

Spatiotemporal characteristics of precipitation changes in the Pearl River Basin, China

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Abstract The change structures of precipitation and precipitation intensity and rainy days are analyzed for the Pearl River Basin (from 1959 to 2009) on the basis of a suite of 24 climatic indices derived from daily precipitation data at 62 meteorological stations with the help of the Mann–Kendall test. Contributions of seasonal precipitation and precipitation intensity class to the annual precipitation are also examined using the inverse distance weighted method. The following four conclusions can be drawn: (1) although the average annual precipitation of the entire basin does not show obvious variation, the number of annual rainy days has decreased significantly in 98.3 % of the stations. These two factors result in an obvious increase in precipitation intensity at 64.5 % of the stations. (2) No clear change trend has been found for seasonal precipitation over the entire area; however, the number of rainy days in each season has decreased significantly. In particular, the number of rainy days in the entire year and in the fall season has decreased in 98.3 and 100 % of the stations, respectively. (3) Although the number of rainy days in drizzle has decreased in 83.9 % of the stations, the number of rainy days

where heavy rain and extremely heavy rain occurred increased in nearly 75.8 and 82.3 % of the stations, respectively. (4) The number of rainy days in fall and winter contributes more to the change in the number of annual rainy days than the number of rainy days in spring and summer. Heavy rain and extremely heavy rain contribute more to the change in total annual precipitation than drizzle; however, they contribute less to the change in the number of annual rainy days than drizzle. The findings in this study can provide important information for formulating water resource and eco-environment management strategies in the Pearl River Basin to policymakers and stakeholders.

1 Introduction

Climate change is heavily influenced by the effects of greenhouse gases, which will ultimately change the spatiotemporal distribution of regional precipitation (Hulme et al. 1998; Alexander et al. 2006; Judit and Rita 2007). The Intergovernmental Panel on Climate Change (IPCC) predicted that the changes in the global water cycle over the twenty-first century will not be uniform; the contrasts in precipitation between wet and dry regions and between wet and dry seasons are expected to increase (http://en.wikipedia.org/wiki/IPCC_Fifth_Assessment_Report). Haren et al. (2013) found that over the past century, total annual precipitation increased in northwestern Europe but decreased in southern Europe. In South America, total annual precipitation decreased gradually in northern tropical areas but increased in southeastern South America (Matsuyama et al. 2002; Barros et al. 2008).

In China, significant variations have been detected in precipitation over the past several decades (Gemmer et al. 2004; Endo et al. 2005; Becker et al. 2006; Choi et al. 2008; Wang et al. 2012, 2013). In general, annual precipitation has

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decreased gradually in the south and increased in the north (Li 2011; Ye et al. 2013); summer and winter have become increasingly wet while spring and autumn are drier (Zhai et al. 2005; Liu et al. 2005). In addition, extreme precipitation events have increased dramatically throughout China (Sui et al. 2013; Xu et al. 2011). Using daily precipitation data for the period 1960–2000 from 272 weather stations in China, Liu et al. (2005) found that annual precipitation had increased by 2 %. During this period, precipitation increased in winter and summer but decreased in spring and autumn. Qian and Lin (2005) analyzed the regional characteristics of daily precipitation at 494 weather stations in China from 1961 to 2000 and detected a gradual decrease in annual and summer precipitation in coastal southeast China. Zhai et al. (2005) studied the seasonal variation of precipitation across China by using a daily precipitation dataset from 740 stations for the period 1951–2000. They found that precipitation in western and northwestern China decreased prior to the 1980s and increased after the 1980s. They also found that precipitation had increased in the summer and winter but decreased in the spring and fall. Li et al. (2013) analyzed the changes in temperature and precipitation in northwestern China by using daily data for the period 1960–2010 from 51 meteorological stations. They found that precipitation has increased in the mountainous areas, oases, and even in the desert areas of arid northwestern China, although the increase in the desert areas was not significant. In addition, extreme precipitation events also exhibited significant variation over the whole country. Zhang et al. (2013a) analyzed the spatio-temporal patterns of extreme precipitation in China using daily precipitation data from 590 stations covering the period 1960–2005. They found that extreme precipitation events are intensifying in southern China, mirrored by a decreasing number of rainy days. Based on daily precipitation records at 303 meteorological stations, You et al. (2011) detected a general increasing trend in extreme precipitation during the period 1961–2003, particularly in the Yangtze River Basin and southeastern and northwestern China. However, the abovementioned studies reach different conclusions, primarily caused by the different data series used in the analyses.

The Pearl River is one of the largest rivers in China, and this basin has occupied a crucial position in the socioeconomic development of China since the country adopted the “open door and reform” policy in the late 1970s. With the socioeconomic development within this basin region, the spatiotemporal distributions of precipitation directly affect the hydrological environment and supplementary water resources in this basin to a certain degree (Zhang et al. 2012). Several studies have demonstrated that precipitation in this basin has exhibited significant change over the past several decades. Zhang et al. (2009) reported that the number of rainy days in the Pearl River Basin has decreased significantly. However, the frequency of extremely high precipitation events has clearly

increased, which has resulted in remarkably increasing precipitation intensity over this basin. In the East River tributary basin, Chen et al. (2011) detected an increasing trend in spring and winter precipitation and a decreasing trend in summer and fall precipitation. Gemmer et al. (2011) reported that on a monthly basis, significant variations were observed in the Pearl River Basin in all months except December. The change in monthly precipitation, rain intensity, number of rainy days, and monthly maximum precipitation exhibited negative trends in October and positive trends in January. Fischer et al. (2011, 2012) emphasized that the annual number of rainy days decreased, and the annual precipitation intensity increased along the coastline and in the far western part of the Pearl River Basin. In general, it can be concluded from these studies that the average annual precipitation of the whole basin did not show obvious variation; however, significant differences were detected in regional and seasonal precipitation, the number of rainy days, and precipitation intensity.

The above studies on the variation of precipitation in the Pearl River Basin have dealt with different precipitation indices, number of stations, temporal settings, and time series. Faced with changing climate and intensifying human activities, more detailed information on the change structures of precipitation should be considered. Using daily precipitation data from 62 stations in the Pearl River Basin for the period 1956–2009, the major objective of this study is to conduct a comprehensive analysis of the change structure of precipitation, precipitation intensity, and rainy days for four seasons and four intensity classes over the Pearl River basin and to assess the contribution of each seasonal precipitation and each precipitation intensity class to annual precipitation.

2 Study region and data

The Pearl River Basin, located in southern China between the longitudes 97° 39' E and 117° 18' E and the latitudes 3° 41' N and 29° 15' N (Fig. 1), is the third largest river basin in China with a drainage area of 0.45 million km² (PRWRC 1991). The West River, North River, East River, and Pearl River Delta are the four major tributaries of the Pearl River Basin with drainage areas of approximately 77.8, 10.4, 5.9, and 5.9 % of the total basin area, respectively. The Pearl River Delta is surrounded by a number of metropolitan cities, with Guangzhou at the northern apex, Macao in the southwest corner, and Hong Kong in the southeast corner. Topographically, the elevation of this basin ranges from 0 m above the mean sea level (m-msl) in the southeast coastal areas to 2,300 m-msl in the northwest and northern mountainous areas.

Located in the subtropical zone, the Pearl River Basin is characterized by high temperatures and abundant precipitation (Liu et al. 2013). The annual mean temperature ranges from 14 to 22 °C, and the annual average precipitation ranges from

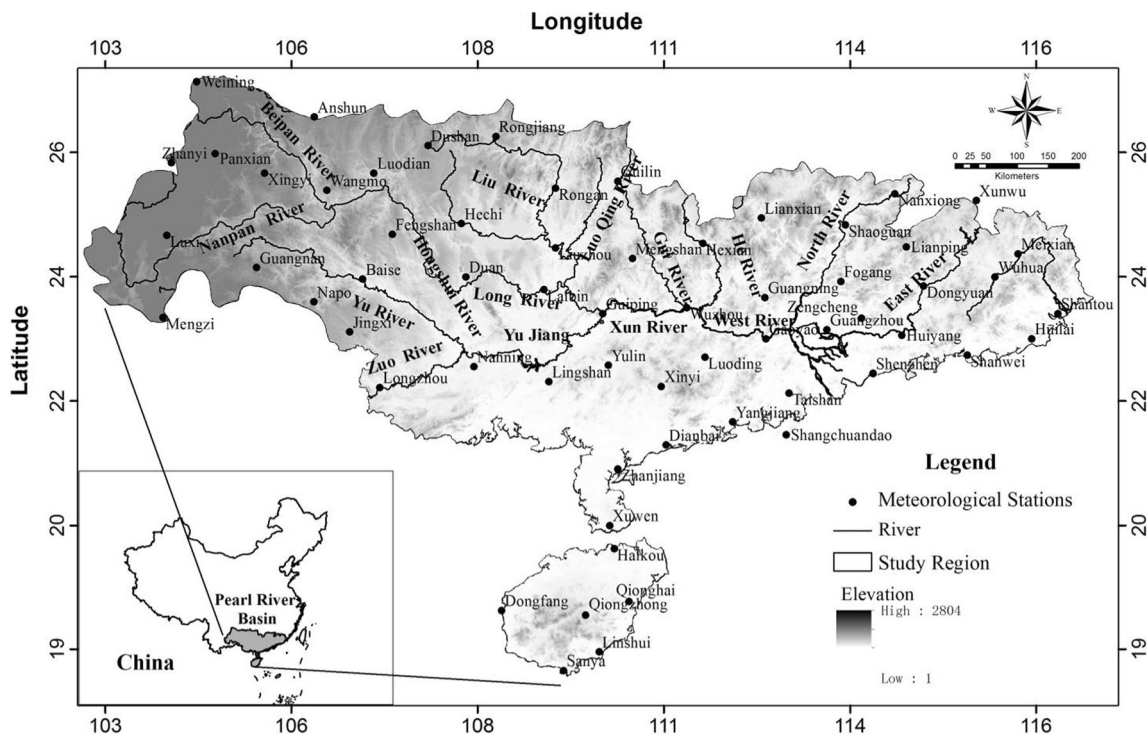


Fig. 1 Location, elevation, and meteorological stations in the study area

1,000 to 2,200 mm (PRWRC 1991). The annual average precipitation decreases from the eastern coastal areas to the western mountainous areas. The wet period is longer and more continuous, and the precipitation intensity is greater in the east than in the west (Liu et al. 2008). April to September is the rainfall season with 70–80 % of the total annual precipitation (Niu and Chen 2010).

The National Meteorological Research Center of China (NMRCC) has established 83 meteorological stations in the region. Climate data obtained from NMRCC include daily precipitation and daily minimum, maximum, and mean temperatures from 1959 to 2009. A software package, RHtests, developed by Wang and Feng of the Climate Research Division of Environment Canada (<http://etccdi.pacificclimate.org/software.shtml>) was used to examine the homogenization of the temperature and precipitation series. Sixty-two stations with consistent data (less than 1 % missing data) were selected for use in this study (Table 1).

3 Methodology

The trend and change point analyses for various precipitation indices were based on the nonparametric Mann–Kendall (MK) test (Mann 1945; Kendall 1970). The MK method does not require time series normality and is less sensitive to outliers and missing values than other methods (Ewa et al. 2011; Tian et al. 2012). The MK method is recommended by the

World Meteorological Organization to analyze trends in hydrometeorological data.

For an ordered set of n observations $X = x_1, x_1, \dots, x_n$, the MK trend statistic S is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \tag{1}$$

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases} \tag{2}$$

where n is the number of data series, and x_j and x_i are the values in period j and i , where $j > i$, respectively. It can be seen from Eq. (2) that the MK test is a distribution-free test statistic because the statistic S only depends on the ranks of the observations (Khaled 2008).

The variance of S is determined as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m [t_i(t_i-1)(2t_i+5)]}{18} \tag{3}$$

where m is the number of tied groups (a tied group is a set of sample data having the same value); t_i denotes the number of

Table 1 Properties of meteorological stations

Stations	Average annual precipitation (mm)	Rainy days (%)	Stations	Average annual precipitation (mm)	Rainy days (%)	Stations	Average annual precipitation (mm)	Rainy days (%)
Nanxiong	1,519.8	41.97	Mengshan	1,743.8	48.73	Yangjiang	1,882.8	43.97
Lianxian	1,555.3	42.94	Hexian	1,547.3	45.93	Dianbai	1,350.2	36.56
Shaoguan	1,611	46.7	Napo	1,387.3	43.94	Shangchuan	1,746.2	39.69
Fogang	2,165.5	45.86	Baise	1,095	34.29	Xuwen	1,164.3	35.26
Lianping	1,763.1	44.65	Jingxi	1,628.1	49.62	Rong'an	1,906.7	48.21
Meixian	1,448.1	40.51	Laibin	1,346.4	42.74	Guilin	1,888.9	46.53
Guangning	1,712.1	47.49	Guiping	1,727.4	46.78	Fengshan	1,522.1	44.33
Gaoyao	1,654.4	43.15	Wuzhou	1,471.8	42.6	Hechi	1,489.6	44.36
Guangzhou	1,740.6	40.78	Longzhou	1,287.4	41.96	Du'an	1,733	45
Dongyuan	1,951.9	42.12	Nanning	1,306.7	42.67	Liuzhou	1,450.5	42.18
Zengcheng	1,947.6	41.19	Lingshan	1,628.3	43.36	Dongfang	790.8	23.63
Huiyang	1,749.7	39.6	Yulin	1,599.7	44.25	Qiongzong	2,054.5	53.62
Wuhua	1,450.4	40.51	Weining	898.2	52.83	Qionghai	1,749.5	45.9
Shantou	1,398.4	36.53	Panxian	1,382.8	52.9	Sanya	1,167	30.33
Huizhou	1,489.2	34.22	Anshun	1,235.4	42.33	Linshui	1,412.9	36.64
Xinyi	1,781.1	42.55	Xingyi	1,338.9	52.49	Xunwu	1,629.3	43.89
Luoding	1,369.3	41.77	Wangmo	1,235.4	42.33	Zhanyi	990.7	38.08
Taishan	1,971.4	40.53	Luodian	1,143.7	40.74	Luxi	921.2	39.4
Shenzhen	1,928.3	38.73	Dushan	1,326.8	51.34	Mengzi	851.4	36.27
Shanwei	1,588.8	34.59	Rongjiang	1,198.6	43.92	Guangnan	995.7	43.1
Zhanjiang	1,409.1	38.78	Haikou	1,455.2	42.94			

ties of extent i . For $n > 10$, the standard normal test statistic Z_S is computed as follows:

$$Z_{MK} = \begin{cases} \frac{S-1}{[\text{Var}(S)]^{1/2}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{[\text{Var}(S)]^{1/2}} & S < 0 \end{cases} \quad (4)$$

If $|Z_{MK}| \geq Z_{1-\alpha/2}$, the null hypothesis is rejected, and a significant trend exists in the data series. $Z_{1-\alpha/2}$ is obtained from the standard normal distribution table. A positive value of Z_{MK} indicates an upward trend, while a negative value indicates a downward trend. In general, the statistical significance of precipitation variation is usually lower than other climate elements due to its large spatial and temporal distribution (Ewa et al. 2011). Therefore, a lower significance level is used to distinguish precipitation change. In this study, the significance levels used are 0.05, 0.1, and 0.2, with corresponding confidence levels (expressed in p) of 95, 90, and 80 %, respectively. The trends in this study are classified as follows: no trend for $p < 80$ %, poor trend for $80 \% \leq p < 90$ %, stable trend for $90 \% \leq p < 95$ %, and significant trend for $p \geq 95$ %.

In this study, the incremental weight method was selected to calculate the contribution of each seasonal precipitation or each precipitation intensity class to the change in precipitation

in the year. The incremental weight method, developed by the U.S. National Weather Service in 1972, is classified as a deterministic method (Jeroen et al. 2012). The general idea of this method is based on the assumption that the attribute value of an unsampled point is the weighted average of known values within the neighborhood (Chen and Liu 2012). In this study, the weight of each seasonal precipitation or precipitation intensity class is calculated as follows:

$$\Delta p_{At} = p_{A(t+1)} - p_{At}; \Delta p_{it} = p_{i(t+1)} - p_{it} \quad (t = 1, 2, \dots, N-1; i = 1, 2, \dots, M) \quad (5)$$

$$\lambda_{it} = (\Delta p_{it} - \Delta p_{At})^{-Q} / \sum_{i=1}^M (\Delta p_{it} - \Delta p_{At})^{-Q} \quad (6)$$

$$\lambda_i = \sum_{t=1}^{(N-1)} \lambda_{it} / (N-1) \quad (7)$$

Here, t is the t -th year, and N is the total number of years. p_{At} is the annual precipitation in the t -th year, and p_{it} is i -th seasonal precipitation index or i -th precipitation intensity class index in the t -th year. M is the number of seasonal precipitations or precipitation intensity classes ($M = 4$). Δp_{At} is the

difference in annual precipitation between the t -th and the $(t-1)$ -th year. Correspondingly, Δp_{it} is the difference in i -th index between the t -th and the $(t-1)$ -th year. λ_{it} represents the contribution rate of the i -th index in the t -th year, λ_i is the average contribution rate for the i -th index, and Q is the power exponent ($Q = 2$ in this study).

4 Results and discussions

Table 2 lists 24 indices for precipitation, intensity, and number of rainy days in the year and four intensity classes and four seasons (spring, March to May; summer, June to August; fall, September to November; and winter, December of the current year to February of the following year) (Bradley et al. 1987). Based on daily precipitation, four intensity classes are classified according to the official standard in China (Sun 2000), i.e., 0–10 mm/day, drizzle; 10–25 mm/day, moderate rain; 25–50 mm/day, heavy rain; and greater than 50 mm/day, extremely heavy rain.

4.1 Precipitation, rainy days, and intensity change trends

4.1.1 Precipitation change trends

Annual total precipitation Figure 2 shows the change trend analysis of annual total precipitation (ATP) in the Pearl River Basin. Thirty-one stations show increasing ATP, and 21 stations show decreasing ATP. Among these stations, five stations with significantly increasing ATP are located in the western part of the basin, and five stations with significantly decreasing ATP are distributed in the central and western parts of the basin. These ten stations account for only 8.1 % of the total number of stations. Thus, the average annual precipitation of the whole basin does not show obvious variation. A similar result was detected by Zhang et al. (2012) in which annual precipitation decreased significantly in only 9.5 % of the stations in the Pearl River Basin, and only 4.8 % of the stations

indicated an obvious increase. However, current studies suggest that different change trends in annual precipitation occurred in different parts of China. For example, Zhai et al. (2005) found that annual precipitation in southern northeast China, north China, and over the Sichuan Basin has decreased significantly, and annual precipitation in western China, the Yangtze River valley, and the southeastern coast has increased significantly. Zhang et al. (2013a) revealed that annual precipitation in northeast China decreased significantly, particularly after 1970. Similar downward trends also occurred over the middle and lower Yellow River and the Huaihe River. However, in the middle and lower Yangtze River and in the southeast rivers, annual precipitation has been increasing, and a significant increase in precipitation was evident in northwest China after 1970.

Seasonal precipitation Figure 2b–e shows obvious distinctions in the change trends of seasonal precipitations over the Pearl River Basin. Fourteen stations show a significant increase in spring precipitation (SPP), and only four stations show significantly decreasing SPP. In this sense, SPP has increased over the basin as a whole. Among the 14 stations with significantly increasing SPP, 13 are located in the northeast windward slopes of the Yunwu and Yunkai mountain ridges and are influenced by the southerly airflow from the sea. Summer precipitation (SUP) has increased in 31 stations and decreased in 29 stations located in the basin. Among these stations, eight stations with significantly increasing SUP are located in the west, and 16 stations with significantly decreasing SUP are distributed at the center of the basin, accounting for 12.9 and 25.8 % of the total number of stations, respectively. Forty-nine stations are characterized by decreasing fall precipitation (FAP), accounting for more than 79 % of the stations, which indicates that FAP has decreased significantly over almost the entire basin. However, stations with significantly decreasing FAP are primarily located in the upstream area of the basin, which is not influenced by moist air from the South Sea. Decreasing FAP has triggered several fall droughts in this

Table 2 Definitions of precipitation indices

Precipitation indices	Definitions	Units
ATP	Annual total precipitation	mm
ATD	Total rainy days in a year	day
API	Annual precipitation intensity	mm/day
SPP, SUP, FAP, WIP	Amount of precipitation for the spring, summer, fall, and winter seasons	mm
SPD, SUD, FADFAD, WID	Total rainy days for the spring, summer, fall, and winter seasons	day
SPI, SUI, FAIFAI, WII	Rainfall intensity for the spring, summer, fall, and winter seasons	mm/day
DRP, MRP, HEP, EHP	Amount of precipitation for drizzle, moderate rain, heavy rain, and extremely heavy rain	mm
DRD, MRD, HED, EHD	Total rainy days for drizzle, moderate rain, heavy rain, and extremely heavy rain	day

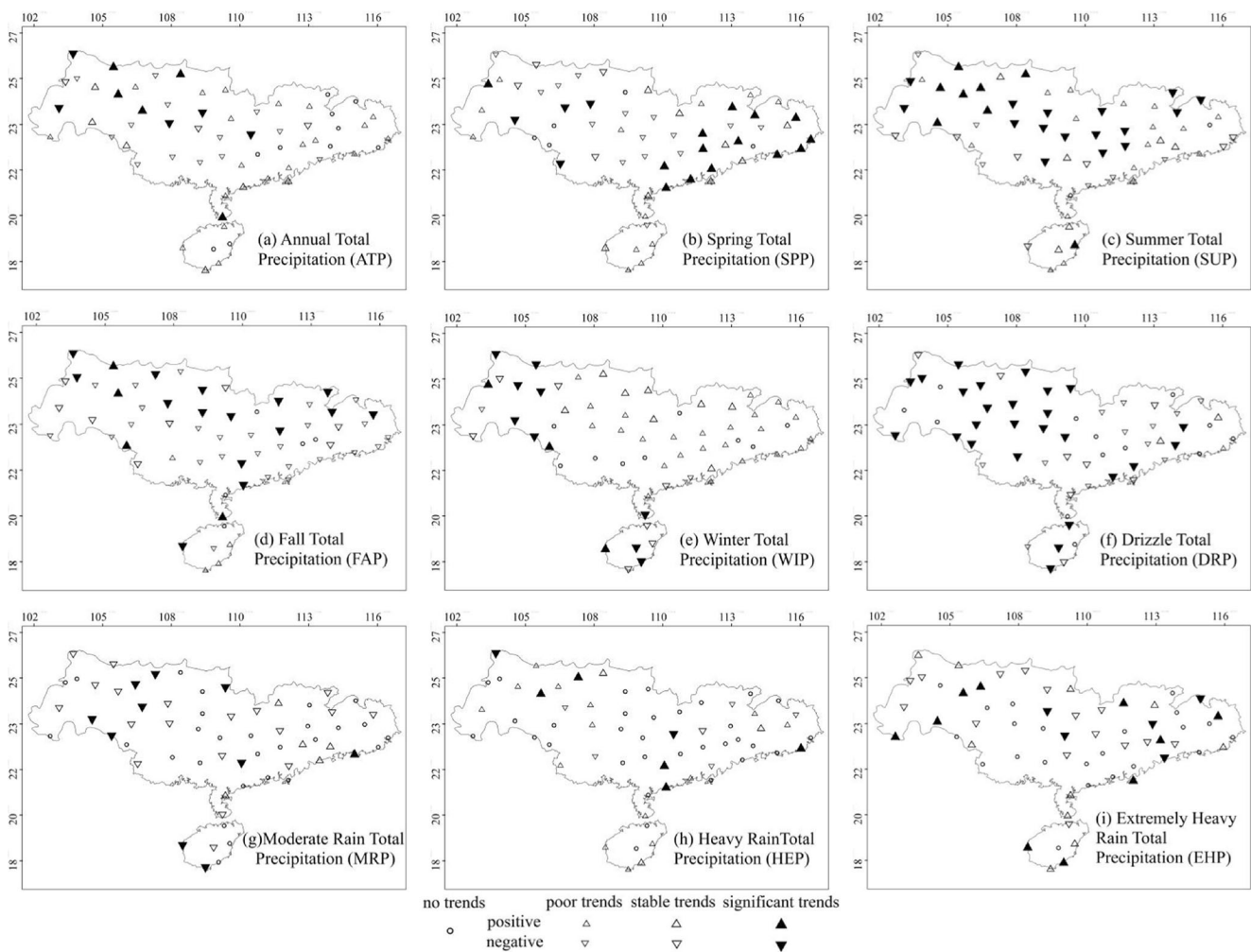


Fig. 2 a–i The change of precipitation amount in the study area

region, such as those in 2003, 2004, 2005, 2007, 2009, and 2010. Winter precipitation (WIP) has increased at 35 stations and decreased at 18 stations, which indicates that WIP has increased over the basin as a whole. In summary, spring and winter precipitation has increased gradually, while summer and fall precipitation has decreased slightly. This finding is

consistent with the results reported by Chen et al. (2011). In his study, the change trends of seasonal precipitation in the East River tributary basin were analyzed. However, seasonal precipitation in other parts of China has shown different change trends than that of the Pearl River Basin. For example, Zhai et al. (2005) revealed that southern northeast China has

Table 3 Statistics of trends in precipitation amount

Precipitation indices	Stations with positive trend	Stations with negative trend	Stations with no trend	Stations with significant positive trend	Stations with significant negative trend	Stations with significant trend
Annual	31	21	10	5	5	10
Spring	34	23	5	14	4	18
Summer	31	29	2	8	16	24
Fall	8	49	5	4	15	19
Winter	35	18	9	3	9	12
Drizzle	3	46	13	0	26	26
Moderate rain	6	28	28	1	9	10
Heavy rain	22	8	32	5	2	7
Extremely heavy rain	20	20	22	10	5	15

shown an increasing trend in spring precipitation but a decreasing trend in summer precipitation. In contrast, Zhai et al. (2005) reported that eastern China is characterized by decreasing spring precipitation and increasing summer precipitation. In addition, in western China, precipitation, particularly in the Sichuan Basin, decreases in the summer, and, in south China, precipitation increases in both summer and winter.

Precipitation intensity class Change trends of drizzle (DRP), moderate rain (MRP), heavy rain (HEP), and extremely heavy rain (EHP) are shown in Fig. 2f-i, respectively, and listed in Table 3. It can be seen that DRP and MRP have decreased in 46 and 28 stations, respectively; however, DRP and MRP increased in only three and six stations, respectively. This indicates that light rains, i.e., drizzle and moderate rain, have decreased significantly. However, heavy rains, i.e., HEP and EHP, have increased in 22 and 20 stations, respectively. The intensification of extreme precipitation was thought to be the cause of several terrible floods in the Pearl River Basin in the

recent years, such as the floods that occurred in 1994, 1998, 2005, 2008, and 2009.

4.1.2 Rainy day change trends

Number of rainy days annually The change trend of annual rainy days (ATD) is shown in Fig. 3a, which shows 61 stations characterized by decreasing ATD, accounting for more than 98.3 % of the stations. This indicates that ATD has decreased significantly over the whole basin. This is particularly evident in the western, eastern, southern, and central part of the basin where 48 stations (77.4 % of the stations) are characterized by significantly decreasing ATD. The decrease in ATD has triggered frequent periods of drought over the entire basin (Fischer et al. 2011), such as the severe droughts that occurred in 2003, 2004, 2005, 2007, 2009, and 2010 (http://www.pearlwater.gov.cn/wndt/t20091029_32879.htm). However, the number of rainy days in other parts of China showed different change trends. Ye et al. (2005) revealed that the

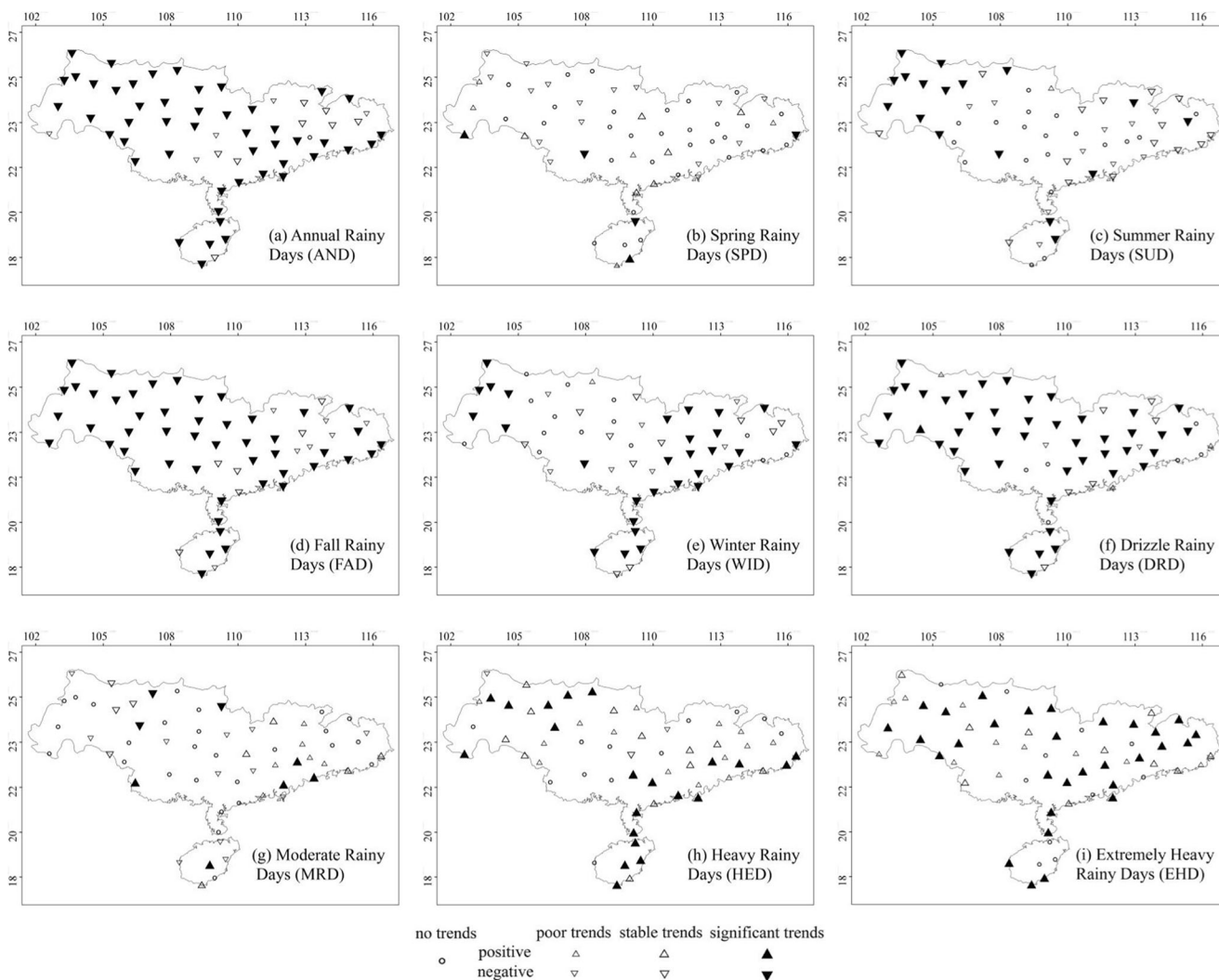


Fig. 3 a-i The change of rainy days in the study area

Table 4 Statistics of trends in total rainy days

Precipitation indices	Stations with positive trend	Stations with negative trend	Stations with no trend	Stations with significant positive trend	Stations with significant negative trend
Annual	0	61	1	0	48
Spring	13	19	30	2	3
Summer	1	42	19	0	17
Autumn	0	62	0	0	49
Winter	1	47	14	0	29
Drizzle	4	52	6	1	44
Moderate rain	16	19	27	5	3
Heavy rain	47	3	12	21	0
Extremely heavy rain	51	0	11	30	0

number of rainy days decreased significantly in east China but increased in west China. Zhai et al. (2005) found that the number of rainy days has decreased significantly throughout most parts of China, with northwest China being an exception. Except for several sites in the southern middle section of the Yangtze River, Fu et al. (2008) observed a decreasing trend in the number of rainy days for the whole of China.

Number of rainy days seasonally The analysis of the change trends of rainy days in spring (SPD), summer (SUD), fall (FAD), and winter (WID) is shown in Fig. 3b–e, respectively, and listed in Table 4. It can be seen that 19, 42, 62, and 47 stations (30.6, 67.7, 100, and 75.8 % of stations, respectively) are characterized

by increasing SPD, SUD, FAD, and WID, which indicates that the number of rainy days in each season has decreased to different degrees over the basin. In particular, FAD and WID have decreased significantly in 49 and 29 stations, respectively (79.0 and 46.8 % of stations, respectively). The decrease in precipitation and the number of rainy days in the fall has been blamed as the cause of several severe droughts in the region. For example, the drought that occurred from late 2009 to the spring of 2010 seriously affected more than 80 % of the vegetation ecosystem in Yunnan Province and the Guangxi Autonomous Region. More than 60 million residents suffered drinking water shortages, and more than one million hectares of crops died as a result of drought (Zhang et al. 2013b).

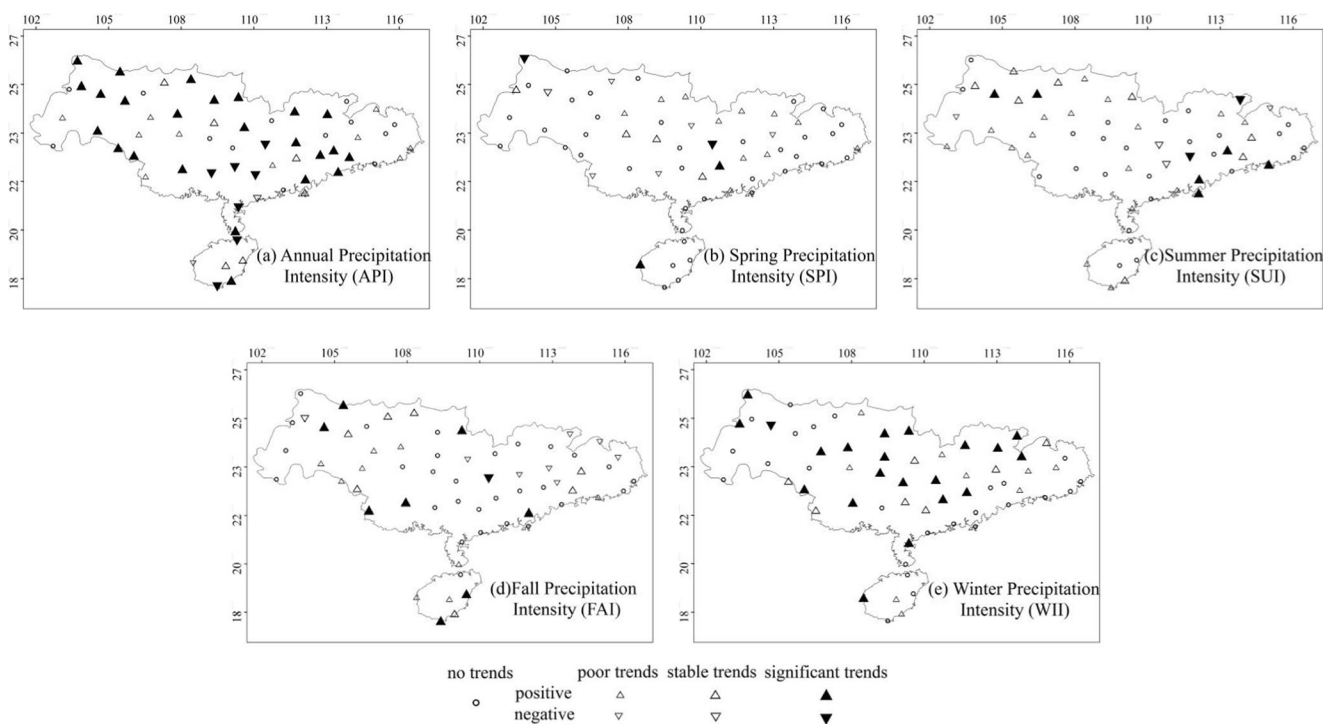


Fig. 4 a–d The change of precipitation intensity in the study area

Table 5 Statistics of trends in total precipitation intensity

Precipitation indices	Stations with positive trend	Stations with negative trend	Stations with no trend	Stations with significant positive trend	Stations with significant negative trend
Annual	40	9	13	24	7
Spring	17	8	37	2	2
Summer	31	6	25	6	2
Fall	24	9	29	8	1
Winter	36	1	25	20	1

Number of rainy days in precipitation intensity classes Change trends of drizzle (DRD), moderate rain (MRD), heavy rain (HED), and extremely heavy rain (EHD) are shown in Fig. 3f–i, respectively, and listed in Table 4. It can be seen that DRD has decreased in 52 stations, accounting for nearly 83.9 % of the stations. Although the number of rainy days in the year and the number of days in drizzle has declined in the basin, the number of days with heavy rain, i.e., HED and EHD, has increased at 47 and 51 stations (75.8 and 82.3 % of the stations, respectively). After 1990, increasing HED and EHD has resulted in frequent heavy floods, such as those in 1994, 1998, 2005, 2008, and 2009.

4.1.3 Precipitation intensity change trends

Five precipitation intensity indices, including annual precipitation intensity (API) and four seasonal precipitation intensities (SPI, SUI, FAI, and WII), were selected to analyze the precipitation intensity change trends (shown in Fig. 4 and Table 5). The precipitation intensity for a station in a year or a season is the total precipitation divided by the number of rainy days in the year or the season.

Based on the significant decrease in the number of annual and seasonal rainy days, precipitation intensity has increased both annually and seasonally. As

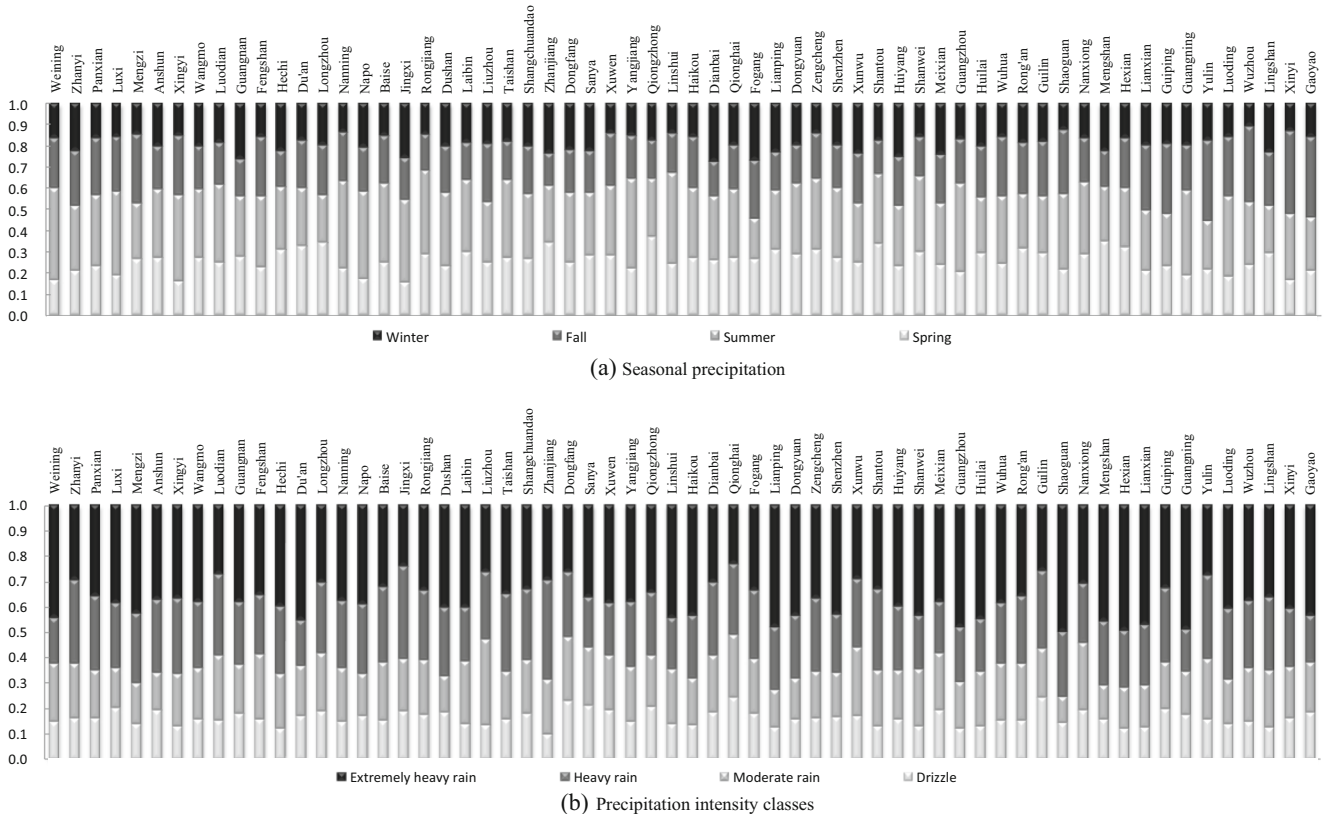


Fig. 5 a, b The contribution rates of precipitation amount indices in the study area

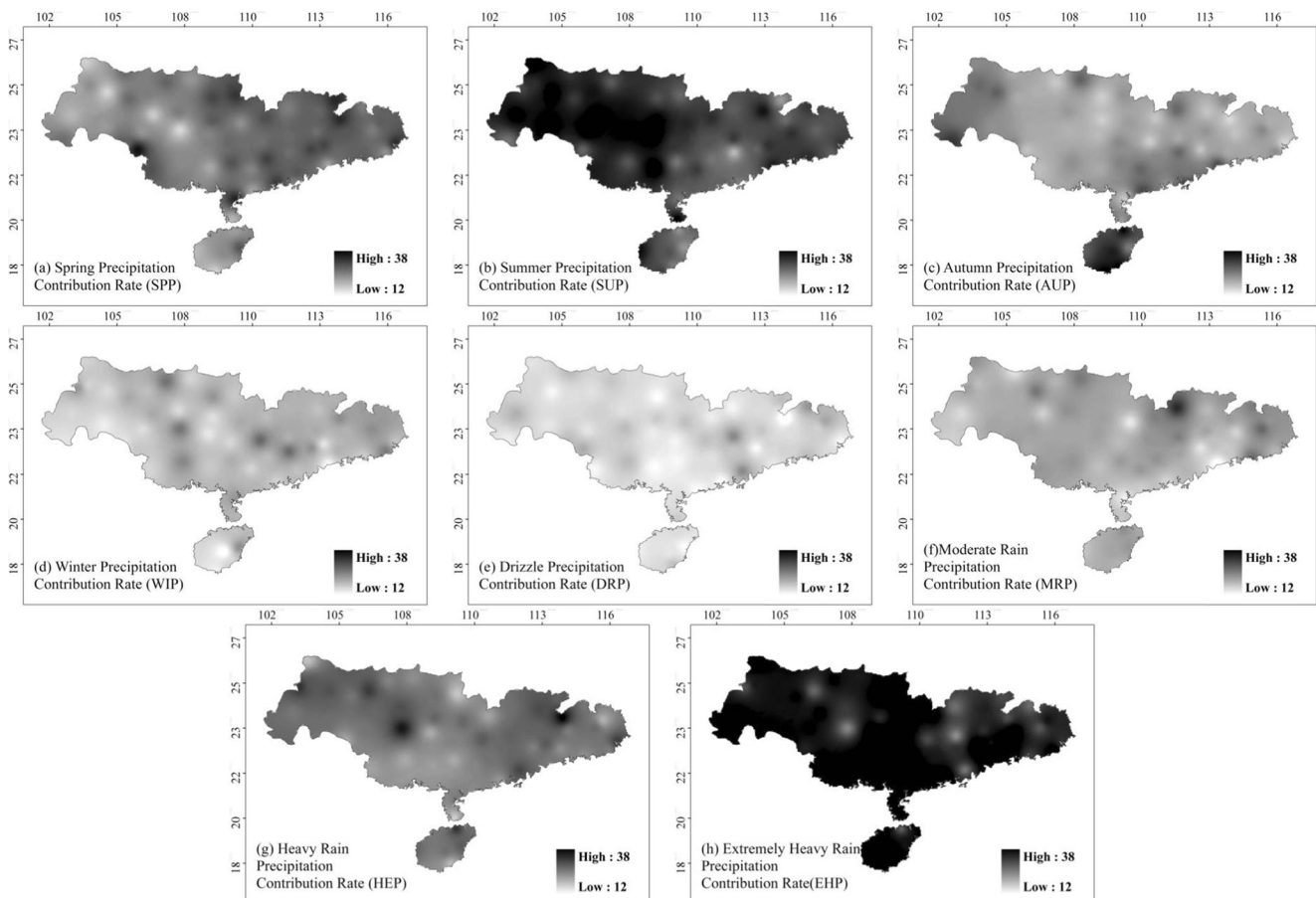
Table 6 Statistics of contribution in precipitation indices

Precipitation indices	Spring (%)	Summer (%)	Fall (%)	Winter (%)	Drizzle (%)	Moderate rain (%)	Heavy rain (%)	Extremely heavy rain (%)
Precipitation amount	25.8	32.0	23.4	18.8	15.9	20.5	26.0	37.6
The number of rainy days	22.8	24.7	26.8	25.7	47.6	20.3	16.8	15.3

expected, 40 stations primarily located in the western and the eastern parts of the basin are characterized by increasing API. Among these stations, the API of 24 stations (38.7 % of the stations) has increased significantly. The increasing API can be partially explained by the weakening East Asian summer monsoon (Fischer et al. 2011). The four seasonal precipitation intensities, i.e., SPI, SUI, FAI, and WII, have increased in 17, 31, 24, and 36 stations, respectively, and decreased in only eight, six, nine, and one stations, respectively. It is obvious that the four seasonal precipitation intensities have increased to different degrees. The decrease in the number of rainy days and the increase of precipitation

intensity combine to imply an increasing risk of drought and flood events over the basin (Zhang et al. 2012).

In summary, the number of rainy days with heavy rains and the annual precipitation intensity has increased to different degrees, while the number of rainy days annually and seasonally has decreased significantly over the basin. These factors contribute to more frequent heavy floods and extreme droughts, which inevitably has a negative impact on the utilization and supply of water resources in this basin. In particular, it is expected that the freshwater supply of the PRD, the downstream region of the basin, will be at greater risk because this region also suffers serious saltwater intrusion during dry seasons (Zhang et al. 2013c).

**Fig. 6** a–h The distribution of contribution rates of precipitation amount indices in the study area

4.2 Contributions of seasonal precipitation or different intensity classes to annual precipitation

4.2.1 Contribution analysis for total annual precipitation

Contributions of seasonal precipitation to total annual precipitation The contribution rates of seasonal precipitation to the change in total annual precipitation are shown in Fig. 5a and listed in Table 6. It is evident from Table 6 that for ATP, SPP, SUP, FAP, and WIP have average contribution rates of 25.8, 32.0, 23.4, and 18.8 %, respectively. For changes in ATP, SUP has the highest contribution rate, followed by SPP and FAP; WIP has the lowest contribution rate. As shown in Fig. 2, SPP, SUP, FAP, and WIP demonstrate the same change trends as ATP at 33, 40, 25, and 22 stations, respectively, i.e., SUP has the same change trend as ATP at the largest number of stations (40). Therefore, SUP makes the largest contribution to the changes in ATP. On the other hand, the more precipitation the season has, the higher contribution to the change of ATP. For instant, average precipitation in spring, summer, fall, and winter accounts for 28.1, 46.1, 18.3, and 7.5 % of ATP, respectively. SUP accounts for the highest proportion of ATP (46.1 %); therefore, its contribution rate to the change in ATP is also the highest (32.0 %); WIP, which accounts for the

lowest proportion of ATP (7.5 %), has the lowest contribution rate (18.8 %).

Figure 6a–d shows the contribution rates for seasonal precipitation. The contribution rate of one seasonal precipitation to the change in ATP is determined by its change significance level and its change trend. That is, if the change trends of one seasonal precipitation are different from those of ATP at most stations, irrespective of its change significance level, this seasonal precipitation has a low contribution rate to the change in ATP. To illustrate, SUP and ATP both decreased significantly in the central part of the Pearl River Basin. Correspondingly, the contribution of SUP in this region is high. However, although FAP increased significantly in the northern part of the basin, its contribution rate is low because FAP exhibits an opposite change trend to that of ATP in this region.

Contribution of different precipitation intensity classes to annual total precipitation The analyses of the contribution rates of four precipitation intensity classes to the change in ATP are presented in Fig. 5b and Table 6, which show that the average contribution rates of DRP, MRP, HEP, and EHP are 15.9, 20.5, 26.0, and 37.6 %, respectively. EHP has the highest contribution rate to the change in ATP; HEP and MRP have lower contribution rates, and DRP has the lowest rate. Similar to

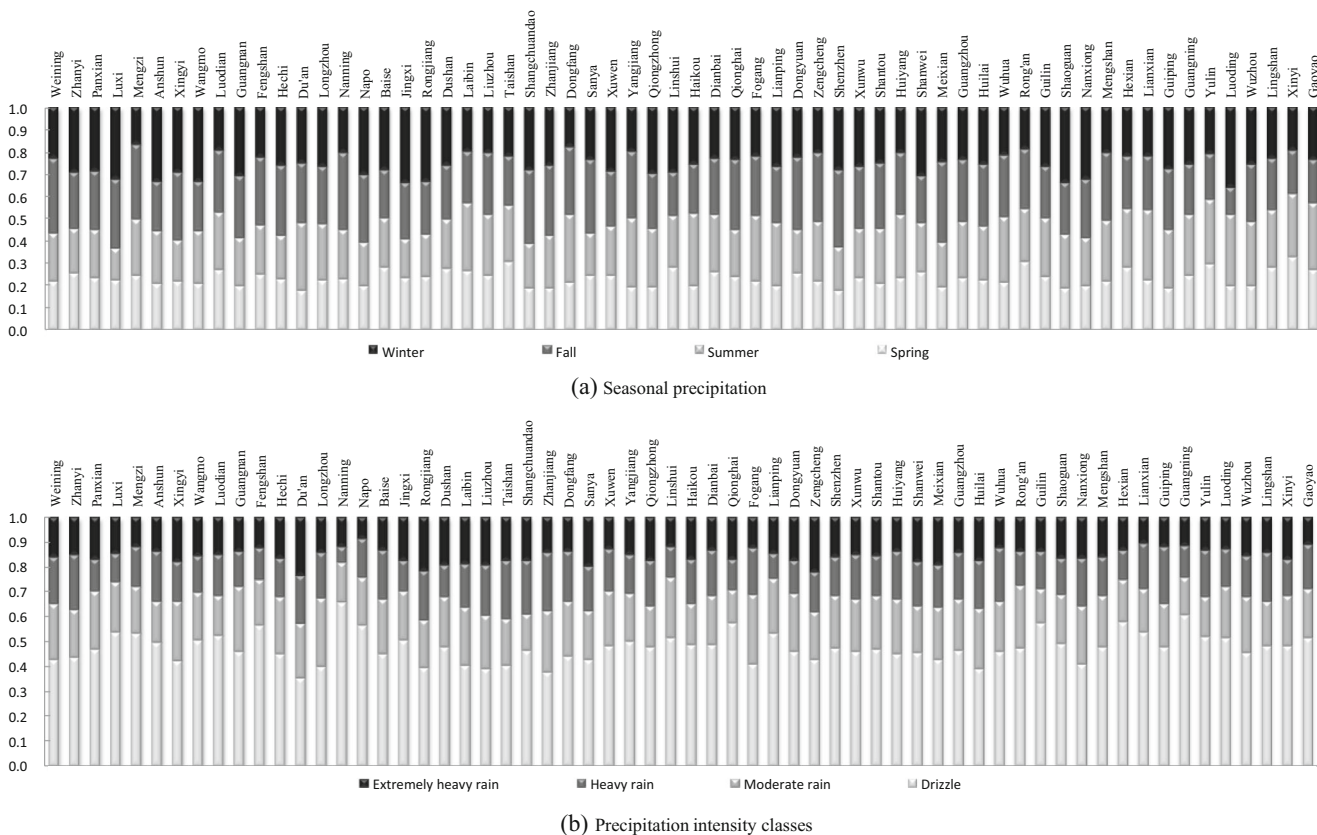


Fig. 7 a, b The contribution rates of rainy day indices in the study area

the contribution of seasonal precipitation, the contribution rate of one precipitation intensity class to the change in ATP is also determined by its change significance level and its change trend. It can be seen from the spatial distributions of contributions for four intensity classes (Fig. 6e–h) that DRP decreased significantly at the center of this basin; however, its contribution rate remains small because DRP has an opposite change trend to that of ATP in this region.

4.2.2 Contribution analysis for the number of rainy days

Contribution of rainy days in four seasons to rainy days in the year The contribution rates of rainy days in four seasons to the change of ATD are displayed in Fig. 7a, which shows that the average contribution rates of SPD, SUD, FAD, and WID are 22.8, 24.7, 26.8, and 25.7 %, respectively. FAD and WID make high contributions to the change in ATD, and SPD makes the least. It can be seen from the change trends of ATD (Fig. 3a) and the change trends of rainy days in four seasons (Fig. 3b–e) that seasonally, the greater the number of stations with same change trends as ATD, the higher contribution to the change in ATP. To illustrate, ATD has decreased in more than 98 % of the stations. Correspondingly,

decreasing SPD, SUD, FAD, and WID were also detected at 19, 42, 62, and 47 stations, respectively. Compared with SPD and SUD, FAD and WID have more stations with the same decreasing trend as that of ATD; thus, the contribution rates of FAD and WID are higher than those of SPD and SUD (Fig. 8a–d). Due to the significant decrease in FAD and WID and their higher contribution rates to the change in ATD, since 2002, severe droughts in fall and winter have occurred continually over the basin, such as those in 2003, 2004, 2005, 2007, 2009, and 2010.

Contribution of rainy days in different intensity classes to annual rainy days The contribution rates of rainy days in each precipitation intensity class to the change in ATD are shown in Fig. 7b, which shows that the average contribution rates of DRD, MRD, HED, and EHD are 47.6, 20.3, 16.8, and 15.3 %, respectively. DRD provides the highest contribution rate to the change in ATD, followed by MRD, HED, and EHD in that order. It is also evident from the change trends of ATD (Fig. 3a) and the change trends of rainy days in different intensity classes (Fig. 3f–i) that the more stations with the same change trends as ATD that one intensity class has, the higher is the contribution to the change in ATP. ATD and DRD both

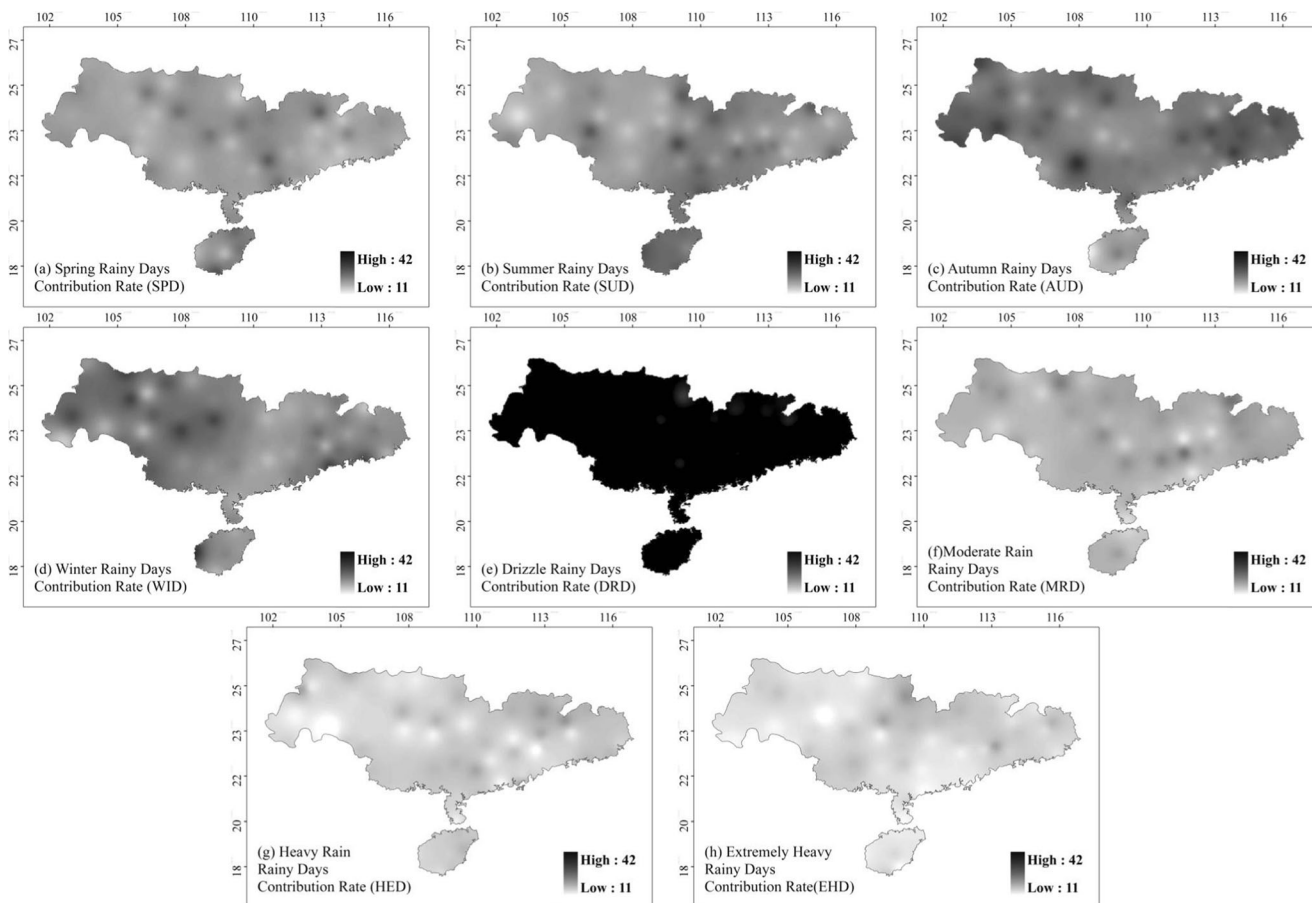


Fig. 8 a–h The distribution of contribution rates of rainy day indices in the study area

decreased in nearly all stations, while HED and EHD have an opposite increasing change trend as compared to ATD at 75.8 and 82.3 % of the total number of stations, respectively. Thus, the contribution rate of DRD to the change in ATD is clearly higher than that of HED and EHD (Fig. 8g, h).

5 Conclusions

The spatiotemporal variations of precipitation obviously affect hydrological processes and water resource management in the Pearl River Basin (Yang et al. 2010). Analyses of the long-term characteristics of precipitation structure, the change trends of 24 indices, including precipitation intensity and rainy days in the year, in four seasons and in four precipitation intensity classes were performed using the MK test. Furthermore, the contribution rates of each seasonal precipitation or each precipitation intensity class to the annual precipitation were calculated by the incremental weight method. The main conclusions of this study are as follows:

1. The annual total precipitation does not show an obvious change over the entire basin. Only 8.1 % of all the stations were characterized by both significantly increasing and decreasing trends. In addition, the seasonal precipitation also showed no clear change trend. Summer and fall precipitation decreased in 25.8 and 24.2 % of stations, respectively, and spring precipitation only increased in 19.4 % of the stations. However, the numbers of rainy days in the year and in each season decreased significantly over the basin. In particular, the number of rainy days in the year decreased in 98.3 % of stations, which results in an increase in the annual average precipitation intensity at 64.5 % of the stations.
2. The numbers of rainy days in four precipitation intensity classes show different change trends. The number of rainy days in drizzle decreased at 83.9 % of the total number of stations, while the number of rainy days in heavy rain and extremely heavy rain increased respectively at nearly 75.8 and 82.3 % of the stations. These factors combine to cause frequent extreme weather events, such as severe floods, droughts, and rainstorms, which have occurred continually over the last decade (Fischer et al. 2011).
3. Compared with the precipitation in the other three seasons, summer precipitation contributes more to the change in annual total precipitation. The number of rainy days in fall and in winter makes a higher contribution to the change in annual rainy days than that of the other two seasons. The significant decrease and higher contribution rates of rainy days in fall and winter were considered the cause of severe droughts in the fall and winter after 2000,

such as the severe drought in the dry season of 2009–2010 that spread throughout southwest China.

4. Compared with drizzle, heavy rain and extremely heavy rain contribute more to the change in the total annual precipitation; however, they make a smaller contribution to the change in the number of annual rainy days. The increase in precipitation and heavy and extremely heavy rainy days and the decrease in the number of annual rainy days and days when drizzle occurs have triggered frequent extreme weather events in the Pearl River Basin, such as the heavy floods in 1994, 1998, 2005, 2008, and 2009 and the extreme droughts in 2003, 2004, 2005, 2007, 2009, and 2010.

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