on average. In summer, the precipitation was more than 200 mm for all of the stations, except for Gongshan, which had the minimum precipitation (62.6 mm). Ten of the 14 stations had more than 300 mm of precipitation, and three stations had 200–300 mm of precipitation. In autumn, ten of the 14 stations had 100–200 mm of precipitation on average; however, three of the 14 stations had less than 100 mm, and only one station had more than 200 mm of precipitation. The precipitation is exiguous in winter, and only one of the 14 stations had more than 50 mm, but 11 of the 14 stations had less than 25 mm. Because nearly 60 % of the annual precipitation was concentrated in summer, the spatial distribution of summer precipitation was similar to that of the annual precipitation. The mean annual precipitation maximum occurred in Bomi (835.8 mm) and Chayu (795.2 mm), followed by Jiali (720.0 mm), Linzhi (675.4 mm), Deqin (649.2 mm), Dingqing (648.9 mm) and Suoxian (586.9 mm). Clearly, Bomi, Chayu and Jiali are the three high-precipitation centers. The distribution of precipitation is not obvious with elevation in the STP. For example, the three highest annual maxima in precipitation occurred in Bomi, Chayu and Jiali, which have elevations of 2736.0, 2327.6 and 4488.8 m, respectively. However, the two lowest annual minima in precipitation occurred in Gongshan (174.4 mm) and Longzi (282.6 mm), which have elevations of 1583.3 and 3860.0 m, respectively.

However, the four river valleys in the STP, i.e., the Yarlung Zangbo, Nujiang, Lancangjiang and Jinshajiang River Valleys, are actually water vapor channels. A distinct precipitation pattern occurs for each watershed. Overall, the precipitation from southwest to northeast in the STP gradually decreases. Because the Yarlung Zangbo Valley is the primary and most significant water vapor channel of the TP and of China, the precipitation in the Yarlung Zangbo River Valley is most abundant, followed by the Nujiang, Lancangjiang and Jinshajiang Rivers. The precipitation is more dominant in autumn and winter (Fig. 5).

5.3 Precipitation trends in the STP

Figure 6 shows the results of the MK test for precipitation in the STP. The mean seasonal and annual precipitation time series show a positive trend, except in summer. The spring precipitation trends are more significant than the other seasonal trends and are the only statistically significant increases at the 99 % confidence level. The mean annual precipitation increased by 1.0 mm year^{-1}. The trend magnitudes in spring, summer, autumn and winter were 0.8, −0.1, 0.4 and near to 0 mm year^{-1}, respectively. On the seasonal scale, the largest precipitation increase also occurred during spring.

The trend analysis for the mean seasonal and annual precipitation based on the selected 14 stations over 1961–2012 indicates that most of the stations have a positive trend, but a few stations have significant increases at the 95 % confidence level. Eleven stations showed increasing annual precipitation trends, while two of the stations were significant at the 95 % confidence level. In contrast, three stations showed a decreasing annual precipitation trend, and none were significant at the 95 % confidence level (Table 4). For the annual series, 79 % of the stations had increasing trends, 14 % of which were significant at the 95 % confidence level. Seasonally, more than 50 % of the stations exhibited overall increasing trends; 79 and 93 % exhibited increases in autumn and spring, respectively. Seven stations show a decreasing trend for the summer series, but only one was significant at the 95 % confidence level (Table 4). The stations primarily showed increasing trends, which result in an overall increase in the precipitation in the STP during the study periods.

For the mean annual precipitation in Fig. 7, the Bomi and Gongshan stations had significant increases at the 95 % confidence level. The Bomi station is located in the Yarlung Zangbo River Valley, namely, in the water vapor channel. The Gongshan station is also located in the water vapor channel of the Hengduan Mountains that are oriented south–north. However, the Chayu, Deqin and Batang stations, which are in or around the “area of three parallel rivers” (i.e., the Nujiang, Lancangjiang and Jinshajiang Rivers), had slight and insignificant decreasing trends. The analytical results indicate that the mean annual precipitation primarily increased from 1961 to 2012 in the STP. Previous observational results have also shown that the primary climate change trends are a temperature rise and precipitation increase in the TP (Wu et al., 2005). The research in this study indicated that the precipitation trend in the STP is similar to that for the entire TP.

On the seasonal scale, based on Fig. 7, 13 of the 14 stations exhibited an increasing trend, and five of the trends were significant at the 95 % confidence level during spring. The stations with a significant increasing trend are primarily centered at the northwest corner of the STP where the main area of the TP is located; however, only one station (Chayu) with a negative trend is located along the southern edge of the TP. Seven of the 14 stations with negative trends in summer are distributed in the Nujiang River and Jinshajiang River Valleys, while the seven stations with positive trends are located in the Yarlung Zangbo and Lancangjiang River Valleys. Chayu, which had a statistically significant decrease, and Gongshan, which experienced a significant precipitation increase at the 95 % confidence level, are located in the Hengduan Mountains. In autumn, the stations with decreasing trends are primarily distributed in the Nujiang and Jinshajiang River Valleys. Six of the 14 stations with negative trends are distributed in high-precipitation areas (e.g., Chayu and Linzhi) along the Lancangjiang and Jinshajiang Rivers in winter.

No obvious change was observed for the mean seasonal and annual precipitation trend magnitudes in the STP, and the absolute values of the trend magnitudes were less than 5 mm year^{-1} (Table 5). The seasonal and annual precipitation trend magnitudes were more than 1 mm year^{-1} or less than -1 mm year^{-1} at only a few stations. Table 5 also shows that the maximum and minimum seasonal and annual precipitation trend magnitudes were 4.9 and -1.8 mm year^{-1}, respectively. The maximum seasonal and annual precipitation trend magnitude was primarily centered in Bomi; however, the minimum seasonal and annual precipitation trend magnitude was primarily centered in Chayu.

The spatial distribution of the mean seasonal and annual precipitation trend magnitudes for the stations is shown in Fig. 8. The largest decrease in magnitude occurred in the Lancangjiang River and Jinshajiang River Basin (e.g., Chayu and Zuogong). The largest increase in magnitude was primarily centered in the Yarlung Zangbo River Basin (e.g., Bomi). Spring experienced relatively larger precipitation increases. Overall, the increasing precipitation magnitudes in or near the main area of the TP were larger than those in other areas, whereas the decreasing precipitation magnitudes primarily occurred in the eastern TP.

5.4 Extreme precipitation trends in the STP

To identify the changing precipitation trends in the STP, the seasonal and annual extreme precipitation series, such as the maximum, minimum and range time series, are tested using the MK test (Table 6). The range indicates the difference between the maximum and minimum precipitation.

For the precipitation maximum, the spring, autumn and annual series showed a significant increasing trend at the 95 % confidence level (99 % confidence level for spring), and the summer series is the only seasonal series that exhibited a slight and insignificant decrease. The increasing trend magnitude for the annual precipitation maximum time series was 2.4 mm year^{-1}. The largest increasing trend magnitude of the precipitation maximum time series occurred during spring, while the decreasing trend magnitude of the precipitation maximum time series was −0.2 mm year^{-1} in summer.

All of the time series exhibited an increasing trend, but the increasing trend for summer was significant at the 95 % confidence level for the minimum precipitation time series. But the increasing trend magnitude for the annual minimum precipitation time series was 0 mm year^{-1}. The seasonal trend magnitude maximum occurred in spring, followed by autumn, summer and winter for the minimum precipitation time series.

The precipitation range time series exhibited overall increasing trends, except in summer, when a slight and insignificant decrease occurred. The largest seasonal increasing trend occurred in spring, followed by autumn and winter. The annual increasing trend was 2.2 mm year^{-1}, while the summer decreasing trend was −0.2 mm year^{-1}. Chou and Lan (2011) have found that the annual range of precipitation tends to increase with global warming. In the STP, the enhancement of the annual range of precipitation is apparent, due to a faster increase in the maximum precipitation than in the minimum precipitation. Table 6 clearly reveals that the range of the annual maximum precipitation exhibited a significant increase at the 95 % confidence level, while the range of the annual minimum precipitation exhibited a slight and insignificant increase. In contrast, the range of the annual maximum precipitation increased at a rate of 2.4 mm year^{-1}, while the range of the annual minimum precipitation increased at a rate of 0 mm year^{-1}. The range of the annual precipitation increased at a rate of 2.2 mm year^{-1}.

6 Conclusions

Previous studies have examined and reported the precipitation in the TP using station data or reanalysis gridded data that are not spatially uniform. Few studies have been performed on trends in STP precipitation. In this study, a station dataset spanning 52 years (1961–2012) is examined in detail to identify temporal and spatial precipitation trends in the STP for the first time. Under the background of global warming, the results not only reveal the precipitation trends in the STP but also provide further information for understanding the regional climate variations over the TP.

The area-averaged precipitation, which comprises the long-term precipitation trend in the TP and the global trend, tended to increase in the STP. Increasing trends were observed in the seasonal and annual precipitation, except for the summer precipitation, over 1961–2012. Eleven of the 14 stations showed increasing trends, two of which were significant at the 95 % confidence level; three of the 14 stations showed a slight and insignificant decreasing trend in the mean annual precipitation. Although the trends (e.g., autumn, winter and annual) are not significant, the precipitation generally increased, as revealed by the positive values of the MK trend.

The extreme precipitation, such as the maxima and minima, also increased, but the trends and magnitudes of the maxima were overall more significant than those of the minima, except in summer; as a result, the spring and autumn precipitation was relatively higher, and the annual range of precipitation in the STP increased.

Spring precipitation was more significant than the precipitation in the other seasons. Spring precipitation experienced a significant increasing trend at the 99 % confidence level, while only summer experienced a slight and insignificant decreasing precipitation trend. Only one of the 14 stations showed a slight and insignificant decreasing trend, while 13 of the 14 stations showed increasing trends in spring precipitation. The greatest precipitation increase also occurred in spring.

The spatial distribution of precipitation does not obviously change with elevation but does change with the complex topography (e.g., water vapor transfer channel and mountain chains) in the STP. The Yarlung Zangbo River Basin is the rain center of the STP because the Brahmaputra-Yarlung Zangbo Valley is the primary and most significant water vapor channel in China. The precipitation increases in or near the main area of the TP are more dominant than those in the other areas.

7 Discussions

Generally, precipitation is influenced by many factors, and it exhibits local characteristics in the STP. The findings in this study suggest that determining the precise influence of the STP on the regional and global climate is necessary.

Previous results have shown that precipitation generally increases with the elevation in the Asian monsoon region and generally decreases with elevation in the Indian monsoon region (Lu et al., 2007). D. Q. Zhang et al. (2004) have observed sensitivity in the precipitation increase with elevation. However, in the STP, the precipitation trend with elevation is unclear, while the precipitation clearly changes with complex topography. High precipitation consistently occurred in the water vapor channel of the STP. The valley of the Brahmaputra-Yarlung Zangbo is the primary and most significant water vapor channel in China and is related to the onset of the Asian monsoon, air–land processes, and the special distribution of water vapor over the TP. The interaction between the topographic effects of the TP and the monsoonal water vapor flow in the STP forms a strong water vapor flow from the TP to the Yangtze River Basin (Gao et al., 1985). Thus, the distribution of precipitation in the STP is also closely related to the amount and structure of water vapor transfer from the water vapor channel. For example, the stations (e.g., Jiali, Linzhi, Bomi and Chayu) located along the water vapor channel have abundant precipitation, whereas low precipitation occurs in the Nujiang, Lancangjiang and Jinshajiang River Valleys due to blocking by the Nyainqentanglha and Taniantaweng Mountains. Although the Jiali station is located in the main area of the TP at a high elevation (4488.8 m), high precipitation occurs because it is located along the water vapor channel of the Yarlung Zangbo River Valley. Based on the results of this study, whether areas have abundant precipitation depends on whether the areas are located along the water vapor transfer channel of the STP. The results reflect the complex changes in the regional precipitation in the STP because the atmospheric circulation causes complex variations in the precipitation and changes the elevation dependence of the precipitation. However, the mechanisms involved in these trends require further investigation.

Geographically, the precipitation decreased in the high-elevation region and increased in the low-elevation region. The climate variation appears to be more sensitive at high elevations than at low-moderate elevations (He et al., 2003). This result further proves that the precipitation variation at high elevations is more significant than that at low elevations (Hou et al., 2002; Wilhelm et al., 2012; Zhang et al., 2009). Wang et al. (2013) have also indicated that the high-elevation regional climate is characterized by greater precipitation increases than lower elevations in the Jinshajiang River Basin. However, the largest increase and decrease occurred in the areas with more precipitation (e.g., Bomi and Chayu) in the STP, in contrast to other studies.

Because the TP is located in a monsoon region, the Asian monsoon variation should play a key role in shaping the precipitation distribution. All of the physics regarding the precipitation characteristics are not known; thus, further studies that analyze the relationship between the Asian monsoon and the regional precipitation in the STP are required.

Significant research has shown that the increasing precipitation is more significant in spring than in the other three seasons under global warming, including in the STP. However, summer is the only season that exhibits a slight and insignificant decrease under the background of increasing area-averaged precipitation in the STP. The annual precipitation is dominated by summer precipitation, when 56 % of the total annual precipitation occurs. Previous studies have indicated that since 1951, statistically significant increases in the number of heavy precipitation events (e.g., above the 95th percentile) are more prevalent than statistically significant decreases (IPCC, 2013). Whether the precipitation is uniformly distributed over time and whether the number of heavy precipitation events tend to decrease require further investigation in the STP.

The TP, including the STP, experiences the water vapor flow from the South China Sea and the Indian Ocean, which is closely related to the occurrence of subsequent precipitation in southern China, particularly in the Yangtze River Basin (Shi et al., 2009; Xu et al., 2002). Whether the precipitation variation in the STP can be used to project trends in southern China, particularly in the Yangtze River Basin, remains unknown.

The conclusions in this study benefit future studies that may combine atmospheric circulations and other meteorological factors to determine causes of the precipitation trends. In addition, only the MK test was used for the trend analysis in this investigation. The conclusions in this research must be verified using additional trend analysis methods. However, only 14 meteorological stations with 52 year long records were used. If all of the meteorological stations were averaged, different trends may be detected. Although these tasks are beyond the scope of this study, they are of interest to ongoing research in this field.

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Table 1. List of the meteorological stations in the STP.

Station ID	Station name	Longitude (° E)	Latitude (° N)	Elevation (m)	Period of record
55696	Longzi	28.42	92.47	3860.0	1960–2012
56106	Suoxian	31.88	93.78	4022.8	1957–2012
56116	Dingqing	31.42	95.60	3873.1	1954–2012
56125	Nangqian	32.20	96.47	3643.7	1957–2012
56137	Changdu	31.15	97.17	3315.0	1954–2012
56144	Dege	31.80	98.58	3184.0	1957–2012
56202	Jiali	30.67	93.28	4488.8	1961–2012
56227	Bomi	29.87	95.77	2736.0	1961–2012
56247	Batang	30.00	99.10	2589.2	1959–2012
56312	Linzhi	29.67	94.33	2991.8	1960–2012
56331	Zuogong	29.67	97.83	3780.0	1978–2012
56434	Chayu	28.65	97.47	2327.6	1969–2012
56444	Deqin	28.48	98.92	3319.0	1954–2012
56533	Gongshan	27.75	98.67	1583.3	1958–2012

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Table 2. Statistics of the precipitation series from 1961 to 2012 in the STP.

Time	Mean (mm)	Variance	SD	Coefficient of skew	Coefficient of kurtosis	Maxima (mm)	Minima (mm)	Range (mm)
Spring	104.5	558.2	23.6	0.2	0.3	171.5	48.9	122.6
Summer	314.7	2653.6	51.5	0.1	−0.6	440.2	217.6	222.6
Autumn	122.8	550.4	23.5	0	−0.3	175.0	68.8	106.2
Winter	14.9	16.6	4.1	0.3	−0.8	23.3	8.0	15.3
Annual	556.9	3909.6	62.5	−0.2	−0.7	701.3	426.8	274.5

Table 3. Decadal variations in the mean seasonal and annual precipitation in the STP (mm).

Time	1961–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–2012
Spring	79.6	105.9	100.0	108.0	117.4	134.6
Summer	336.2	294.8	304.7	324.7	316.8	310.0
Autumn	106.9	121.4	129.9	132.9	120.3	126.8
Winter	12.0	15.4	15.9	16.2	15.1	12.8
Annual	534.4	537.7	550.2	582.0	570.2	583.7

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Table 4. Number of stations for MK trend tests of the mean precipitation from 1961 to 2012 in the STP.

Time	Positive and not significant trend		Positive and significant trend (α = 0.05)		Negative and not significant trend		Negative and significant trend (α = 0.05)	
	Number of stations	Percentage	Number of stations	Percentage	Number of stations	Percentage	Number of stations	Percentage
Spring	13	93	5	36	1	7	0	0
Summer	7	50	1	7	7	50	1	7
Autumn	11	79	3	21	3	21	0	0
Winter	8	57	2	14	6	43	0	0
Annual	11	79	2	14	3	21	0	0

Table 5. Extreme values of the trend magnitudes in the precipitation over the 14 meteorological stations from 1961 to 2012 in the STP.

Time series	β_{max} (mm year^{-1})	Station of the β_{max}	β_{min} (mm year^{-1})	Station of the β_{min}
Spring	3.0	Bomi	−0.2	Chayu
Summer	1.6	Zuogong	−1.8	Chayu
Autumn	1.4	Bomi	−0.4	Zuogong
Winter	0.3	Bomi	−0.4	Chayu
Annual	4.9	Bomi	−0.7	Chayu

Table 6. MK test statistic Z and magnitude of trend β (mm year^{-1}) for the extreme precipitation series from 1961 to 2012 in the STP. Positive values indicate an increasing trend, and negative values indicate a decreasing trend. MAXP is the maximum precipitation and MINP is the minimum precipitation.

Series	Spring		Summer		Autumn		Winter		Annual	
	Z	β	Z	β	Z	β	Z	β	Z	β
MAXP	2.7[c]	2.7	−0.3	−0.2	2.1[b]	1.1	0.9	0.2	2.0[b]	2.4
MINP	1.0	0.1	2.2[b]	0	1.8[a]	0.1	1.6	0	0.8	0
Range	2.5[b]	2.6	−0.3	−0.2	1.9[a]	0.9	0.7	0.2	1.9[a]	2.2

[a] Trend is significant at the 90 % confidence level.
[b] Trend is significant at the 95 % confidence level.
[c] Trend is significant at the 99 % confidence level.

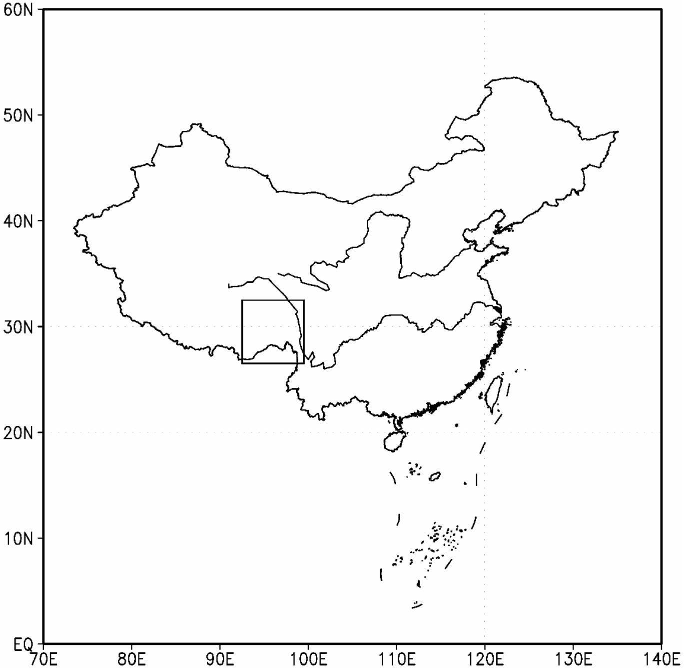

Figure 1. Location of the STP in China (the square areas show the STP).

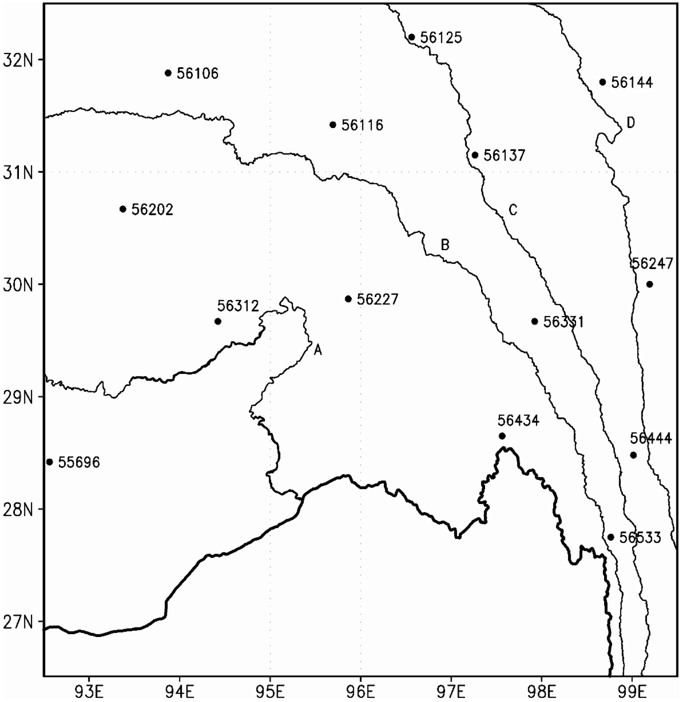

Figure 2. Sketch of the spatial distribution of the meteorological stations used in the STP. A: the Yarlung Zangbo River; B: the Nujiang River; C: the Lancangjiang River; and D: the Jinshajiang River. The heavy solid line represents the national boundaries of China.

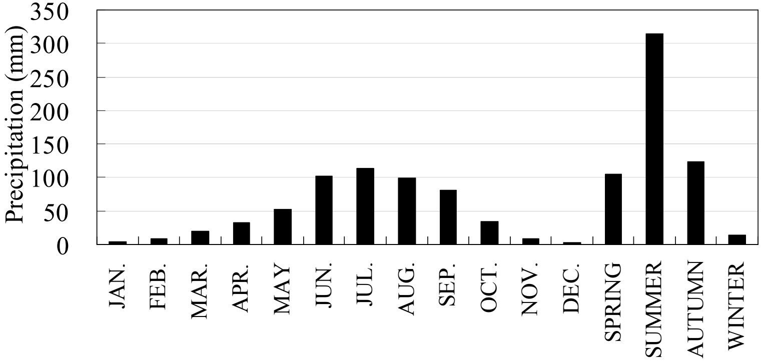

Figure 3. Temporal distribution of the mean monthly and seasonal precipitation from 1961 to 2012 in the STP.

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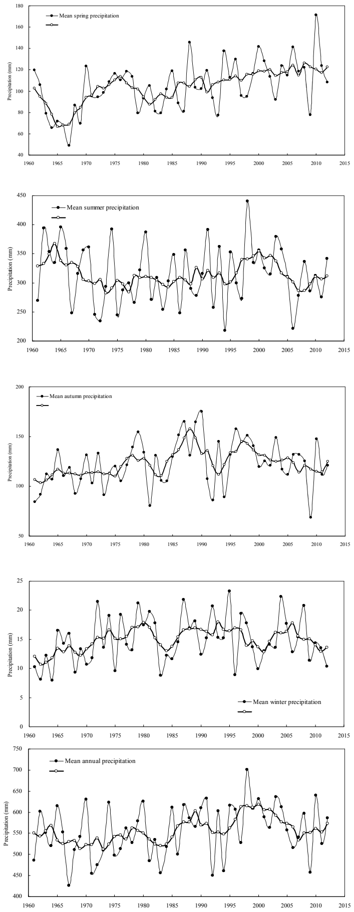

Figure 4. Time series of the mean precipitation from 1961 to 2012 in the STP.

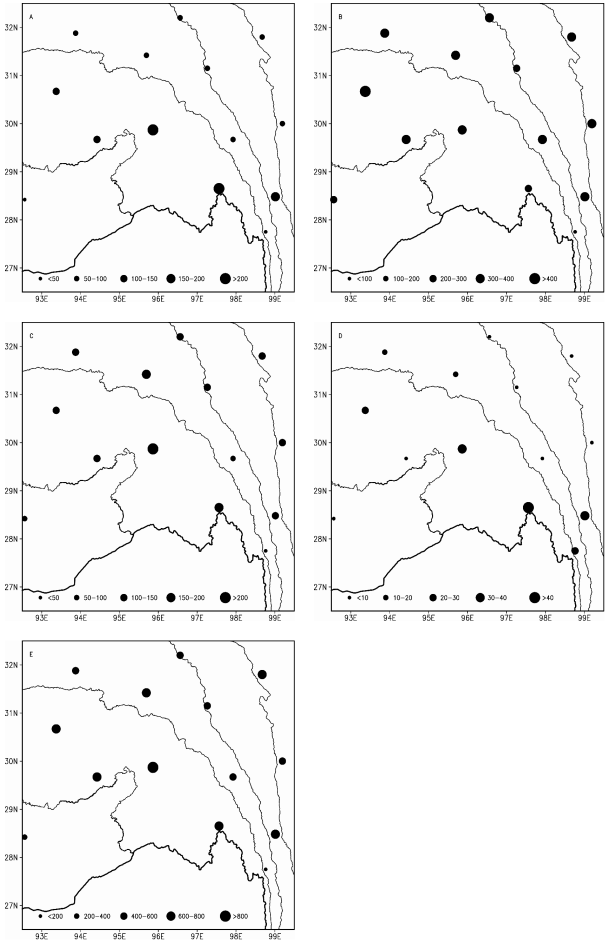

Figure 5. Spatial distribution of the mean seasonal and annual precipitation from 1961 to 2012 in the STP. A: spring; B: summer; C: autumn; and D: winter (units: mm).

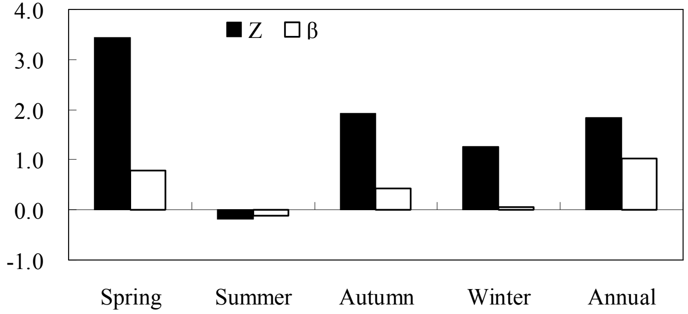

Figure 6. MK test statistic Z and magnitudes of trend β (mm year^{-1}) from 1961 to 2012 in the STP.

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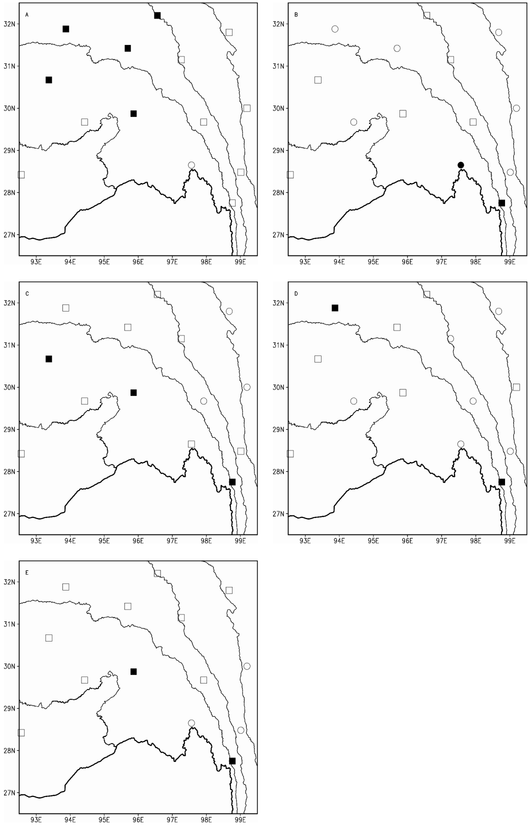

Figure 7. Trend results for the mean seasonal and annual precipitation for the stations from 1961 to 2012 using the MK test (unfilled square: positive and not significant; filled square: positive and significant trend at the 95 % confidence level; unfilled circle: negative and not significant; and filled circle: negative and significant trend at the 95 % confidence level. A: spring; B: summer; C: autumn; D: winter; and E: annual).

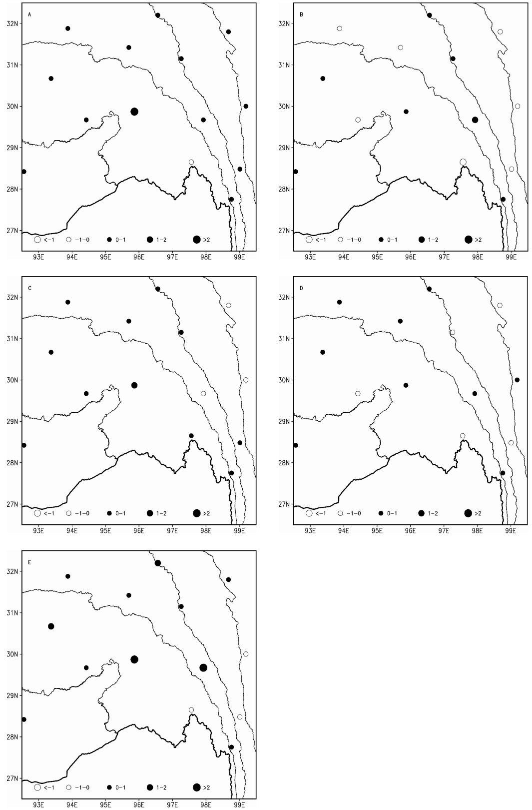

Figure 8. Spatial distributions of the mean seasonal and annual precipitation trend magnitudes from 1961 to 2012 in the STP. A: spring; B: summer; C: autumn; and D: winter (units: mm year^{-1}).