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Is southwestern China experiencing more frequent precipitation extremes?

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Abstract

Climate extremes have and will continue to cause severe damages to buildings and natural environments around the world. A full knowledge of the probability of the climate extremes is important for the management and mitigation of natural hazards. Based on Mann–Kendall trend test and copulas, this study investigated the characteristics of precipitation extremes as well as their implications in southwestern China (Yunnan, Guangxi and Guizhou Province), through analyzing the changing trends and probabilistic characteristics of six indices, including the consecutive dry days, consecutive wet days, annual total wet day precipitation, heavy precipitation days (R25), max 5 day precipitation amount (Rx5) and the rainy days (RDs). Results showed that the study area had generally become drier (regional mean annual precipitation decreased by 11.4 mm per decade) and experienced enhanced precipitation extremes in the past 60 years. Relatively higher risk of drought in Yuanan and flood in Guangxi was observed, respectively. However, the changing trends of the precipitation extremes were not spatially uniform: increasing risk of extreme wet events for Guangxi and Guizhou, and increasing probability of concurrent extreme wet and dry events for Yunnan. Meanwhile, trend analyses of the 10 year return levels of the selected indices implied that the severity of droughts decreased in Yunnan but increased significantly in Guangxi and Guizhou, and the severity of floods increased in Yunnan and Guangxi in the past decades. Hence, the policy-makers need to be aware of the different characterizations and the spatial heterogeneity of the precipitation extremes.

Keywords: climate extremes, copula, disaster

1. Introduction

Southwestern China is characterized by overpopulation, underdevelopment, complex terrain, karst landform and fragile ecosystems, which makes it sensitive to climate change (Cai 1996, Deng *et al* 2009, Fan *et al* 2011, Hao and Zhao 2011). Moreover, natural hazards such as floods and droughts occur frequently in this area. For example, five

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severe droughts had hit southwestern China since 2000 (Liu *et al* 2007, Mao *et al* 2007, Yin 2013). Particularly, the 2009/2010 extreme drought resulted in a considerable reduction of crop production in 4.35 million ha farmlands, shortages of drinking water for 160.9 million people and 110.6 million animals, and serious impacts on vegetation production (Wang *et al* 2010, Zhang *et al* 2012a). The accumulative economic loss totaled \$2.8 billion (Yin 2013). On the other hand, floods also happened frequently in this area (Blanchard 2007, Fauna 2010, Jiang 2011, Mu 2006, Zhu 2011). Catastrophic floods had caused serious damages to constructions and natural environments in this area. Furthermore, the coupling of extreme events (e.g., drought followed immediately by flooding), which tend to occur more frequently in recent years (Fauna 2010, Zhu 2011), have triggered other natural hazards such as landslides.

There is growing concern about extreme climate events due to the vulnerability of our society to the adverse impacts of such events. A recent climate report published by Intergovernment Panel on Climate Change (IPCC) pointed out that large uncertainty exists about the 'future vulnerability, exposure, and responses of interlinked human and natural systems' IPCC (2014). In recent years, many have studied the trends or patterns of the climates extremes at regional and global scales (Anagnostopoulou and Tolika 2012, de Vries *et al* 2013, Tramblay *et al* 2012, Wan *et al* 2013, Wang *et al* 2013a, 2013b). There have been also many studies that focused on the change of climate extremes in China (Liu *et al* 2006, Wang *et al* 2013a, 2013b, Zhai *et al* 1999), but most of these studies focused on the changing patterns of several climate extreme indices (Fischer *et al* 2011, Li *et al* 2012, Zhang *et al* 2010). For southwestern China, Zhang *et al* (2010) found that the changes in precipitation extremes in Guizhou were not significant. Similarly, Li *et al* (2012) reported that changes in precipitation extremes were relatively small, and only the regional trends in consecutive wet days (CWD), extremely wet day precipitation and maximum 1 day precipitation were significant in this area. However, historical records and some studies seem to suggest that extreme hydrologic events are happening more frequently in this area (Yan *et al* 2013, Zhang *et al* 2013a). Indeed, the more frequent occurrence of extreme hydrologic events is an indication of the increasing probability of precipitation extremes in southwestern China. However, it could not be adequately explained by the insignificant changing trends in climate extremes alone. Hence, the probability of occurrence should be considered.

Actually, knowledge of the probability and/or risk of climate extremes is very important for the management and mitigation of natural hazards (Calanca 2007, Cancelliere and Salas 2010, Unkasevic *et al* 2004, Zhang *et al* 2012b). Meanwhile, most hydro-meteorological events are intrinsically multivariate; knowledge of the joint probabilistic characteristics of the precipitation extremes would provide more helpful information for policy making and project planning. Nevertheless, few studies have paid attention to the probabilistic properties of the climate extremes in southwestern China, especially to their multivariate probabilistic properties (Zhang *et al* 2012b, 2013b, 2013c).

This study aims to (1) investigate the trends and probabilistic characteristics of precipitation extremes, (2) analyze the joint probabilistic characteristics and tendencies of bivariate precipitation extremes and (3) evaluate the changing patterns of floods or droughts implied by the precipitation extremes.

2. Data and methodology

2.1. Study area

The study area includes Yunnan, Guizhou, and Guangxi provinces, which covers a total area of 8.0×10^5 km^2 in the southwestern part of China. This region exhibits large variations in elevations ranging from sea level (coastal area in southern Guangxi) to 6740 m (Mount Kawakarpo in northwestern Yunnan), and characterized by a very complex topography (figure 1). In particular, karst landform is prevalent in this region, covering about 28%, 37.8%, 73% of Yunnan, Guangxi and Guizhou provinces, respectively (Deng *et al* 2009, Lan and Mo 1995, Wan 2003). The precipitation decreases from southeast to northwest and from south to north; it varies from more than 2500 mm in the north coast of Beibu Gulf (Guangxi) to less than 700 mm in the northwest and northeast of Yunnan. The low precipitation in some areas may attribute to the dry-hot valley microclimates, which are sporadically distributed over the upper reaches of the Yangtze, Nujiang, Yuanjiang, Langcang, Honghe river valleys (Gao *et al* 2012, Jin 1999, Ou 1994, Xu *et al* 2008). The precipitation in this region also shows clear seasonal variations, increasing from about 28 mm month^{-1} in January and February to about 230 mm month^{-1} in June and July, and then decreasing gradually to 30 mm month^{-1} in December. More than 73% of the precipitation is received in the period of May to September.

2.2. Dataset and indices

In this study, a long term (1951–2012) continuous dataset of daily precipitation from a dense network of 70 meteorological stations (figure 1) was used. This dataset was developed by the Climate Data Center (CDC) of the National Meteorological Center of the China Meteorological Administration (CMA) and has gone through the quality control procedures of the CDC. The precipitation data used in this paper was acquired from http://cdc.cma.gov.cn/home.do. The RclimDex procedure was used to execute the quality controls (Wang *et al* 2013a), which was developed by Zhang and Yang (2004) at the Canadian Meteorological Service. In this study, rainy days (RDs) were defined as those days with precipitation greater than or equal to 1 mm. The threshold of 1 mm rainfall in the definition of 'RDs' was used to avoid artificial trends, which could arise from a tendency of some observers failing to report small rainfall amounts (Zhang *et al* 2012b). For the purpose of this study, extreme precipitation events

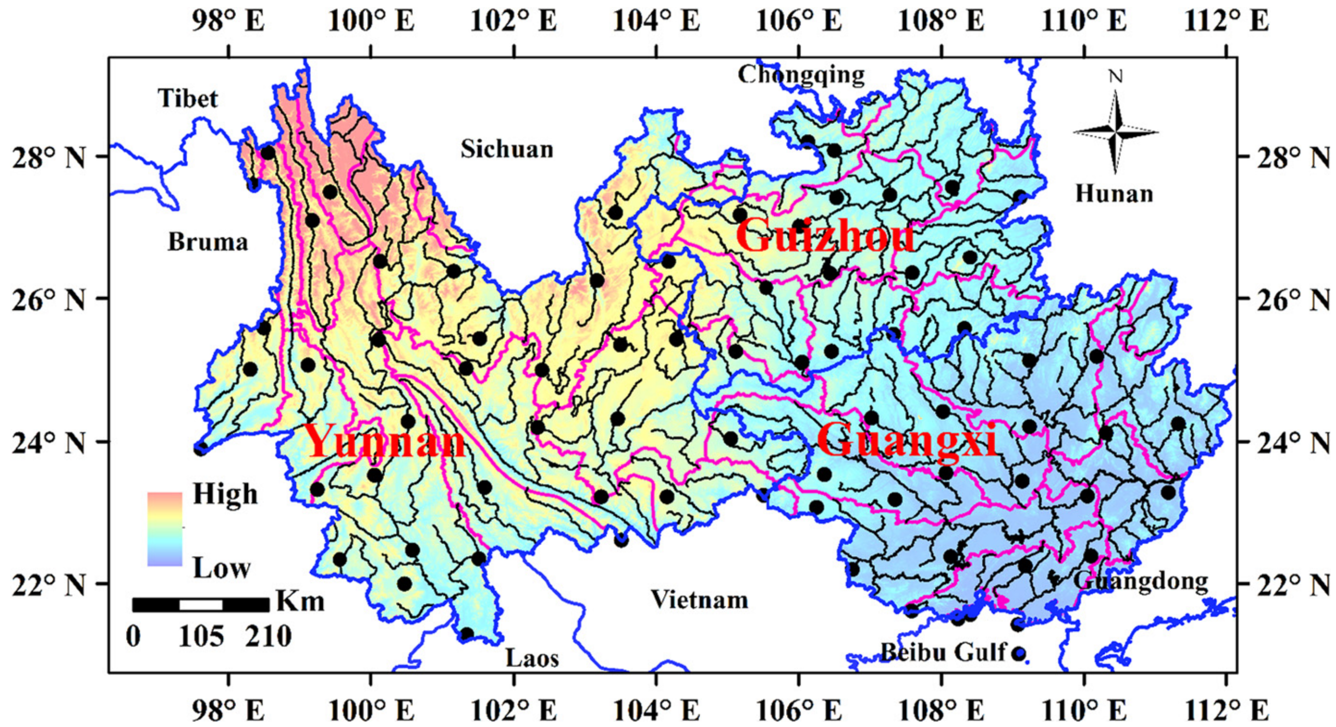

Figure 1. Topography map of southwestern China, while the dark dots show the locations of the meteorological stations, the thick pink lines are the basin boundaries and the thin dark lines are the main rivers.

Table 1. Precipitation indices defined in this study.

Abbreviations and	Units	Definitions
Consecutive dry days (CDD)	day	Maximum number of consecutive days with precipitation <1 mm
Consecutive wet days (CWD)	day	Maximum number of consecutive days with precipitation ⩾1 mm
Annual total wet day precipitation (PT)	mm	Annual total precipitation in wet days (precipitation ⩾1 mm)
Heavy precipitation days (R25)	day	Annual count of days when precipitation ⩾25 mm
Max 5 day precipitation amount (Rx5)	mm	Annual maximum consecutive 5 day precipitation
Rainy days (RDs)	day	Annual count of days when precipitation ⩾1 mm

were characterized by six precipitation indices, which were the consecutive dry days (CDD), CWD, annual total wet day precipitation (PT), heavy precipitation days (R25), max 5 day precipitation amount (Rx5) and the RDs. The definitions and units of these indices are summarized in table 1. These indices were calculated using the widely used RclimDex procedure (Li *et al* 2012, Wang *et al* 2013a, Zhang *et al* 2000). In particular, the CDD was used to represent the extreme dry events, longer CDD indicates more severe meteorological drought. The CWD, PT, Rx5, R25 and RDs were employed to imply the wet events. In particular, a high value of Rx5 usually suggests flood. In addition, the regional average series were calculated as an arithmetic mean of values at all stations in this study:

$$x_t = \frac{1}{n_t} \times \sum_{i=1}^{n_t} x_{i,t}, \tag{1}$$

where the x_t is the regional averaged index at year t, $x_{\mathrm{i},t}$ is the index for station i at year t.

Actually, the meteorological drought may be previously due to long periods of low precipitation (Palmer 1965). Whereas in the formation of floods, there would be several factors such as regional geography (e.g., rivers), meteorology (e.g., precipitation), land surface (e.g., vegetation) and human activity (e.g., reservoirs, dykes) performing important functions (Xu *et al* 2005). Nevertheless, paroxysmal large amount of water could be the prerequisite, which mainly attribute to heavy precipitation events (e.g. rainstorms). On the other hand, historical records illustrated that 53 droughts occurred in southwestern China from the year 1951 to 2011, with the return period being shorter than 2 years (Wang 2012). On the other hand, data showed that more than 100 floods occurred in Honghe river basin (Yunnan) since the year 1950 (Ma 2009). In guangxi, the return periods of floods were 3.3 years and 10 years in the Xijiang river basin during the periods of 1991–2010 and 1900–1990 (Su and Liang 2012). Whereas in Guizhou, there have been 42, 43 and 35 floods that hit Guiyang, Liupanshui and Anshun City since 1980, respectively (Shi *et al* 2008). These data indicate that the return periods of both floods and droughts in southwestern China were no longer than 10 years. Hence, it would be rational to use the 10 year return levels (see in the next parts) of the indices to imply severe floods and droughts in this area.

2.3. Mann–Kendall test

There are many statistical techniques available to detect trends within the time series, among which the Mann–Kendall trend test (MK test) (Kendall 1975, Mann 1945) is a wildly used nonparametric trend detection method (Wang *et al* 2013a, 2013b, Zhang *et al* 2009), as it is less sensitive to outliers than parametric statistics. Moreover, the rank-based nonparametric MK test can examine trends in a time series without requiring normality or linearity. However, it has been reported many times that the presence of serial correlation may lead to an erroneous rejection of the null hypothesis (Yue *et al* 2002). Therefore, a modified pre-whitening method, namely trend free pre-whitening (MK-TFPW), was applied to our dataset in order to eliminate the effect of serial correlation (Yue and Wang 2002). We used $\alpha = 0.05$ to determine if a trend is statistically significant. On the other hand, we also calculated the trends with the linear least square method.

2.4. Analysis of precipitation indices and return levels

Precipitation indices used in this study can be classified as discrete or continuous variables, CDD, CWD, R25 and RDs are discrete and PT, Rx5 are continuous. Generally, probability distributions of discrete variables are the binary distribution, binomial distribution, Poisson distribution, geometric distribution, negative binomial distribution (Stern 1980). However, the discrete distributions may not fit the discrete variables well (no significant at 0.05 level), but the continuous distribution does in many times. In this study, the Gaussian, Student's *t*, Poisson, exponential, Rayleigh, Weibull, generalized extreme value (GEV), binomial, negative binomial, lognormal, geometric, generalized Pareto (GP), extreme value distribution (EV) were used to analyze distributions of the indices. These distributions were applied frequently in many other studies (Bardossy and Pegram 2009, Richardson 1981, Wilks 1999, Zhang *et al* 2012b). The parameters of these distributions were commonly estimated using the maximum likelihood estimator (Bardossy and Pegram 2009, Wilks 1999). The goodness-of-fit was evaluated by the Kolmogorov Smirnov test in order to choose the appropriate distribution for each precipitation index series.

Using the selected distribution, the 10 year return levels for indices were calculated based on the entire time series. Next, for analyzing the trend of the 10 year return levels, a moving window approach was used, the 10 year return levels from 30 year (a climate timescale) moving windows (e.g., 1951–1980, 1952–1981, …, 1983–2012) were generated (Ghosh *et al* 2012, McCabe *et al* 2004). Hence, about 25–33 values of 10 year return levels were obtained at each station (the starting years of the time series differed slightly from each other). Thereafter, the trends of the 10 year return levels were analyzed using the MK test.

2.5. Copulas selection and joint return periods

For multivariate frequency analyses, copulas have recently received much attention, because they provide flexible representation of multivariate distributions (Chen *et al* 2013, Madadgar and Moradkhani 2013, Mishra and Singh 2011, Singh and Singh 1991, Yusof *et al* 2013). The most attractive feature of the copula approach is that it simplifies the task of modeling multivariate distributions into modeling separate marginal distributions by considering the inherent correlations and dependencies among them. There is a wide range of copulas to be selected in order to yield the correlated joint distribution (Leonard *et al* 2008). In recent years, copulas have been used for analyzing hydro-meteorological extremes widely (Madadgar and Moradkhani 2013, Renard and Lang 2007, Scholzel and Friederichs 2008, Zhang and Singh 2007, Zhang *et al* 2012b, 2013b). In this study, the Gumbel-Hougaard (GH), Clayton, Frank, Ali-Mikhail-Haq (AMH), Gaussian and tcopulas were used to analyze the joint probability distribution of precipitation extremes. These copulas were also frequently used in other studies (Yusof *et al* 2013, Zhang and Singh 2007). The descriptions of the copulas distributions can be found in Trivedi and Zimmer (2007). The parameters for the copulas were estimated using the maximum likelihood method. The Akaike Information Criterion (AIC) was used for identifying the appropriate probability distribution, which can be expressed as (Akaike 1974, Zhang and Singh 2007):

$$AIC = -2 \times log\left(maximized\ likelihood\ for\ the\ model\right) + 2 \times \left(number\ of\ fitted\ parameters\right). \tag{2}$$

The copula that has the smallest AIC was chosen. Consequently, based on the selected copula, two joint return periods were investigated:

$$T_{(X>x,Y>y)} = \frac{1}{p(X > x,\, Y > y)} = \frac{1}{1 - F_x(x) - F_y(y) + F(x,\, y)}$$
$$T_{(X>x,Y<y)} = \frac{1}{p(X > x,\, Y < y)} = \frac{1}{F_y(y) - F(x,\, y)} \tag{3}$$

where $F_x(x)$ and $F_y(y)$ are marginal distributions for variables X and Y, respectively; $F(x, y)$ is the corresponding joint probability distribution; the $T_{(X>x,\ Y>y)}$ represents the joint return period that X and Y are larger than a threshold value; $T_{(X>x,\ Y<y)}$ is the joint return period that X is larger than a threshold value while Y is lower than a threshold value. In this study, the threshold value used for each index was its 10 year return level.

In order to meet the study objectives, several combinations are selected. The $T_{(\mathrm{CDD/Rx5:}\ X>x,\ Y>y)}$ was constructed to analyze the characteristic of the events that drought and flood encounter within a year; $T_{(\mathrm{CDD/PT:}\ X>x,\ Y<y)}$, $T_{(\mathrm{CDD/RDs:}\ X>x,\ Y<y)}$ and $T_{(\mathrm{CDD/CWD:}\ X>x,\ Y<y)}$ were used to investigate the characteristic of co-occurrence of extremely long no-rain period and low precipitation; the $T_{(\mathrm{PT/Rx5:}\ X>x,\ Y>y)}$ and $T_{(\mathrm{CWD/R25:}\ X>x,\ Y>y)}$ were employed to reflect the characteristic of the extreme wet events. Finally, the changing trends of joint return periods were also investigated using the same

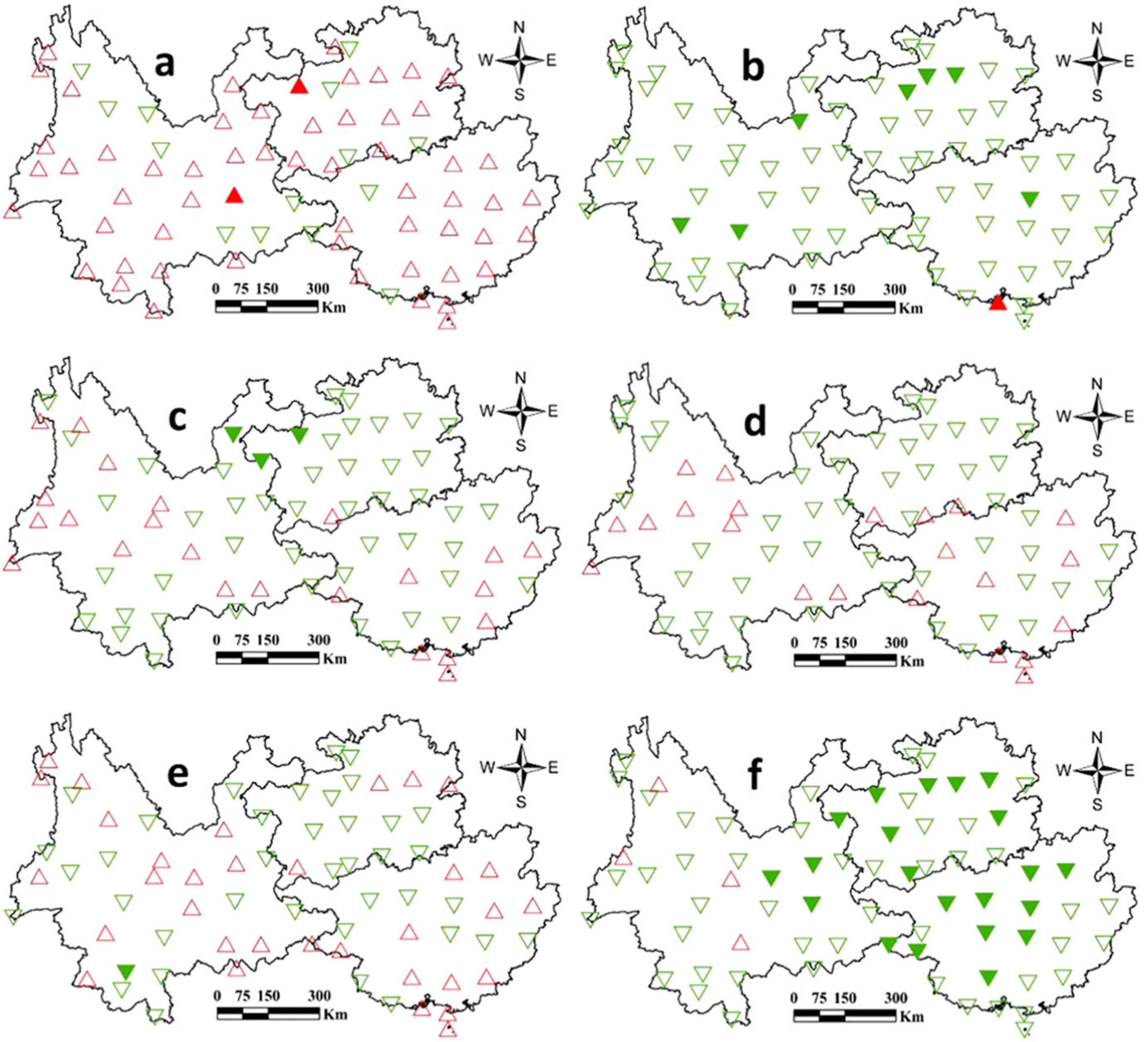

Figure 2. Spatial distribution of annual trends of (a) CDD; (b) CWD; (c) PT; (d) R25; (e) Rx5; (f) RDs. Filled *red* triangle denotes significant increase, inverted filled *green* triangle denotes significant decrease, inverted open *green* triangle denotes no significant decrease, and open *red* triangle denotes no significant increase. The same symbols in the following figures denote the same meanings.

method as that used for the 10 year return levels described above.

3. Results

3.1. Variation of precipitation extremes

In terms of the CDD, most of the stations exhibited increasing trends, although the increases were not significant ($p > 0.05$), while only 13 out of 70 stations had decreasing trends (figure 2(a)), which were mainly located in northwestern and southeastern part of Yunnan. Figure 2(b) showed that almost all the stations indicated decreasing tendencies in CWD and six of these stations showed significant trends ($p < 0.05$). As for the PT, 22 out of the 70 stations showed increasing trends, which were mainly located in southern and eastern part of Guangxi and mid and western part of Yunnan. Most of the stations showed decreasing trends in R25, however, 22 stations in northwestern Yunnan and the western and southern part of Guangxi, accounting for 31% of the total stations, exhibited increasing trends in R25 (figure 2(d)). The changes of Rx5 seemed to be more complex. The Rx5 at the stations located in Guizhou and the adjoining areas mainly decreased, whereas most of the stations in southern and northeastern part of Guangxi and southeastern and western part of Yunnan, had increasing Rx5 (figure 2(e)). The RDs at most of the stations decreased, among which 21 stations in the eastern part of the study area showed significant tendencies. As a whole, figure 2 indicated that the precipitation extremes generally had no

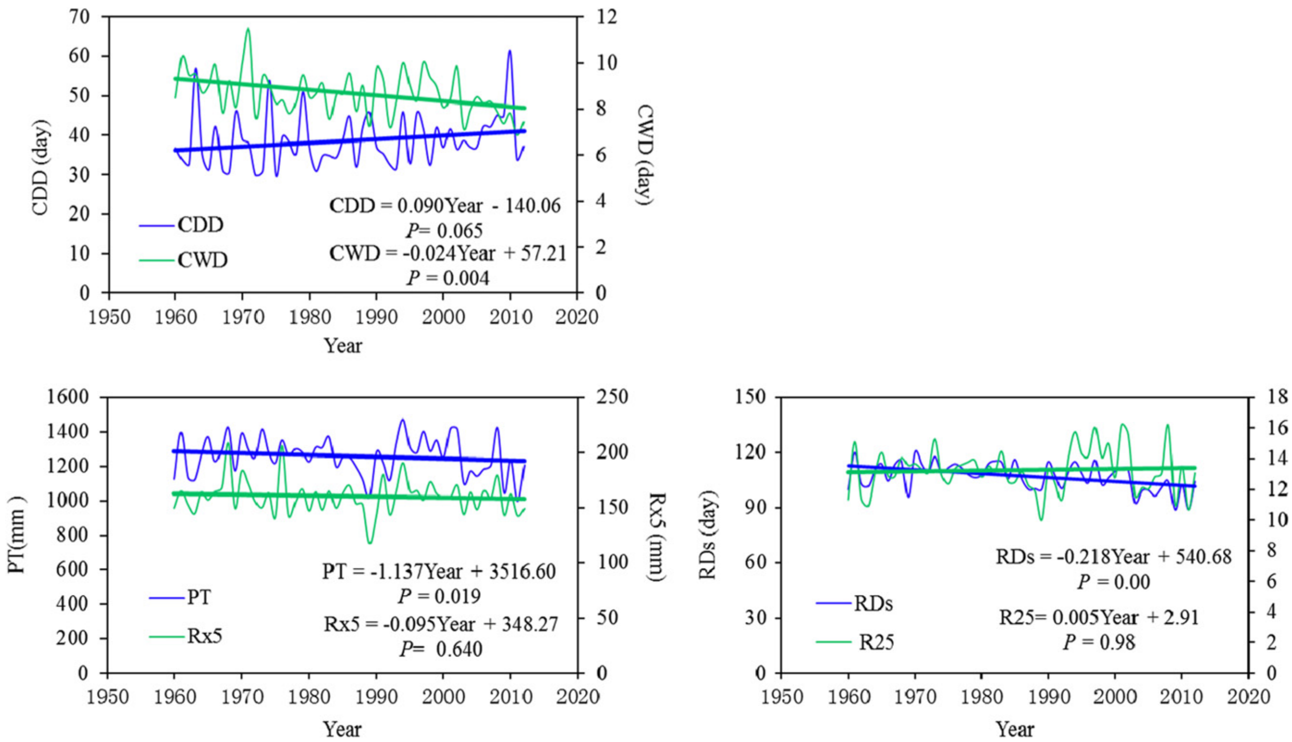

Figure 3. Dynamics of regional averaged indices in southwestern China.

Table 2. *P* values for the K–S test and the probability distributions with the highest goodness-of-fit for the precipitation data at the Kunming station, Yunnan, China. High *P* value means good fitting of distribution model.

Indices	CDD	CWD	PT	R25	Rx5	RDs
The best distribution	Lognormal	GEV	Lognormal	GEV	Lognormal	*t*
P values	0.84	0.52	0.93	0.74	0.96	0.67

significant trends. At the regional scale, the results in figure 3 showed that the regional averaged CWD, PT and RDs significantly decreased in the past several decades, while the CDD, Rx5 and R25 changed insignificantly ($p > 0.05$). Yet, the p value (0.065) still indicated that the CDD increased obviously in this area. In particular, the regional mean CWD, PT, Rx5 and RDs decreased by 0.24 day, 11.4 mm, 0.95 mm and 2.2 day per decade, and the CDD and increased by 0.98 day and 0.05 day per decade in the past half century (figure 3).

3.2. Spatial distribution and changing trends of 10 year return levels

Precipitation indices from the Kunming station were used as examples to show the selection of the best distributions, and the results are shown in table 2. In addition, 62.5% of the P values for all the indices at all stations were higher than 0.7 (data not shown here). Note that in the subsequent sections, the indices as CDD_{10}, CWD_{10}, PT_{10}, $Rx5_{10}$, $R25_{10}$ and RDs_{10} would refer to those 10 year return levels.

The CDD_{10} were generally large in Yunnan plateau and had an apparent downward trend from Yunnan, Guangxi to Guizhou (figure 4(a)). In Yunnan, there were nine stations with CDD_{10} longer than 80 days, and most of the stations were in the range of 60–80 days. The CDD_{10} mainly ranged 40–60 and 30–40 days in Guangxi and Guizhou province, respectively. CWD_{10} were mainly lower than 15 days, and it exceeded 20 days at a few stations in western Yunnan (figure 4(b)). The spatial distribution for PT_{10}, $R25_{10}$ and $Rx5_{10}$ was similar to each other, with decreasing trends in the three indices from southeast to northwest. The largest values of PT_{10}, $R25_{10}$ and $Rx5_{10}$ were observed in southern Guangxi (figures 4(c)–(e)). With respect to the RDs_{10}, most of the values were higher than 110 days. Low RDs were found in the mid of Yunnan, mainly due to the dry-hot valley microclimates.

The trends of the 10 year return levels are illustrated in figure 5. Overall, most of the stations experienced significant changing trends in the 10 year return levels ($P < 0.05$) (figure 5). Figure 5(a) showed that the CDD_{10} in Guangxi and Guizhou generally increased significantly, but that in Yunnan showed downward trends, especially in northwestern Yunnan. As for CWD_{10} (figure 5(b)), most of the stations had decreasing trends, while some stations in southern Guangxi and Yunnan experienced upward trends. PT_{10} and $R25_{10}$ in Yunnan and Guangxi increased significantly, and decreased in Guizhou (figures 5(c), (d)). For the $Rx5_{10}$, increasing

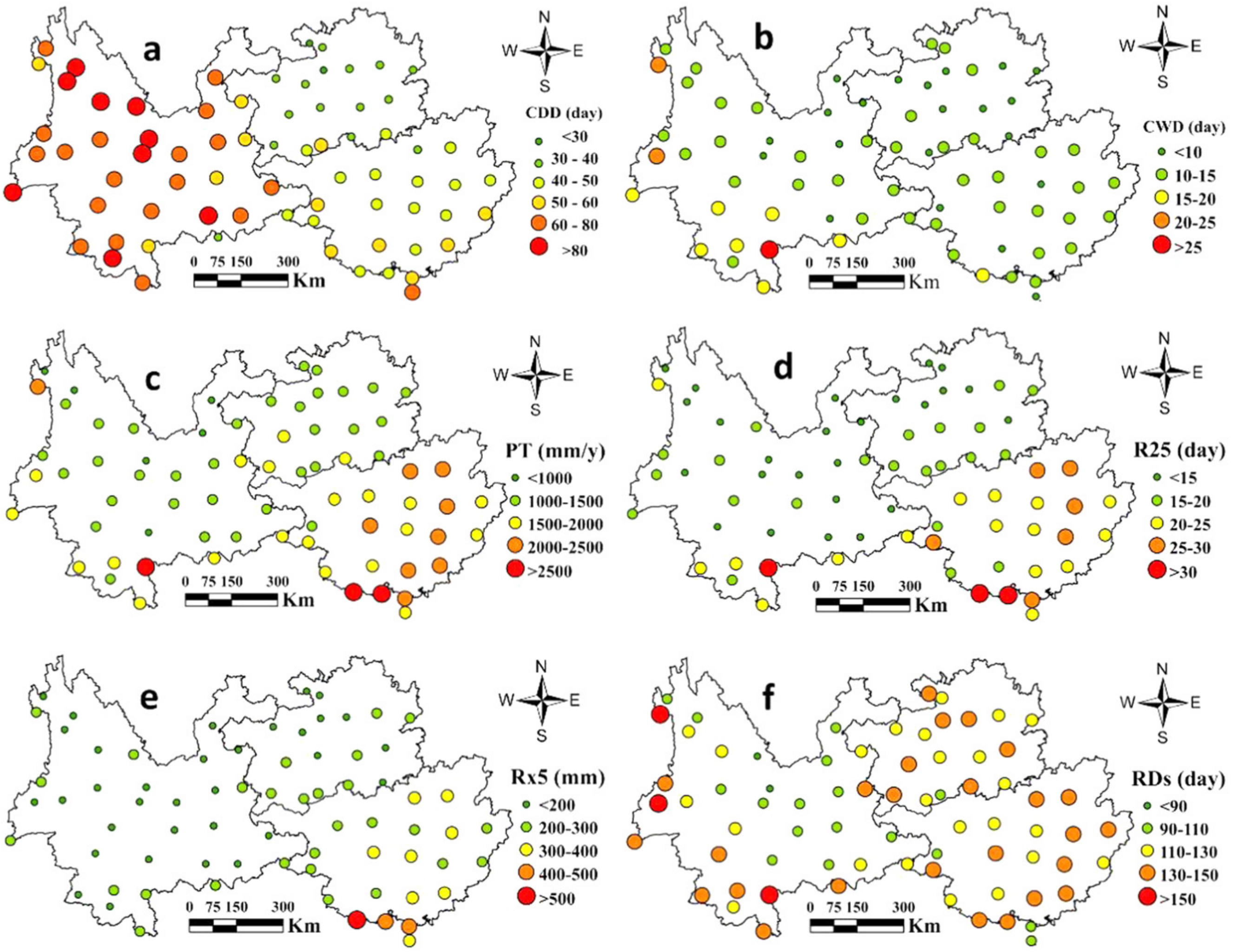

Figure 4. Spatial distribution of (a) CDD_{10}; (b) CWD_{10}; (c) PT_{10}; (d) $R25_{10}$; (e) $Rx5_{10}$; (f) RDs_{10}. The precipitation indices plotted in this figure are all with return period of 10 years.

trends were observed in southern and western part of Yunnan, northeastern part of Guangxi and middle part of Guizhou (figure 5(e)). The RDs_{10} exhibited significantly decreasing tendencies in large part of the study area except in northwestern Yunnan (figure 5(f)).

3.3. Joint distribution of precipitation indices

Similar to the 10 year return levels, precipitation indices from the Kunming station were also taken as the examples to show the selection of the appropriate copulas. Relationships between different pairs of indices are shown in figure 6, the AIC values and the selected copulas are presented in table 3. Figure 7 shows the empirical and copula based joint distribution of different indices pairs, which indicate that the copula based distribution does reflect the dependence structure of precipitation indices.

As shown in figure 8(a), there existed an apparent decreasing trend in $T_{(\mathrm{CDD/Rx5:}\ X>x,\ Y>y)}$ from Yunnan to Guangxi and Guizhou. Large $T_{(\mathrm{CDD/Rx5:}\ X>x,\ Y>y)}$ were observed in Yunnan and small ones were found in Guizhou, implying smaller probability of concurrent long CDD and high Rx5 in Yunnan. In other words, the risk of co-occurrence of drought and flood within a year is lower in Yunnan plateau. From figure 8(b), the $T_{(\mathrm{PT/Rx5:}\ X>x,\ Y>y)}$ are generally below 60 years in most of the area, relative high values mainly occurred in southern Guangxi and eastern Yunnan. Figure 8(c) illustrates the distribution of $T_{(\mathrm{CWD/R25:}\ X>x,\ Y>y)}$, reflecting the probability of concurrent long CWD and high-volume precipitation events. This probability was smaller in large parts of Guizhou and western Yunnan, and was relatively higher in southern part of the study area. Figure 8(d) shows the probability distribution patterns of high CDD and low precipitation. High $T_{(\mathrm{CDD/PT:}\ X>x,\ Y<y)}$ were generally found in Guangxi and low values in Yunnan. The $T_{(\mathrm{CDD/RDs:}\ X>x, Y<y)}$ at most of the stations were below 10.4 years, and relatively high values mainly occurred in southwestern part of Yunnan (figure 8(e)). The spatial patterns of $T_{(\mathrm{CDD/CWD:}\ X>x,\ Y<y)}$ is similar to that of $T_{(\mathrm{CDD/Rx5:}\ X>x,\ Y>y)}$. High $T_{(\mathrm{CDD/CWD:}\ X>x, Y<y)}$ values mainly distributed in Yunnan, indicating that the probability of concurrent long CDD and long CWD was lower in Yunnan. As a whole, the results as shown in figures 8(b) and (c) indicated that the probability of

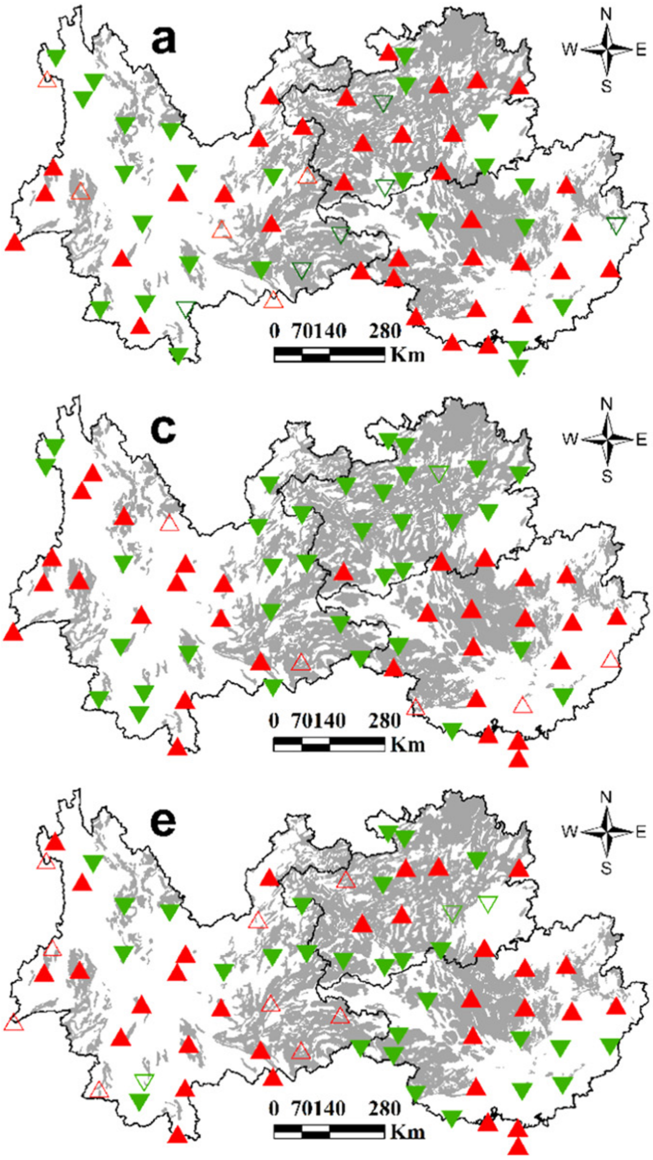

Figure 5. Spatial distribution of changing patterns of (a) CDD_{10}, (b) CWD_{10}, (c) PT_{10}, (d) $R25_{10}$, (e) $Rx5_{10}$ and (f) RDs_{10}. The gray colored area represents the karst region in the study area.

concurrent high PT and Rx5, and long CWD and high R25 was much larger in Guangxi, implying higher risk of floods. On the other hand, the large $T_{(CDD/Rx5:\ X>x,\ Y>y)}$, low $T_{(CDD/PT:\ X>x, Y<y)}$ and $T_{(CDD/RDs:\ X>x, Y<y)}$ in large part of Yunnan reflected that this area suffered high risk of droughts. However, the results in Guizhou were relatively more complex. The low $T_{(CDD/RDs:\ X>x, Y<y)}$ and $T_{(CDD/CWD:\ X>x, Y<y)}$ suggested high risk of dry events, but the low $T_{(CDD/Rx5:\ X>x,\ Y>y)}$, $T_{(PT/Rx5:\ X>x,\ Y>y)}$, $T_{(CDD/Rx5:\ X>x,\ Y>y)}$ and high $T_{(CDD/PT:\ X>x, Y<y)}$ also indicated high risk of concurrent extreme wet and dry events.

Changes in joint return periods are illustrated in figure 9. Similar to the 10 year return levels, the joint return periods at most of the stations had significant trends in the past several decades. In northwestern Yunnan, large part of Guizhou and southern part of Guangxi, the $T_{(CDD/Rx5:\ X>x,\ Y>y)}$ increased, and in southern Yunnan and on the eastern border of Guizhou and Guangxi, it decreased significantly (figure 9(a)). The figure 9(b) shows significantly decreasing $T_{(PT/Rx5:\ X>x,\ Y>y)}$ in large part of Yunnan, middle part of Guizhou and northern Guangxi, and increasing $T_{(PT/Rx5:\ X>x,\ Y>y)}$ in southern and southeastern Guangxi and eastern Guizhou. The $T_{(CWD/R25:\ X>x,\ Y>y)}$ displayed generally downward trends (figure 9(c)). Whereas, the $T_{(CDD/PT:\ X>x, Y<y)}$ and $T_{(CDD/RDs:\ X>x, Y<y)}$ increased significantly in large part of Yunnan and Guizhou, and decreased in southern Guangxi (figures 9(d), (e)). As for $T_{(CDD/CWD:\ X>x, Y<y)}$, it exhibited decreasing trends in northwestern Yunnan, middle and southwestern part of Guizhou and southwestern part of Guangxi.

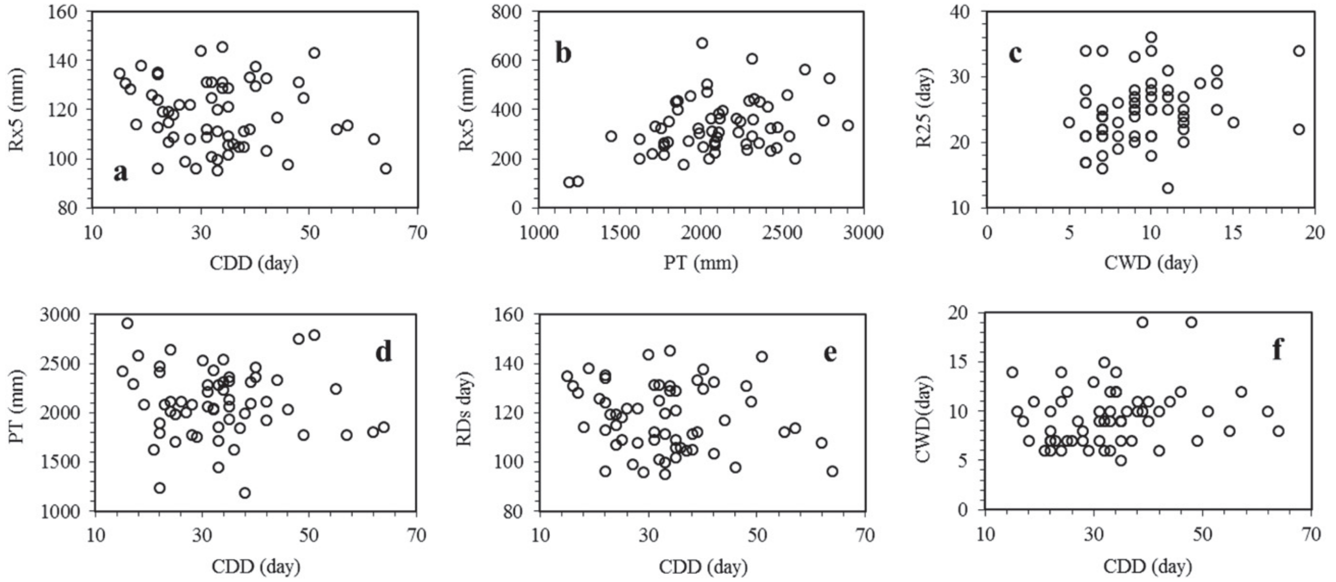

Figure 6. Scatter plots of (a) CDD and Rx5, (b) PT and Rx5, (c) CWD and R25, (d) CDD and PT, (e) CDD and RDs, (f) CDD and CWD at the Kunming station.

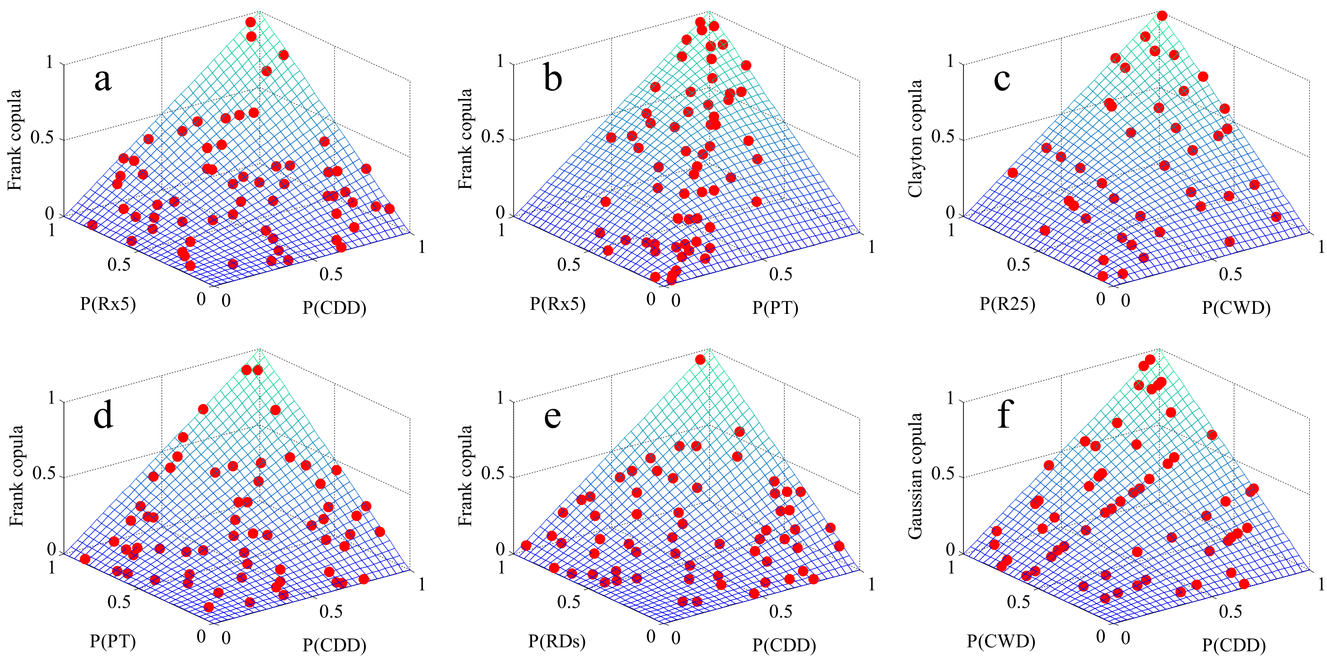

Figure 7. Empirical and copula based distribution for the precipitation pairs, (a) CDD and Rx5, (b) PT and Rx5, (c) CWD and R25, (d) CDD and PT, (e) CDD and RDs, (f) CDD and CWD at the Kunming station.

Table 3. Joint return periods of bivariate variables at the Kunming station, the return periods of individual precipitation variables are ten years. Low AIC value means good fitting of joint distribution model.

	CDD/Rx5	PT/Rx5	CWD/R25		CDD/PT	CDD/RDs	CDD/CWD
Copula	Frank	Frank	Clayton	Copula	Frank	Frank	Gaussian
AIC value	−0.96	6.88	1.02	AIC value	−0.94	−2.06	0.12
$T_{(X>x \text{ and } Y<y)}$	152.9	24.2	54.4	$T_{(X>x \text{ and } Y<y)}$	10.7	10.4	11.6

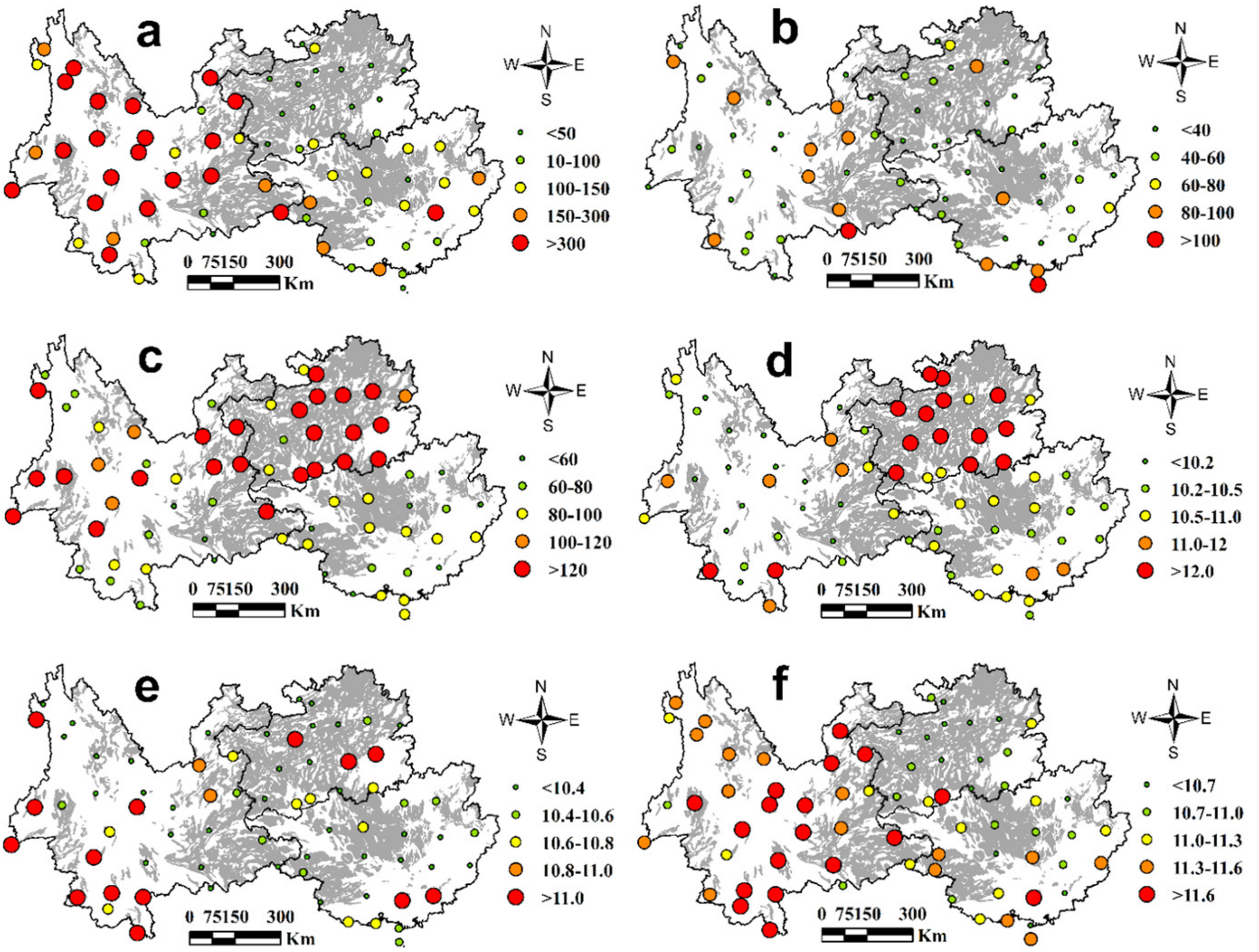

Figure 8. Distribution of joint return periods for different bivariate precipitation (a) $T_{(\mathrm{CDD/Rx5}:\ X>x \text{ and } Y>y)}$, (b) $T_{(\mathrm{PT/Rx5}:\ X>x \text{ and } Y>y)}$, (c) $T_{(\mathrm{CWD/R25}:\ X>x \text{ and } Y>y)}$, (d) $T_{(\mathrm{CDD/PT}:\ X>x \text{ and } Y<y)}$, (e) $T_{(\mathrm{CDD/RDs}:\ X>x \text{ and } Y<y)}$, (f) $T_{(\mathrm{CDD/CWD}:\ X>x \text{ and } Y<y)}$; the $T_{(\mathrm{CDD/Rx5}:\ X>x \text{ and } Y>y)}$ represents the joint return period that *X* and *Y* are larger than a threshold value and the two variables are CDD_{10} and $\mathrm{Rx5}_{10}$ in this case. The gray colored area represents the karst region in the study area.

4. Discussion

Humans and natural environment are vulnerable to the impacts of climate and weather extremes (Chen *et al* 2012, Lobell *et al* 2011, Manton 2010, Parker *et al* 2008, Rocklov and Forsberg 2009, Wang et al 2013a, b). From ancient times to the present, climate extremes have brought upon severe impacts on society and natural environment in the world. Southwestern China is a sensitive region for climate change due to its geographic, ecological and social background. Comprehensive knowledge of the probability or risk of the weather extremes is essential for the management and mitigation of natural hazards (Calanca 2007, Cancelliere and Salas 2010, Unkasevic *et al* 2004, Zhang *et al* 2012b). This study investigated the trends and probabilistic characteristics of six precipitation extremes such as the CDD, CWD, PT, heavy precipitation days (R25), max 5 day precipitation amount (Rx5) and the RDs in southwestern China. It would be meaningful for evaluating the changing patterns of floods or droughts and improving water resources management in this region.

The results showed that the selected precipitation extremes at most of the stations in southwestern China generally had insignificant changing trends. At regional scale, the overall trends for CWD, PT and RDs was significantly decreasing, while that for CDD, Rx5 and R25 were insignificantly ($P > 0.05$). Nevertheless, the insignificantly changing indices still implied that southwestern China was generally becoming drier (the regional averaged annual precipitation deceased by 11.37 mm 10 yr^{-1}), which is consistent with the findings in other regions (Fu *et al* 2013, Lacombe *et al* 2012). Results suggested that the 10 year return levels for the selected indices exhibited strong regional features. The CDD_{10} decreased from 60–80 days in Yunnan toward 40–60 days in Guangxi and 30–40 days in Guizhou; while the PT_{10}, $\mathrm{R25}_{10}$ and $\mathrm{Rx5}_{10}$ generally decreased from southeastern part to northwestern part of the study area. Furthermore, unlike the initial extreme precipitation indices (the indices in table 1), the 10 year return levels showed significant trends ($P < 0.05$).

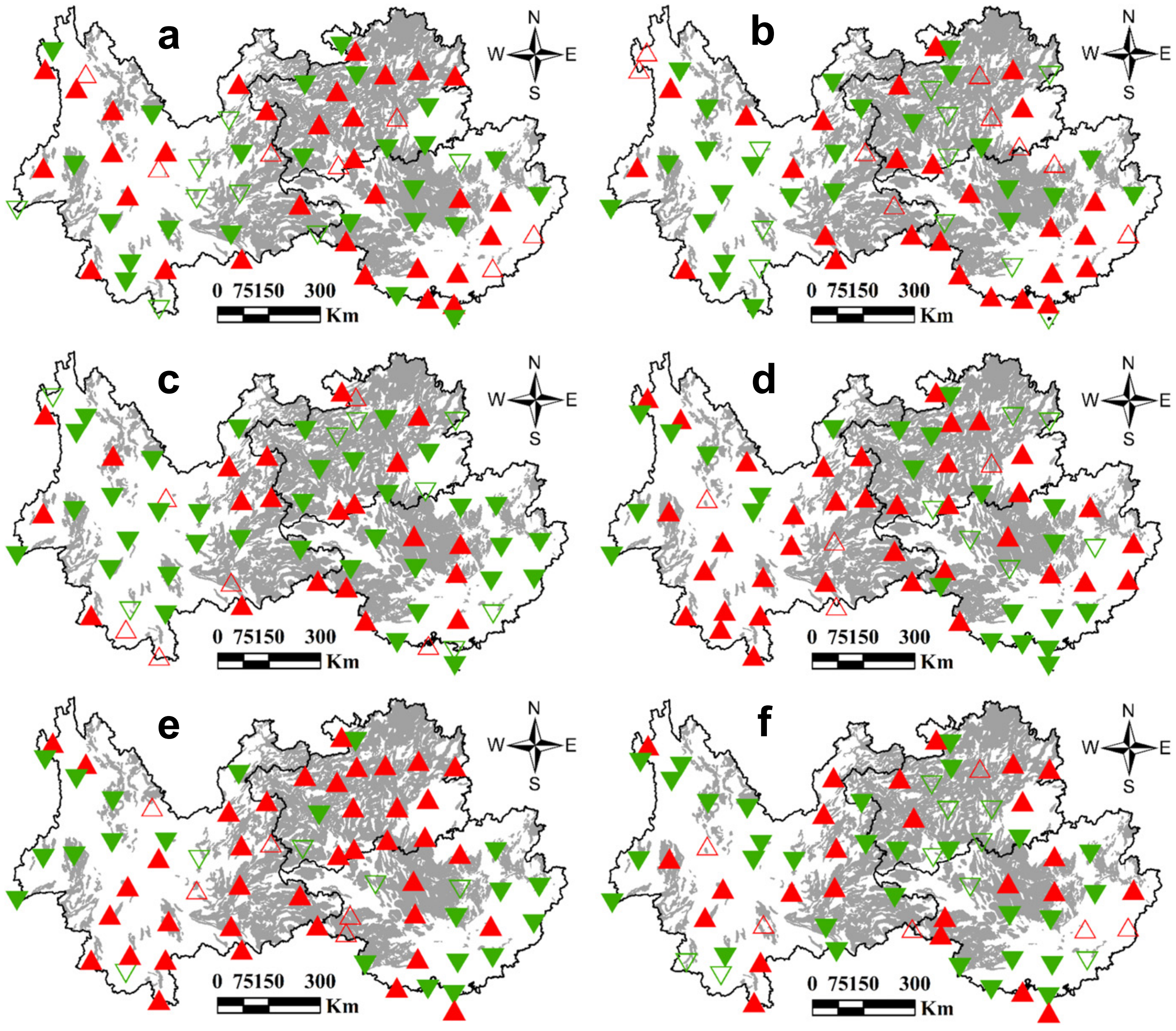

Figure 9. Spatial distribution of changing patterns of the joint return periods for different bivariate precipitation indies(a) $T_{(\mathrm{CDD/Rx5}:\ X>x\ \mathrm{and}\ Y>y)}$, (b) $T_{(\mathrm{PT/Rx5}:\ X>x\ \mathrm{and}\ Y>y)}$, (c) $T_{(\mathrm{CWD/R25}:\ X>x\ \mathrm{and}\ Y>y)}$, (d) $T_{(\mathrm{CDD/PT}:\ X>x\ \mathrm{and}\ Y<y)}$, (e) $T_{(\mathrm{CDD/RDs}:\ X>x\ \mathrm{and}\ Y<y)}$, (f) $T_{(\mathrm{CDD/CWD}:\ X>x\ \mathrm{and}\ Y<y)}$. The gray colored area represents the karst region in the study area.

The 10 year return levels generally represent the max magnitudes of the indices at 90% occurrence probability. The results implied that the magnitude or severity of potential drought was much larger in Yunnan than in other areas (higher CDD_{10}, figure 4), but the severity of potential flood was relatively high in Guangxi. However, the changing patterns of CDD_{10} revealed that the severity of the potential droughts decreased in past decades in Yunnan but increased significantly in Guangxi and Guizhou. Similarly, the increasing trends of PT_{10} (figure 5(c)), $\mathrm{R25}_{10}$ (figure 5(d)) and $\mathrm{Rx5}_{10}$ (figure 5(e)) in Yunnan and Guangxi also implied increasing magnitude of the possible floods in the past decades (Su and Liang 2012, Zhao and Pan 2008).

According to the results of joint return periods (figure 8) and the corresponding changing characteristics (figure 9), it could be inferred that Guangxi might have relatively higher risk of floods and the probability and magnitude of these extreme wet events became higher in the past several decades (figure 9). Consistently, more frequent floods was also observed in Guangxi in recent years (Su and Liang 2012, Zhao and Pan 2008). The high level of CDD_{10} (figure 4), low $T_{(\mathrm{CDD/PT}:\ X>x\ \mathrm{and}\ Y<y)}$ and $T_{(\mathrm{CDD/CWD}:\ X>x\ \mathrm{and}\ Y<y)}$ (figure 8) indicated that a large part of Yunnan was characterized by high risk of drought, but the severity of the potential droughts has decreased in the past decades as the CDD_{10} decreased significantly. However, the risk of concurrent extreme wet and dry events increased in Yunnan, (decreasing $T_{(\mathrm{CDD/Rx5}:\ \mathrm{X>x\ and\ Y>y})}$ in figure 9). Guizhou generally suffered high probability of co-occurrence of extreme wet and dry events (low $T_{(\mathrm{CDD/Rx5}:\ X>x\ \mathrm{and}\ Y>y)}$ in figure 8) and increasing risk of extreme wet events, demonstrated by the decreasing $T_{(\mathrm{PT/Rx5}:\ X>x\ \mathrm{and}\ Y>y)}$ and $T_{(\mathrm{CWD/R25}:\ X>x\ \mathrm{and}\ Y>y)}$ showed in figure 9

(Shi *et al* 2008). However, the magnitude of the potential drought might have increased (Wu *et al* 2013) but that of the floods might have reduced.

The trends of the selected indices showed that southwestern China was generally becoming drier (decreasing precipitation in the past years). However, the results above also indicated that the risk of floods increased. The reasonable explanation was that the extreme precipitation events were increasing (Zhang *et al* 2010), which might be inherent with the global climate change. Data showed that the temperature in southwestern China increased by a rate higher than 0.01 °C yr^{-1} during the past decades (Wang and Meng 2007). Studies indicated that tropospheric warming leads to enhancement of moisture content in the atmosphere and is associated with increase in heavy rainfall events (Allen and Ingram 2002, Trenberth *et al* 2005). Similarly, a global increase in extreme rainfall events has been suggested in the literatures as a consequence of atmospheric and oceanic warming (O'Gorman and Schneider 2009, Sugiyama *et al* 2010).

On the other hand, results presented above suggested that the changing trends of precipitation extremes were lack of uniform in southwestern China (Ghosh *et al* 2012, Li *et al* 2012). Previous studies reported that the trend in daily rainfall variance was related to the trend in large-scale moisture availability (Goswami *et al* 2006, Zhang *et al* 2008). A previous study (Zhang *et al* 2010) showed that, in the past several decades, the annual moisture flux was overall increasing since 1960 in the study area. Particularly, the summer latitudinal moisture flux increased slightly since 1960; the summer longitudinal moisture flux increased slightly in Yunnan but decreased slightly in Guangxi and Guizhou before 1990, and then decreased in northern Yunnan but significantly increased in the rest region of the study area after 1990. In winter, the latitudinal moisture flux insignificantly decreased in northern Yunnan and increased in Guizhou and Guangxi, especially in the eastern and southern part of the study area before 1990, but significantly increased after 1990. Whereas, the winter longitudinal flux decreased in Yunnan and increased in Guangxi and Guizhou since 1960. Actually, floods in southwestern China generally occurred in summer (Ma 2009, Su and Liang 2012) and droughts happened in winter and spring (Wang 2012). The increasing summer moisture flux should be the important reason for the increasing probability of extreme wet events in Yunnan, and increasing winter latitudinal moisture flux would play important roles in the decreasing severity of the potential droughts. Similarly, the significantly increasing summer flux after 1990 would be the reasonable explanation for the increasing risk of floods in Guangxi and Guizhou.

Besides the overall effects of global climate change, local topographic heterogeneity could also effect. For example, Guizhou and northern Guangxi have more complex terrain that might result in more complicated changing patterns in precipitation extremes. It is well known that physiographic factors such as elevation, slope, aspect, and topographic convergence could influence meteorological elements (Dobrowski 2011, Fu 1983, Weng and Luo 1990, Bristow and Campbell 1984). Studies showed that complex topography affects the microclimate significantly (Onol 2012, Young *et al* 1997) through influencing the radiation and airflow. In the study area, the existence of hot-dry valley is due to the topography (Gao *et al* 2012, Jin 1999, Ou 1994, Xu *et al* 2008). Meanwhile, changes in urbanization, deforestation or other land-use considerations might be other reasons for the spatial heterogeneity of the changing trends of precipitation extremes (Ghosh *et al* 2012).

5. Conclusions

This study investigated the trends and probabilistic characteristics of six precipitation extremes in southwestern China, including the CDD, CWD, PT, heavy precipitation days (R25), max 5 day precipitation amount (Rx5) and the RDs, using MK test and copulas, aiming at their implications for natural hazards such as floods and droughts. The findings showed that the selected precipitation extremes changed insignificantly, but the corresponding 10 year and the joint return levels exhibited significant changing trends ($P < 0.05$) in the past decades. The results implied that southwestern China was becoming drier and suffering enhanced extreme weather events. However, the risks and the changing patterns of these extreme events were spatially heterogeneous. In particular, Guangxi might have relatively higher risk of floods and suffered increasing risk and severity of extreme wet events. Yunnan was characterized by high risk of drought and increasing probability of concurrent extreme wet and dry events, with decreasing severity of droughts but increasing magnitude of floods. Whereas Guizhou generally suffered high probability of concurrent of extreme wet and dry events and increasing risk of extreme wet events. These findings suggest that differences in characteristics and spatial distribution of precipitation extremes should be carefully considered when making sustainable water resources management policies and more effective natural hazard mitigation strategies.

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