J. Geogr. Sci. 2013, 23(6): 1107-1122
DOI: 10.1007/s11442-013-1066-y

Trends in precipitation over the low latitude highlands of Yunnan, China

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Abstract: The precipitation regime of the low latitude highlands of Yunnan in Southwest China is subject to the interactions between the East Asian Summer Monsoon and the Indian Summer Monsoon, and the influence of surface orography. An understanding of changes in its spatial and temporal patterns is urgently needed for climate change projection, hydrological impact modelling, and regional and downstream water resources management. Using daily precipitation records of the low latitude highlands over the last several decades (1950s–2007), a time series of precipitation indices, including annual precipitation, number of rainy days, mean annual precipitation intensity, the dates of the onset of the rainy season, degree and period of precipitation seasonal concentration, the highest 1-day, 3-day and 7-day precipitation, and precipitation amount and number of rainy days for precipitation above different intensities (such as $\geqslant$10 mm, $\geqslant$25 mm and $\geqslant$50 mm of daily precipitation), was constructed. The Trend-Free Pre-Whitening Mann-Kendall trend test was then used to detect trends of the time series data. The results show that there is no significant trend in annual precipitation and strong seasonal differentiation of precipitation trends across the low latitude highlands. Springs and winters are getting wetter and summers are getting drier. Autumns are getting drier in the east and wetter in the west. As a consequence, the seasonality of precipitation is weakening slightly. The beginning of the rainy season and the period of the highest precipitation tend to be earlier. In the meantime, the low latitude highlands has also witnessed less rainy days, more intense precipitation, slightly longer moderate and heavy precipitation events, and more frequent extreme precipitation events. Additionally, regional differentiation of precipitation trends is remarkable. These variations may be associated with weakening of the East Asian summer monsoon and strengthening of the South Asian summer monsoon, as well as the "corridor-barrier" effects of special mountainous terrain. However, the physical mechanisms involved still need to be uncovered in the future.

Keywords: change trend; Trend-Free Pre-Whitening Mann-Kendall; daily precipitation; spatial pattern; low-latitude highlands

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Received: 2013-01-21 **Accepted:** 2013-04-10
Foundation: National Natural Science Foundation of China, No.41061010; National Science and Technology Support Program, No.2013BAB06B03; No.2011BAC09B07

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1 Introduction

Although uncertainties exist regarding the causes and effects of climate changes associated with global warming (Zhang *et al.*, 2007; Fang *et al.*, 2011), there is widespread observational evidence for the impacts of global warming on the total amount and patterns of precipitation across the globe (Karl and Knight, 1998, Wang *et al.*, 2004; Alexander *et al.*, 2006; IPCC, 2007; Wentz *et al.*, 2007). A distinct wetting trend has been observed in eastern parts of North and South America, northern Europe and northern and central Asia, and a drying trend in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (IPCC, 2007). The overall trend is that dry places become drier and wet places become wetter. In China, no statistically significant trends in annual total precipitation have been detected over the past 50 and 100 years (Liu *et al.*, 2005; Ding *et al.*, 2006). However, remarkable regional differences exist. While precipitation decreases in eastern, northern and northwestern China, it increases in southern China and on the Tibetan Plateau (Chen *et al.*, 1991; Wang *et al.*, 2004; Ding *et al.*, 2006). Total precipitation in a specific period of time is determined by both the number and intensity of precipitation events. Most previous studies have been attached insufficient attention to distinguishing the contributions of frequency and intensity from total precipitation trends (Liu *et al.*, 2005). Recently, great increases in the frequency and intensity of heavy precipitation events, regarded as one of the most noticeable by-products of global warming, have been widely observed at global, continental and regional scales (Zhai *et al.*, 1999; Wang and Zhou, 2005; Zhai *et al.*, 2005; IPCC, 2007). These heavy precipitation events fluctuate markedly from place to place and over time even on small scales owing to the regional differences of climatic background, terrain, and land-surface characteristics. Therefore, knowledge of regional and local precipitation regimes and their separate components' trends is important for adaptation to and mitigation of the negative impacts of climate change.

Precipitation is a primary hydro-climatological variable. Due to uncertainties concerning the precipitation patterns and trends over different regions, the investigation of precipitation variability on a regional scale becomes an essential research topic of climate change and the hydrological cycle. Understanding the variability of precipitation is not only of profound physical, but also of social and economic significance (Sheffield and Wood 2008; Oguntunde *et al.*, 2011). Mountains are known as sources of the world's major rivers and hotspots of biological diversity. Precipitation in mountainous areas is highly variable both spatially and temporally because of the strong influence of topography. However, few long-term precipitation observations available for mountain regions lead to a poor understanding of spatial and temporal trends of precipitation in these regions.

The low latitude highlands of Yunnan in Southwest China are part of a region that is complex with respect to hydro-climatological conditions, and subject to the interaction of several branches of the global atmospheric circulation (Wang and Wang, 1982; Thomas, 1993; Wang *et al.*, 1998). As the region is an intersection area of two Asian summer monsoons, local precipitation is therefore sensitive to the weakening/strengthening of these circulations associated with global climate change (Wang *et al.*, 1998; Yang *et al.*, 2011; Cao *et al.*, 2012). The physical processes in dominating the interannual variation of precipitation in this region are distinct from other "classic" East Asian monsoon region in China. Therefore, previous investigations on climate variability and change at the regional and national levels were difficult to factually interpret temporal and spatial variability in precipitation across the low latitude highlands of Yunnan (Liu *et al.*, 2005; Zhai *et al.*, 2005; Ding *et al.*, 2006). Similarly, long-term variability of precipitation detected using a series of annual areal sums of precipitation failed to exactly describe precipitation trends and their spatial differences (Peng and Liu, 2009; Liu *et al.*, 2010; Liu *et al.*, 2011). Especially in recent a major part of the investigated area has suffered a record-breaking drought (Lü *et al.*, 2012). The need for a comprehensive and detailed analysis of precipitation trends and their spatial patterns at the local level is urgent. This work attempts to meet this demand. We hope that analyses of the variation of precipitation will lead to a better understanding of local climate variability and change and the related potential effects on water resource development and utilization.

2 Study area

Located in the southwest border area of China, Yunnan is a low latitude highland region, covering a total area of about 383,210 km^2, of which 84% is mountain, 10% is high plateau, and 6% consists of basins. With elevations ranging from 76 to 6740 m above sea level (Figure 1), Yunnan borders in the south on Laos, Myanmar and Vietnam, and extends northwards to the southeastern rim of the Himalayas. The climate varies within a three-dimensional continuum, spanning three climatic zones, i.e. tropical, sub-tropical and temperate, and an elevational gradient that ranges from river valleys through mountainous areas to frigid

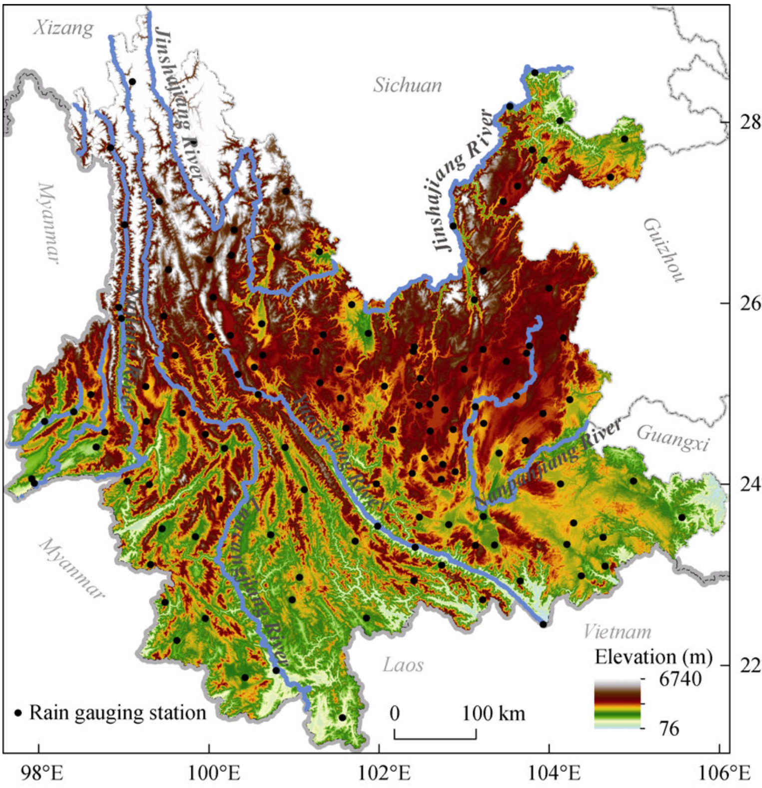

Figure 1 Map of the investigation area with location of the rain gauging stations utilized

highlands. Its mean annual temperature rises from 7℃ in the northwest to 22℃ or more in the Yuanjiang valley. Precipitation in Yunnan is highly seasonal, with a dry season from November to April of the next year and a wet season from May to October. Seasonal changes are determined by a monsoonal regime and further complicated by an extremely uneven and dissected terrain. The mean annual precipitation of the whole region is about 1100 mm, about 85% of which occurs in the wet season. Precipitation is low in the dry and hot river valleys and on the northwestern Yunnan plateau, but very high in southwestern Yunnan.

Runoff regimes are closely associated with precipitation. About 73% to 85% of the runoff occurs in the wet season, and only 15% to 27% in the dry season. The runoff in April and May accounts for only 2% to 3% of the annual runoff. Due to the effects of terrain and altitude, the spatial distribution of water yield is extremely uneven. Over 70% of water resources are located in remote mountainous areas, which contain the upstream watershed areas of several major international rivers (including the Salween, the Mekong, the Red and the Irrawaddy River) and some inland rivers (e.g. Yangtze River). The annual mean water discharge into downstream countries reaches up to $2\ 230 \times 10^8\ m^3$, which is about 60% of the annual outflow into the countries bordering China (He *et al.*, 1999). These transboundary water resources are very important for large areas of Southwest China and of the downstream countries of Cambodia, Laos, Myanmar, Thailand, and Vietnam. Densely populated agricultural areas of the middle Yunnan plateau, on the other hand, are experiencing severe water-deficits during the early growing season. Water scarcity is a major constraint of social and economic development in a large area of the province, and one of the vital factors that threaten urban resilience, food security and ecological health.

3 Data and methods

3.1 Daily precipitation dataset

A dataset of daily precipitation amounts at 133 rain gauging stations covering the low latitude highlands of Yunnan in Southwest China for the period of the 1950s–2007 was obtained from the Yunnan Bureau of Meteorological Administration. This is the best daily dataset currently available for examining precipitation change in the region. Before being used for the subsequent analysis, the dataset of daily precipitation series had already been subject to specific quality-control procedures and statistical homogeneity testing. The year with more than 10% missing days was considered to be missing. All stations with at least 40 non-missing years of data were chosen. In order to get rid of temporal inhomogeneities of the analyzed precipitation series, stations with relocation problems were also discarded. After these procedures, a total of 124 stations were retained for the subsequent trend analysis. Figure 1 shows the study area and the geographical distribution of these selected stations. The density of the station network is satisfactory for the central Yunnan plateau, but not quite satisfactory for southern, northwestern and northeastern Yunnan. Recognizing the orographically structured terrain of Yunnan, we perform the analysis of precipitation trends and its geo-temporal distribution at the station level, but do not provide and discuss a gridded precipitation analysis.

Changes in precipitation amounts can be triggered by changes in the frequency of precipitation events, the intensity of precipitation per event, or a combination of both (Brunetti *et al.*, 2001). In order to quantify the change characteristics of precipitation, several time series of annual precipitation, number of rainy days, the highest 1-day, 3-day and 7-day precipitation, and precipitation amount and number of rainy days for daily precipitation above different intensities (such as ⩾10 mm, ⩾25 mm and ⩾50 mm of daily precipitation), were constructed for further analysis.

3.2 Methods

3.2.1 Determining the dates of the onset of the rainy season

The onset date of the rainy season is usually defined as the time when precipitation reaches a certain threshold value during a 5- or 10-day period and maintains this level for another 5 or 10 days in order to distinguish the onset of the rainy season from short-term precipitation event (Thomas, 1993). Distinct criteria (e.g. threshold values of precipitation and cumulative precipitation) have been proposed to determine the onset date. In this paper, the criterion of the onset date is that daily precipitation is three times above the long-term mean daily precipitation (or 10 mm for areas with a long-term mean daily precipitation above 10 mm), and that the relative coefficient of precipitation C is larger than 1.0 (or 0.75 in wet areas) for a following time span of 5 days, 10 days, one month and a rainy reason (Wang and Wang, 1982; Thomas, 1993). The relative coefficient of precipitation C is given as:

$$C = P_n / \left[\left(\overline{P} / 365 \right) \times n \right] \tag{1}$$

where $\overline{P}$ is the long-term mean annual precipitation and P_n the observed mean daily precipitation of the n-day (n=5, 10, 30…) period.

The coefficient C arbitrarily assigns to one for the less rainy areas where $\overline{P}$ is below 1275 mm, or to 0.75 for the more rainy areas where $\overline{P}$ is below 1700 mm, whereas it is calculated with $\overline{P}$ of 1275 mm for the areas where $\overline{P}$ is between 1275 mm and 1700 mm.

3.2.2 Calculation of degree and period of precipitation seasonal concentration

Markham (1970) proposed a method for determining seasonality of precipitation, which assumes that mean monthly precipitation values are vector quantities, magnitude being the amount of rain, and direction being the month expressed in radians. A measure of the seasonality of precipitation was then obtained by addition of vectors. In this study, daily precipitation is used to calculated C_n and D instead of monthly precipitation. In doing so, C_n and D in equation (2) represents the degree and period of precipitation seasonal concentration. C_n and D are respectively expressed as (Yang, 1984):

$$C_n = \frac{R}{W} = \frac{\sqrt{\left(\sum_{i=1}^{12} r_i \sin\theta_i \right)^2 + \left(\sum_{i=1}^{12} r_i \cos\theta_i \right)^2}}{\sum_{i=1}^{12} r_i} \tag{2}$$

$$D = \arctan \left(\frac{\sum_{i=1}^{12} r_i \sin\theta_i}{\sum_{i=1}^{12} r_i \cos\theta_i} \right) \tag{3}$$

where R is the magnitude of the resultant vector, W is the total mean annual precipitation, r_i is daily precipitation, and θ_i is vector direction for daily precipitation.

3.2.3 Trend analysis

The Mann-Kendall (MK) test is the most frequently used non-parametric test for detecting trends in climatic or hydrological variables. However, it is sensitive to the effect of serial dependence. Thus, a trend-free pre-whitening procedure was developed to remove serial correlation before applying the trend test (Yue *et al.*, 2002). In this method, the slope of the trend is estimated using the Theil-Sen approach (TSA). If the slope nearly equals zero, it is not necessary to analyze for trend. Otherwise, linear trend is assumed and then the data is detrended by the slope. Subsequently the lag-1 series correlation coefficient of the detrended series is computed and subtracted from it. After applying this subtraction, the residuals should represent an independent series. Linear trend and residuals are then recombined to produce a new series, which can preserve the true trend and is no longer affected by the effects of autocorrelation. Subsequently, the Mann-Kendall test is applied to the new series to estimate the significance of the trend. A detailed description of the TFPW-MK (Trend-Free Pre-Whitening Mann-Kendall) test was given in (Yue *et al.*, 2002). In this paper, the TFPW-MK test was employed to detect change trend of precipitation time-series and its derivative variables. Statistical significance is considered at a confidence level of 95%.

4 Results

4.1 Changes in annual precipitation and number of rainy days

Annual precipitation is characterized by insignificant changes almost everywhere, except for four stations located in the eastern and northeastern regions (Figure 2a). About 58.9% of the gauging stations, most of which are located in the central, northern and northwestern parts of the province, show increasing annual precipitation at a rate of 0.5–57 mm per decade. Only 37.9% of all stations, most of them located in the eastern and northeastern regions, show a decrease in annual precipitation at a rate of 0.3–43 mm per decade.

A decrease in the number of rainy days can be detected across major parts of the investigation area (Figure 2b). More than 1/3 of the examined stations show significantly decreasing trends in the number of rainy days. They are distributed all over the province with the exception of northern and northwestern Yunnan. Only a few stations record an increase in the number of rainy days, most of them situated in the Jinshajiang basin (the upper reaches of the Yangtze River). A majority of the stations studied give a slightly trend at less than 5 days per decade (Figure 2b).

Mean annual precipitation intensity is defined as the ratio of annual precipitation and the number of rainy days. Most stations (about 83%) have recorded an increase in mean annual precipitation intensity and most of them grow at an upward rate of less than 0.2 mm per decade (Figure 2c). Significantly increasing trends of mean annual precipitation intensity are observed at some stations (about 20% of the total investigated stations) located in the central, southwestern and northwestern regions.

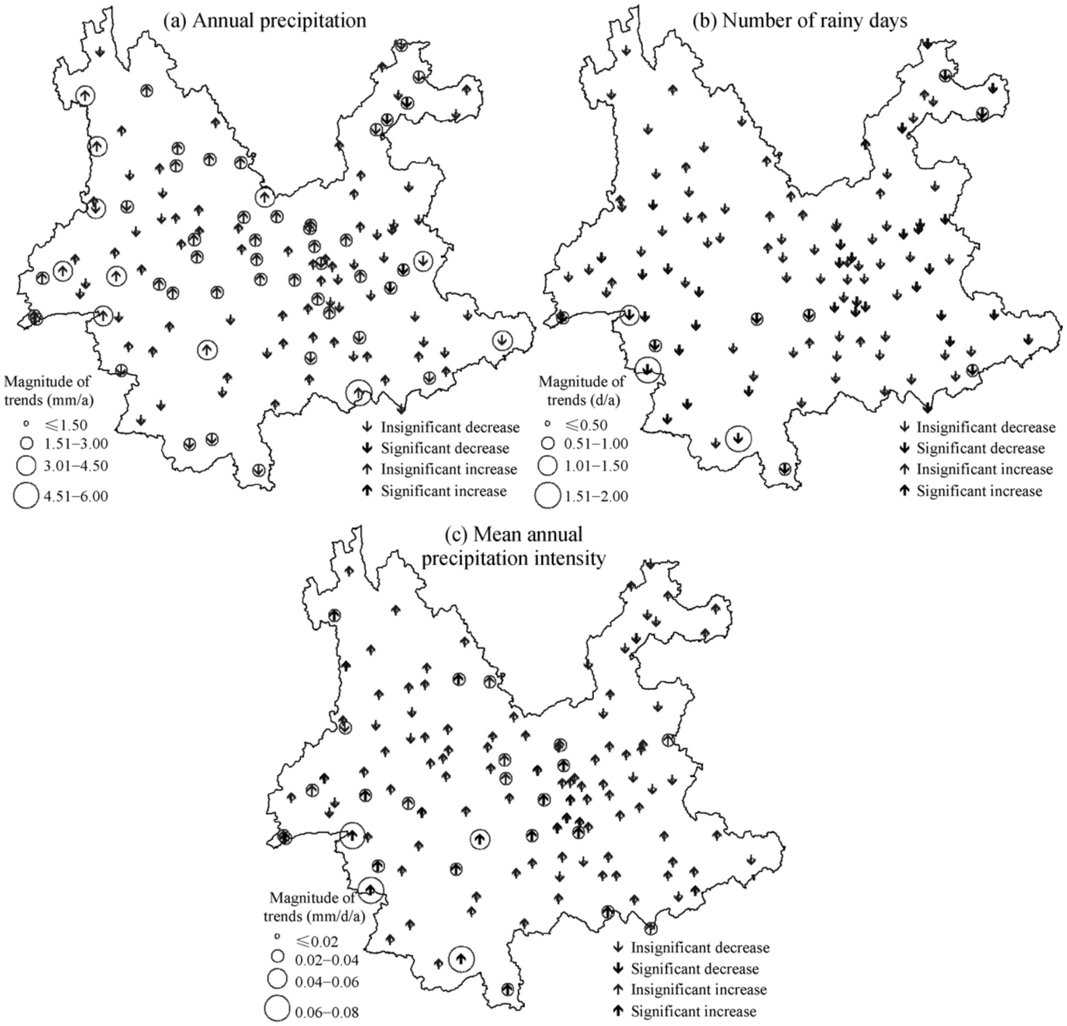

Figure 2 Spatial distribution of trends in annual precipitation and number of rainy days (1950s–2007)

4.2 Changes in precipitation seasonality

4.2.1 Trends in seasonal precipitation

Changes in the seasonal distribution of precipitation are as important as changes in absolute amount. In order to examine further, whether the contribution of seasonal precipitation to annual precipitation shows any significant trend, trend analyses were carried out for each season.

Figure 3 demonstrates a tendency for wetter springs and winters and for slightly drier summers. In spring (from March to May) (Figure 3a), most of the study area experiences an increase in precipitation with the exception of a few stations located in the most north-easterly and south-easterly parts. About 41.9% of all total rainfall stations, most of them located in the mid-west, west and northwest, have recorded a significant increase of spring precipitation. The slopes of this upward trending are mostly below 30 mm per decade.

The change trends of summer (from June to August) precipitation are almost opposite to

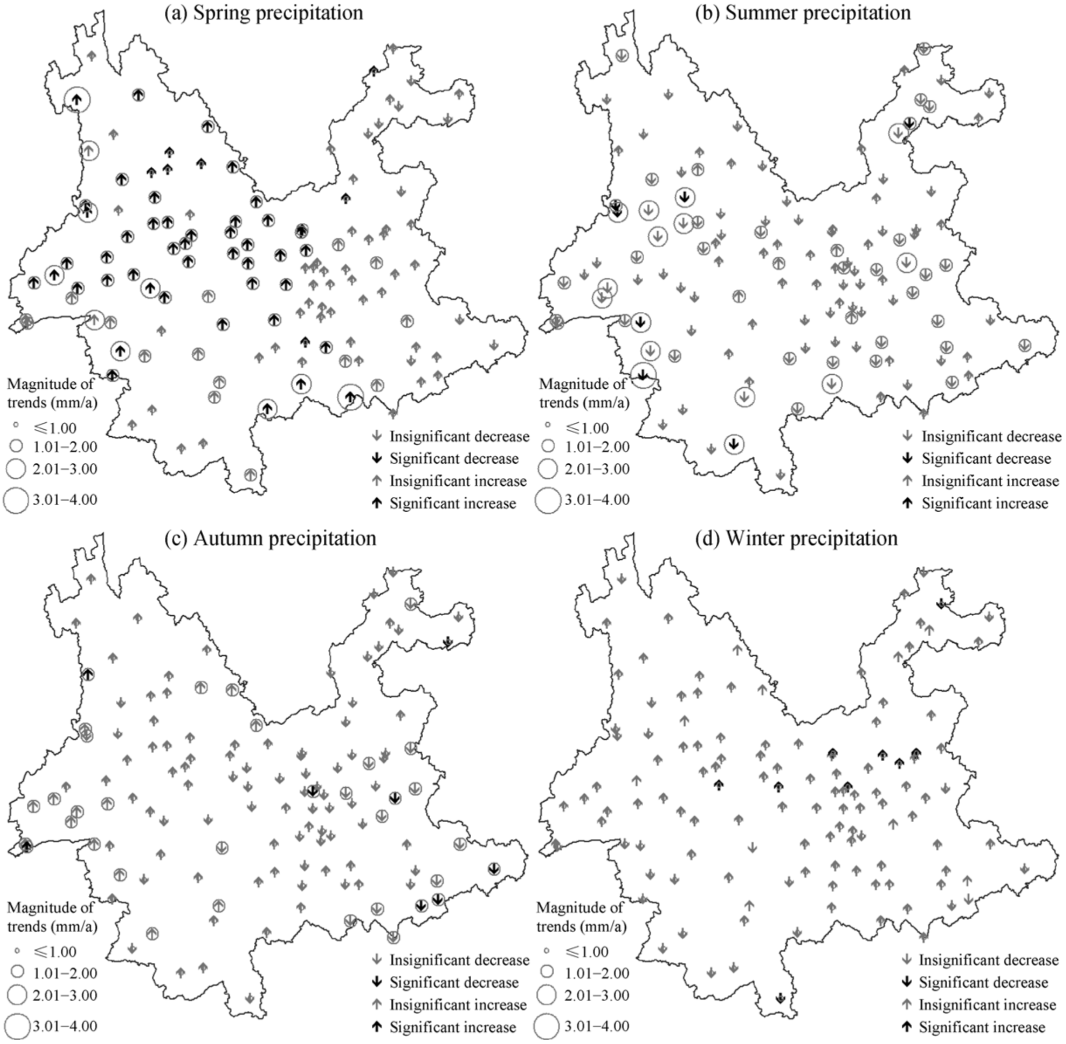

Figure 3 Spatial distribution of trends in seasonal precipitation

those of spring precipitation. Negative trends prevail and their gradients are mostly less than 20 mm per decade (Figure 3b). Almost 3/4 of all stations show decreasing precipitation, out of which 7 stations show a significantly decreasing trend of precipitation. While these stations are scattered throughout the whole region, the majority of stations showing a slightly increasing tendency of precipitation are located in the midwest.

With respect to autumn (from September to November) precipitation, the stations can be divided into two groups: one with a trend of decreasing precipitation and the other with a trend of increasing precipitation (Figure 3c). Positive trends of precipitation are prevailing in the northwestern and southwestern regions, while negative trends prevail in the midwest, northeast and southeast. However, trends are insignificant at most stations and their gradients are less than 20 mm per decade.

Winters, like springs, have a tendency to be wetter (Figure 3d). However, only 7 stations sporadically located in the central region exhibit a significant increase in precipitation at a rate of less than 10 mm per decade. About 21.8% of all the stations, most of which stand along the southwestern border of Yunnan, show a negative trend in precipitation.

4.2.2 Trends in the onset dates of the rainy season

For rainfed agriculture in mountainous areas of Yunnan, timely, predictable and reliable information on the onset of the rainy season is of vital importance. A trend towards earlier onset dates of the rainy season with a median of about 2 days per decade can be observed over a large part of the study area (Figure 4a). However, less than 15% of the stations mainly found in the central and southern regions, exhibit a significant trend towards earlier onset dates with a range of 2–8 days per decade. About 11.2% of all stations show an insignificant trend for delayed onset of the rainy season, mainly in the eastern region.

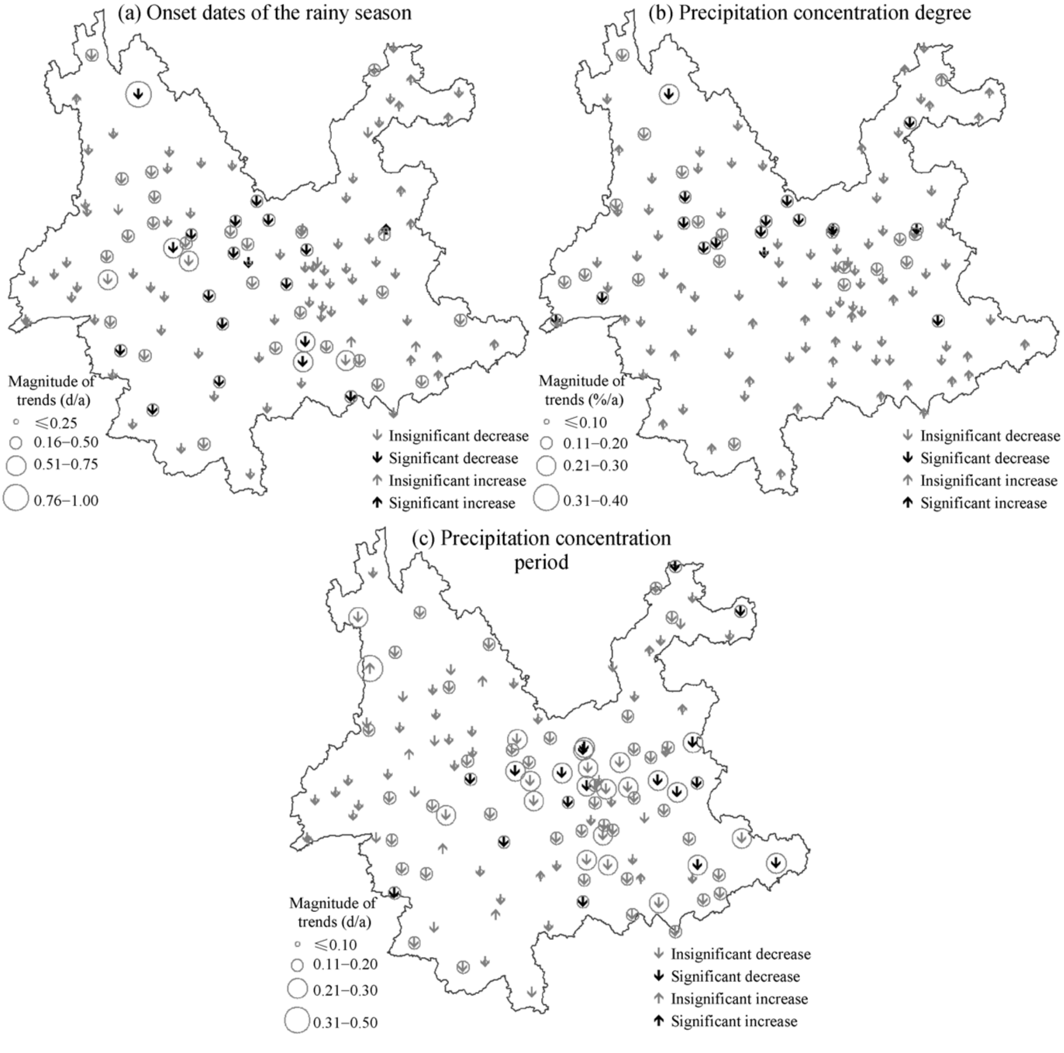

Figure 4 Spatial distribution of trends in the onset dates of rainy season, degree and period of precipitation seasonal concentration

4.2.3 Trends of degree and period of precipitation seasonal concentration

Degree and period of precipitation seasonal concentration are useful parameters for describing seasonality of precipitation. The vast majority of precipitation stations (more than 3/4) reveal a tendency towards a weakening of the degree of precipitation seasonality (less than 2.0% per decade) and towards earlier period of precipitation seasonal concentration (less than 3 days per decade) (Figures 4b and 4c). However, the trend is significantly negative for both parameters in less than 15% of the stations. Stations with more concentrated precipitation are scattered through the south and northeast, while those with earlier period of precipitation seasonal concentration occur sporadically across the entire study area.

4.3 Changes in precipitation characteristics for different precipitation intensities

4.3.1 Trends of precipitation amount and number of rainy days above different precipitation intensities

The trends in precipitation amount and number of rainy days for different precipitation intensity levels (greater than 10 mm, 25 mm and 50 mm of daily precipitation) are shown in Figure 5. There is a tendency to increase precipitation totals exceeding 10 mm and 25 mm of daily precipitation across the low latitude highlands (Figures 5a and 5c). The percentage of stations with an increasing volume of precipitation above 10 mm is 62.1%, and that of stations with precipitation amount higher than 25 mm is 71.0%. These stations are mostly located in the centre, northwest and southwest, and most of them have an insignificant positive trend. The stations with a decrease in precipitation volumes higher than 10 mm and 25 mm account for less than 1/3 of all stations and occur predominantly in the east and northeast. The slopes of these upward/downward trends are mostly less than 30 mm per decade. In the case of daily precipitation exceeding 50 mm, less than half (about 41.9%) of the stations show a positive trend and only a few of them (about 21.2%) exhibit a significantly increasing tendency (Figure 5e). These stations occur mainly in the centre and in the southwest and most of them give a trend at a rate of less than 20 mm per decade. 22.6% of all stations have recorded a decreasing volume of precipitation, out of which only very few stations show a significantly negative trend. They are largely confined to the east. 35.5% of the examined stations, mostly in the northeast and northwest, show no change in trend.

With respect to the number of days with daily precipitation greater than 10 mm, 25 mm and 50 mm, the majority of stations exhibit no discernible trend over the observation period. No trend stations corresponding to the above-mentioned three levels account for about 32.3%, 56.4% and 92.7%, respectively (Figures 5b, 5d and 5f). 39.5% of the examined stations show a positive trend regarding the number of days with more than 10 mm of daily precipitation, while 28.2% show a negative trend. Positive trend stations are located mainly in the central and northwestern parts as well as along the western border, negative trend stations prevail in the east, northeast and southeast. In the case of the number of days with more than 25 mm of precipitation, a positive trend has been recorded by 34.7% of the stations, out of which over 1/4 exhibit a significant trend, and 8.9% a slightly negative trend stations. The positive trend stations occur mostly in the central and northwestern parts. Only nine stations show a positive trend of days with a precipitation of more than 50 mm.

4.3.2 Trends of extreme precipitation

Figure 6 demonstrates trends of some extreme precipitation indices. Changes in the highest volume of precipitation during 1-day, 3-day and 7-day periods follow a mostly positive trend

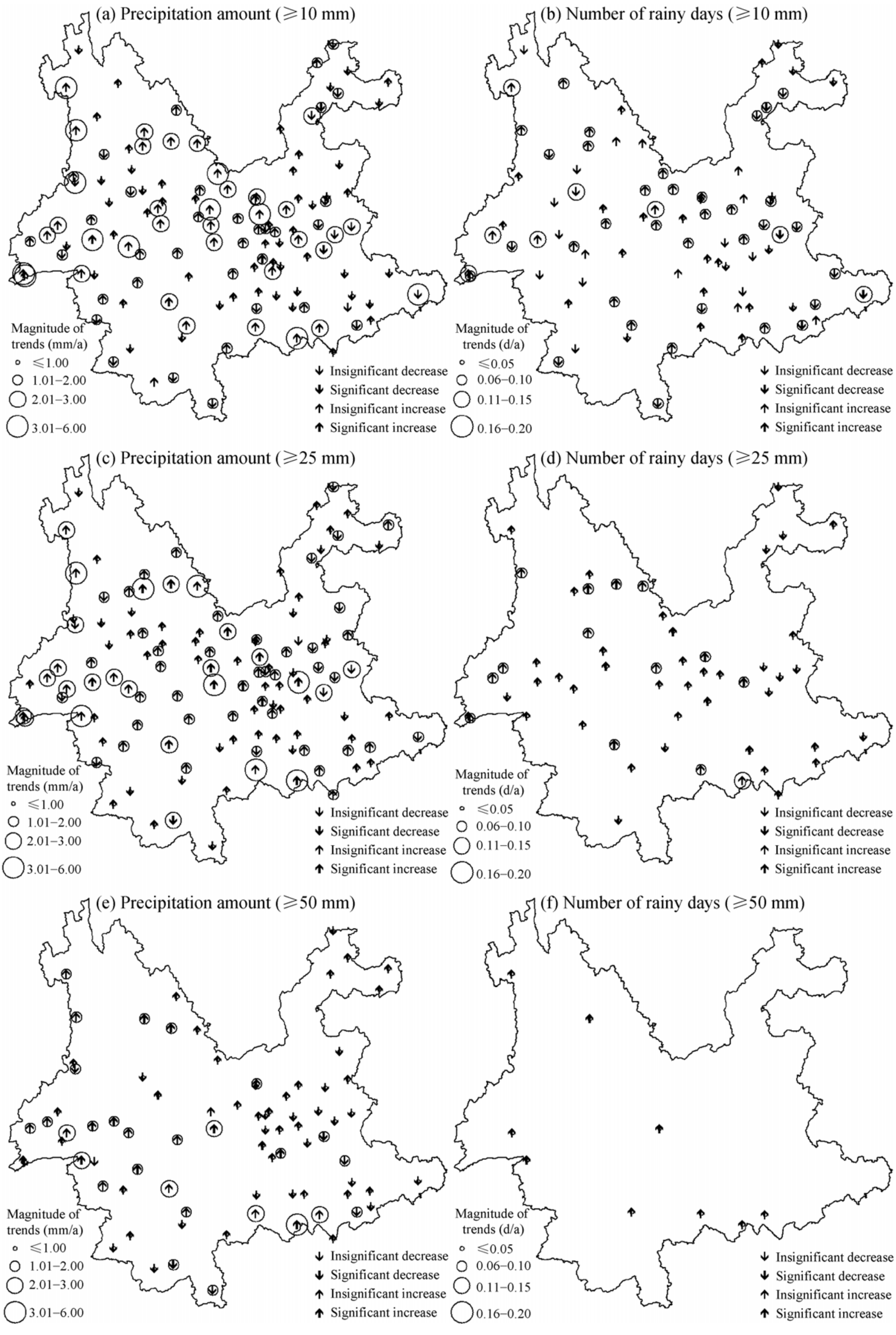

Figure 5 Spatial distribution of trends in precipitation amount and number of rainy days for daily precipitation above different intensities

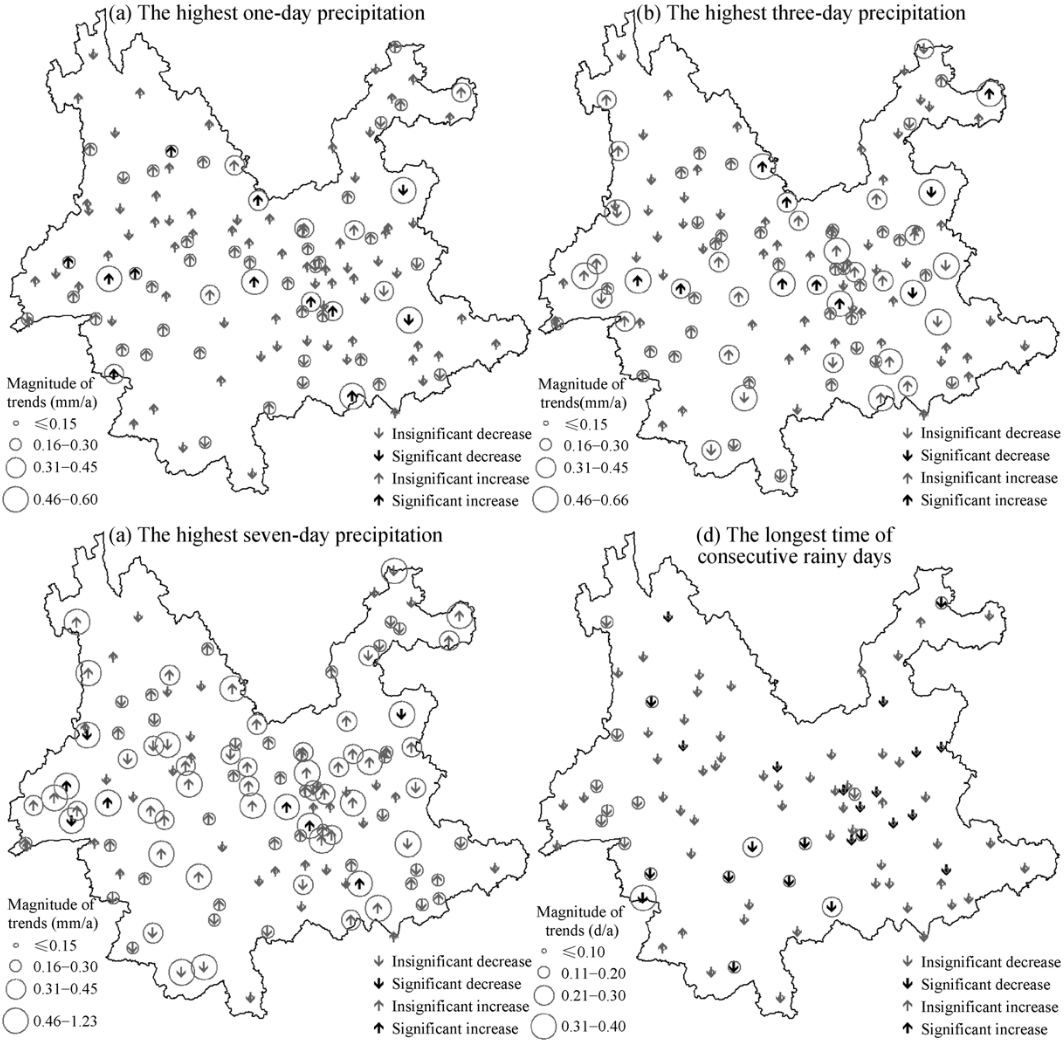

Figure 6 Spatial distribution of trends in the highest one-day, three-day and seven-day precipitation, and the longest time of consecutive rainy days

across the low latitude highlands (Figures 6a, 6b and 6c). However, for most of the stations, the increasing trend is insignificant and its slope value is less than 10 mm per decade. Stations recording a positive trend are located in the center, northwest and southwest, whereas the stations with a negative tendency for the highest 1-day, 3-day and 7-day precipitation occur predominantly in the west, south, northeast and southeast. With respect to the largest number of consecutive days of precipitation, 65.3% of the stations show a negative trend. One-third of them, mostly confined to the central, western and southwestern parts, show a significant tendency towards shorter periods of consecutive rainy days (Figure 6d).

5 Discussion

The change in annual precipitation of the low latitude highlands of the Chinese province of Yunnan over the last decades is not significant. However, there are substantial regional differences in precipitation. The main spatial characteristic of annual precipitation in the low latitude highlands is a drying trend in the the central and northwestern part, and a wetting trend in the eastern and northeastern part. It is difficult to link these specific variations to global warming (Hu *et al.*, 2003), even though it has been widely observed that global warming results in changes of the amount and of the spatial pattern of precipitation (Karl and Knight, 1998; IPCC, 2007). On a global scale, precipitation tends to increase with global warming at low and high latitudes, and to decrease at middle latitudes (IPCC, 2007). In China, there is a general tendency of precipitation becoming slightly less in most parts of the country, especially in the north and the northwest (Chen *et al.*, 1991; Wang *et al.* 2004; Wang and Zhou, 2005). Recent work, however, suggests that there has been no apparent trend in total precipitation over China during the last century, except for a moderate increase since 1956 (Liu *et al.*, 2005; Ding *et al.*, 2006). The trend of annual precipitation in the low latitude highlands of southwestern China is thus comparable to the national trend reported in Ding *et al.* (2006), but distinctly different from trends in other regions of southwestern China such as the Tibetan Plateau and the Sichuan Basin (Wang *et al.*, 2004; Zhai *et al.*, 2005; Li *et al.*, 2010).

The long-term variations of precipitation across the low latitude highlands are highly seasonal. The precipitation during winter and spring shows an increasing trend in nearly all of the study area. The precipitation in summer shows a decreasing trend which is, however, largely confined to the central region. In autumn, the precipitation shows a decreasing trend in the east and an increasing trend in the west. Accordingly, the seasonality of precipitation is changing. The level of precipitation seasonality is becoming slightly weaker; the dates of the onset of the rainy season and of the period of precipitation seasonal concentration tend to be earlier. The seasonality of precipitation has slightly weakened in recent decades. However, precipitation has increased in winter and summer, and decreased in spring and autumn on a countrywide scale (Wang *et al.*, 2004; Liu *et al.*, 2005; Wang and Zhou, 2005; Zhang *et al.*, 2011). It is argued that the national trends of changes in precipitation are associated with a weakening of the East Asian summer monsoon (Wang, 2001; Wang *et al.*, 2004; Wang and Zhou, 2005). In contrast to other “classical” monsoon areas, the amounts and seasonality of precipitation over the low latitude highlands of southwestern China are interactively affected by up to four branches of the atmospheric circulation, most notably by the East Asian monsoon and the South Asian monsoon (Wang and Wang, 1982; Thomas, 1993; Wang *et al.*, 1998; Yang *et al.*, 2007; Yang *et al.*, 2011). Early onset of the rainy season in the low latitude highlands was found to be correlated with La Niña events (Yang *et al.*, 2011). Stronger water vapor transport resulted from the intensification of the anomalous cyclone over the Bay of Bengal is an important factor in the determination of precipitation change in the low latitude highlands of Yunnan during late spring-early summer.

In association with a seasonal shift in precipitation, the number of days per year with precipitation shows a decreasing trend, whereas the mean annual precipitation intensity has an increasing trend. Upward trends in the precipitation amount and number of rainy days have been detected for daily precipitation above different intensities (such as ≥10 mm, ≥25 mm and ≥50 mm), and for the highest 1-day, 3-day and 7-day precipitation throughout the study area except for a few stations in the east and northeast. However, only a fraction of precipitation stations, mostly located in the central part of the low latitude highlands, show a significantly increasing trend in these indices related to heavy and extreme precipitation. These variations suggest that the frequency of heavy and extreme precipitation events is slightly increasing (Peng and Liu, 2009). Research on the trends of precipitation extremes over the whole country showed no obvious trends (Zhai *et al.*, 1999; Zhai *et al.*, 2005). However, the number of days with precipitation above certain intensities (such as ≥10 mm, ≥25 mm and ≥50 mm) has significantly decreased in southwestern China (Zhai *et al.*, 1999), which is in contradiction to the results of this work. This shows that there are significant regional differences in the trends of precipitation extremes in southwestern China. Because heavy precipitation events over the low latitude highlands is determined by the Indo-Pacific Warm Pool (Liu *et al.*, 2011), more occurrences of precipitation extremes might be related to a significant increase in the warm pool intensity since the 1980s (Qiu *et al.*, 2007). Due to the high orographical structure of its terrain, Yunnan Province is most vulnerable against an enhanced frequency of extreme precipitation events and related mountain-specific disasters such as flash floods, landslides, and debris flows.

Distinct regional trends of the above-observed precipitation indices reflect non-uniform changes in precipitation across the low latitude highlands of Yunnan, which might be partly attributed to the complicated interaction between the local terrain and dominant atmospheric circulation. It was found that precipitation patterns in the low latitude highlands of Yunnan are closely associated with the "corridor-barrier" effects of the local distinct Longitudinal Range-Gorge terrain on the link between water vapor transport and atmospheric circulation (He *et al.* 2007). The "corridor" effects help to extend the transport of water vapor farther north onto the hinterland of the highlands, whereas the "barrier" effects block the latitudinal transport of water vapor. The "corridor-barrier" effects result in regional differences in the strength and duration of the two subsystems of the Asian summer monsoon in the different parts of Yunnan, which eventually lead to region-specific patterns and trends of precipitation. Thus, it can be inferred that significant east-west differences and strong north-south similarities of precipitation trends previously observed are mainly attributed to mechanical and thermodynamical effects of special north-to-south mountain-valley terrain in the low latitude highlands of Yunnan. However, precipitation gauges sited preferentially in valleys and mountain basins limits our further evaluation on orographic patterns of precipitation trends in the investigated area.

6 Conclusions

In accordance with the whole of China, no significant trend in annual precipitation has been observed from 1950 to 2007 across the low latitude highlands of China. Seasonal differences in precipitation trends are, on the other hand, conspicuous and different from other "classical" monsoon areas in China. It was found that there is a significant wetting trend in spring, a moderate drying trend in summer, and a moderate wetting trend in winter. Autumn is characterized by a drying trend in the east and a wetting trend in the west. The dates of the onset of the rainy season and of the period of precipitation seasonal concentration have shifted to earlier dates, while the degree of precipitation concentration has become lower. More intense and slightly longer moderate and heavy precipitation occurs across the whole region. The most extreme one-day and multi-day precipitation events have increased slightly.

Consequently, the number of rainy days per year has decreased while the mean annual precipitation intensity has increased. Regional differences in precipitation change were found to be distinct. The most significant differences in precipitation trends are found in the eastern and central parts of the study area, which is associated with the “corridor-barrier” effects of special mountainous terrain. These variations also have complicated linkages with a weakening of the East Asian summer monsoon and a strengthening of the South Asian summer monsoon. Physical mechanisms for precipitation trends in the low latitude highlands still need to be further investigated.

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