Variations in the precipitation extremes over the Guangdong-Hong Kong-Macao Greater Bay Area in China

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Abstract
By using the gridded 0.25° × 0.25° observation dataset of CN05.1 provided by the China Meteorological Administration, this study investigates the variations in nine extreme precipitation indices over the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) in China from 1961 to 2018. Based on trends and interannual variations, the nine kinds of extreme precipitation are classified into four categories: category 1 includes very wet days (R95P), extremely wet days (R99P), the maximum 1-day precipitation amount (RX1day), and the maximum 5-day precipitation amount (RX5day). Category 2 is the number of heavy precipitation days (R10day), the number of very heavy precipitation days (R20day), and the simple daily intensity index (SDII). Categories 3 and 4 are consecutive wet days (CWDday) and consecutive dry days (CDDday), respectively. For the extreme precipitation in category 1, the abrupt change point from fewer to more values occurs in 1991 in summer. Three abrupt change points, from fewer to more in 1972 and 2009 and from more to fewer in 1994, occur in spring. For the extreme precipitation in category 2, the abrupt change point from fewer to more values occurs in 1993 in summer. Three abrupt change points, from fewer to more in 1965 and 2010 and from more to fewer in 1990, occur in spring. Annually and seasonally, abrupt changes occur in the early 2010s for CWDday which clearly increase and for CDDday which clearly decrease. In addition, CWDday exhibit abrupt change points from fewer to more in 1966 and from more to fewer in 1983 in spring. The variations in these extreme precipitation events have significant periodic oscillations of 3–5 years, quasi-8 years, or 8–14 years. During periods 1961–1994, 1995–2009, and 2010–2018, the changes in the annual and most seasonal R95P, R99P, R10day, R20day, and SDII are consistent with those of precipitation. The values in the latter period are increasing compared with those in the former stage. The changes in RX1day, RX5day, CWDday, and CDDday have their own characteristics.

1 Introduction
It is certain that global mean surface temperature has increased since the late nineteenth century and the first decade of the twenty-first century has been the warmest (Stocker et al. 2013). Previous assessments have shown that precipitation extremes appeared to have increased in more regions than they have decreased (Alexander 2016). Temperature extremes showed that consistent warming trends globally and in most land areas over the past century. In addition, precipitation extremes showed global tendencies towards more intense rainfall throughout much of the twentieth century (Donat et al. 2016). Precipitation extremes showed increasing trends in large parts of Eurasia, North Australia, and the midwestern USA during the 1964–2013 period (Papalexiou and Montanari 2019). Zhang and Zhou (2019) found significant increases in the annual maximum daily precipitation and associations with global warming in regional monsoon domains, which included the southern part of the South African monsoon region, the South Asian monsoon region, the North American monsoon region, and the eastern part of the South American monsoon region during 1901–2010. In China, rainstorms or extreme precipitation events have insignificantly increased as a whole over the past 50 years (Ren et al. 2010; Song et al. 2015). However, extreme precipitation and wet days exhibited increasing trends, and the maximum number of consecutive dry days showed a tendency towards shorter durations in over the arid region of northwestern China (Wang et al. 2017). The number of extreme precipitation days in northwestern China has...
obviously increased (Li et al. 2020). The frequency and amount of extreme precipitation increased in South China, Southeast Asia, and North China but had a decreasing trend in the Yangtze River basin (Sun and Zhang 2017; Cui et al. 2019; Wang et al. 2020). There were three periods with highly frequent precipitation extremes since 1960: early 1960s, middle and late 1990s, and early twenty-first century (Sun and Zhang 2017). The frequency of extreme precipitation events has been decreasing during the past 48 years in the upper Yellow River basin (Ma and Gao 2019). The regionally average daily rainfall intensity exhibited significant decreases, whereas consecutive dry days significantly increased, but the changes in days of erosive rainfall, heavy rain, rainstorms, maximum 5-day precipitation, and very-wet-day and extremely wet-day precipitation were not significant during 1960–2013 on the Loess Plateau in China (Sun et al. 2016). Southwestern China has generally become drier and experienced enhanced precipitation extremes in the past 60 years (Liu et al. 2014, 2015). Wang et al. (2017) analyzed twelve indices of extreme precipitation over Northeast China and found that consecutive dry days decreased significantly while the other precipitation indices did not have significant decreasing trends. Light rain events displayed a decreasing trend in summer and winter half years over East China and an increasing trend in winter half years over Northwest China (Huang and Wen 2013). The spatial distribution of summer extreme precipitation events demonstrated remarkable regional differences, and an increasing trend was found in the middle and lower reaches of the Yangtze River, South China, and Northwest China, while a decreasing trend occurred in Northeast China, North China, and part of Southwest China (Long et al. 2016). However, Zeng and Lu (2015) concluded that the rainfall of summer extreme precipitation was increased over South China and decreased over North China. Lu et al. (2020) concluded that the increasing trends of extreme precipitation amounts and days were mainly located in the southeastern coast and western China.

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is a city cluster that consists of the Hong Kong and Macao special administrative regions and the cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Zhongshan, Dongguan, Huizhou, Jiangmen, and Zhaoqing in the Pearl River Delta region in South China. It is the 4th largest bay area in the world after the New York Bay Area, San Francisco Bay Area, and Tokyo Bay Area. Its population reached 69.57 million in 2017, and it is crucial to enhancing China’s social and economic progress in the near future. The status and trend of extreme climates are of great significance to the formulation of disaster prevention and mitigation and sustainable development policies in the GBA.

In South China, there was spatial disparity in the trend magnitudes of extreme precipitation indices, and approximately 60.85%, 75.32%, and 75.74% of the grid boxes showed increasing trends for the maximum 5-day precipitation (RX5day), simple daily intensity index (SDII), and very wet day precipitation (R95), respectively (Ren et al. 2015). A consistent anomaly distribution was the main type of extremely heavy precipitation, and extremely heavy precipitation events were less frequent in the 1960s and 1980s, while an increasing trend from the late 1980s existed in South China (Lu et al. 2012). The wet day precipitation, consecutive wet days, and numbers of heavy precipitation days exhibited nonsignificant decreasing trends. The consecutive dry days and simple daily intensity index have significantly increased, while other extreme precipitation indexes had non-significant increasing trends in the Pearl River Basin in South China (Zhao et al. 2014). Summer extreme precipitation underwent significant increase in South China after 1992/1993 and played important roles in the corresponding summer total precipitation variations (Li et al. 2016). Extreme heavy precipitation increased significantly during the pre-flood season since the 1990s, and drought and flood disasters increased since 1993 during the postflood season in South China (Li et al. 2010, 2012). Extreme precipitation indices had significant interannual periodic variations of 3–5 years and 6–8 years in the pre-flood season and the postflood season, respectively, and increased slightly (Cai et al. 2018).

In summary, variations in extreme precipitation are different with seasons and regions. There are similarities and differences between different types of extreme precipitation. Some conclusions are still vague and contradictory, and the study of extreme precipitation in China needs to be further improved. At present, scholars pay more attention to the changes in extreme temperature events and typhoons on the coast of South China, but the analysis of the variations in extreme precipitation events on the coast of South China is not sufficient. This paper will compare and analyze variations in precipitation extremes over the GBA in China and reveal the characteristics of extreme precipitation under global warming. Additionally, this study provides a scientific basis for relevant departments to address climate change.

2 Data and methods

The gridded 0.25° × 0.25° observation dataset of CN05.1 provided by the China Meteorological Administration was used in this study. It includes daily temperatures and precipitation during the period 1961–2018. This homogenized high-resolution dataset was based on interpolation from 2416 station observations with quality control measures applied, such as deleting outliers that were far different from the actual climate state and surrounding meteorological conditions.
stations (Wu and Gao 2013). The dataset has been widely used to quantify precipitation extremes (Wang et al. 2017).

The CN05.1 dataset was constructed from observations at 2400 stations across China and interpolated by the “anomaly approach,” i.e., a gridded climatology was first calculated, and then a gridded daily anomaly was added to the climatology to produce the final dataset (Wu and Gao 2013; Wang et al. 2017).

In this paper, a rectangular area (21.5°N–24.5°N, 111.5°E–115.5°E) was used as the GBA (see in Fig. 1 the red box area), which included the main body of GBA and its surrounding areas. Figure 1 shows the spatial distribution of the trends for annual mean air temperature and annual total precipitation during 1961–2018 in China. The warming trend in China passes the significance test of confidence level \( \alpha = 0.05 \), and the most significant warming is in the western and northern regions of China. Compared with the warming trend in China, the GBA is a relatively significant region. The most significant increase in precipitation in China is in the middle and lower reaches of the Yangtze River and the coastal areas of South China. The increase in precipitation in the vast areas of Northwest China and the southern part of Northeast China also passes the significance test (\( \alpha = 0.05 \)). Precipitation has increased in the GBA, which is one of the most significant areas in China.

To date, there are many definitions of extreme precipitation, and most studies used the extreme climate indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI, Zhang et al. 2011). In this study, nine basic indices of ETCCDI were used to analyze the characteristics of precipitation extremes. They were as follows:

1. R99P (extremely wet days): total precipitation when the daily precipitation > 99th percentile of 1961–2018 daily precipitation (unit: mm).
2. R95P (very wet days): total precipitation when the daily precipitation > 95th percentile of 1961–2018 daily precipitation (unit, mm).
3. RX1day (maximum 1-day precipitation amount): maximum 1-day precipitation (unit, mm).
4. RX5day (maximum 5-day precipitation amount): maximum consecutive 5-day precipitation (unit, mm).
5. R10day (number of heavy precipitation days): count of days when the daily precipitation \( \geq 10 \) mm (unit, day).
6. R20day (number of very heavy precipitation days): count of days when the daily precipitation \( \geq 10 \) mm (unit, day).
7. SDII (simple daily intensity index): average precipitation on wet days (unit, mm).
8. CWDday (consecutive wet days): maximum number of consecutive wet days when the daily precipitation \( \geq 1.0 \) mm (unit, day).
9. CDDday (consecutive dry days): maximum number of consecutive dry days when the daily precipitation < 1.0 mm (unit, day).

We calculated annual and seasonal regional mean values of air temperature (TM), precipitation (PRE), and nine extreme precipitation indices over the GBA from 1961 to 2018. Winter (DJF) refers to December of the previous year to February of the current year, spring (MAM) refers to March to May of the current year, summer (JJA) refers to June to August of the current year, and autumn (SON) refers to September to November of the current year. Due to the lack of data for December 1960, the DJF average value of 1961 is the mean of January to February of 1961, and for the cumulative variable, the DJF value of 1961 was 3 times the mean of January to February. Linear regression was used to assess trends. A t-test was used to test the significance, and we used \( \alpha = 0.05 \) to determine whether the trend was statistically significant. The Mann–Kendall method (Goossens and Berger 1986; McLeod et al. 1991) was used to detect abrupt changes. The MK test has been widely used to detect the significance of abrupt changes and

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**Fig. 1** Spatial distribution of the trends for annual mean air temperature (a) and annual total precipitation (b) during 1961–2018. The red box area is the GBA. The black dots are the grid points passing the statistical significance test with a confidence level of \( \alpha = 0.05 \)
locate the approximate change point of any potential trend in the anomalies. UF and UB are the forward and backward sequential statistics, and the intersection of them denotes the approximate beginning of the trend. In this work, UF and UB were calculated according to the equations introduced by Zhang et al. (2014). In addition, the Morlet wavelet analysis (Torrence and Compo 1998) was used to study interannual oscillations, and the wavelet powers and their significance were analyzed. Wavelet software was provided by C. Torrence and G. Compo and is available at the URL: http://paos.colorado.edu/research/wavelets/. Finally, the responses of extreme precipitation to abrupt climate change were analyzed and discussed.

3 Results

3.1 Variation characteristics of various extreme precipitation

The climatic inclinations of the regional average annual and seasonal extreme precipitations in the GBA from 1961 to 2018 are investigated in Table 1. Trends and variations in these regional extreme precipitation anomalies are shown in Figs. 2, 3, and 4. We find that the trends of R95P and RX1day are negative in SON and positive in DJF, MAM, and JJA. In contrast, the trend of RX5day is negative in MAM and positive in DJF, JJA, and SON. The trend of R99P is negative in MAM and SON and positive in DJF and JJA. The confidence levels for R95P, R99P, and RX5day reach a significance level of α = 0.05 only in JJA. The trends of R10day and R20day are positive except in SON. The confidence levels for R10day and R20day reach a significant level of α = 0.05 in JJA. The trend of SDII is negative in MAM and SON and positive in DJF and JJA. The confidence level for SDII reaches a significance level of α = 0.05 only in JJA. The trends of CWWday (CDDday) are positive (negative) in all seasons, and the confidence levels reach a significant level of α = 0.05 in spring. In general, R95P, R99P, RX5day, R10day, R20day, and SDII have a significant increasing trend in summer, while RX1day, CWWday, and CDDday have no obvious trends. In spring, CWWday increases significantly, but CDDday decreases significantly, and there is no significant trend for other extreme precipitation. In winter and autumn, the nine indices all have no significant trends. Annually, R10day, R20day, and CWWday have significant increasing trends, CDDday has a significant decreasing trend, but R95P, R99P, RX1day, RX5day, and SDII have no significant trends.

Annually, the trend and interannual variation of R95P are basically consistent with those of R99P, RX1day, and RX5day (Fig. 2a, b, c, d). The characteristics of these 4 kinds of extreme precipitation are also basically consistent in DJF (Fig. 2e, f, g, h), MAM (Fig. 2i, j, k, l), JJA (Fig. 2m, n, o, p), and SON (Fig. 2q, r, s, t), respectively. The annual, DJF, MAM, JJA, and SON correlation coefficients of R95P and R99P are 0.95, 0.99, 0.93, 0.95, and 0.92. Then, the annual, DJF, MAM, JJA, and SON correlation coefficients of R95P and RX5day are 0.65, 0.91, 0.82, 0.82, and 0.90, respectively. All of these coefficients pass the statistical test with a significance level of α = 0.001. These 4 kinds of extreme precipitation are classified into the same category and represented by R95P which will be used to detect abrupt changes and interannual oscillations.

The trend and interannual variation in annual R20day are basically consistent with those of annual R10day and SDII (Fig. 3a, b, c). Additionally, the characteristics of these 3 kinds of extreme precipitation are also basically consistent in DJF (Fig. 3d, e, f), MAM (Fig. 3g, h, i), JJA (Fig. 3j, k, l), and SON (Fig. 3m, n, o). The annual, DJF, MAM, JJA, and SON correlation coefficients of R95P and RX1day are 0.93, 0.94, 0.95, 0.92, and 0.93. And the annual, DJF, MAM, JJA, and SON correlation coefficients of R95P and R20day are 0.73, 0.91, 0.83, 0.91, and 0.77, respectively. All of these coefficients also pass the statistical test with a significance level of α = 0.001. These 3 kinds of extreme precipitation are

| Table 1 | Climatic inclinations of the regional average annual and seasonal extreme precipitation in the GBA from 1961 to 2018 |
|---------|----------------------------------------------------------|
| TM      | PRE                  | R95P      | R99P      | RX1day    | RX5day    | R10day    | R20day    | SDII     | CWDday   | CDDday   |
| Unit    | °Ca−¹    | mma−¹      | mma−¹      | mma−¹      | mma−¹      | daya−¹    | daya−¹    | mma−¹    | daya−¹    | daya−¹    |
| Annual  | 0.021*   | 5.517*     | 1.716      | 0.366      | 0.066      | 0.388      | 0.154*     | 0.073*    | 0.003       | 0.050*     | −0.083*    |
| DJF     | 0.027*   | 0.972*     | 0.517      | 0.246      | 0.196      | 0.442      | 0.020       | 0.015     | 0.007       | 0.025       | −0.078     |
| MAM     | 0.016*   | 1.928      | 0.349      | −0.145     | 0.008      | −0.128     | 0.045       | 0.021     | −0.005      | 0.072*     | −0.055*    |
| JJA     | 0.015*   | 2.515*     | 1.018*     | 0.632*     | 0.120      | 0.589*     | 0.086*      | 0.039*    | 0.023*      | 0.009       | −0.032     |
| SON     | 0.026*   | 0.126      | −0.169     | −0.367     | −0.025     | 0.012      | 0.003       | −0.002    | −0.005      | 0.024       | −0.037     |

*represents passing the statistical significance test with the confidence level of α = 0.05.

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classified into the same category and represented by R20day which will be used to detect abrupt changes and interannual oscillations.

The variations in CWDday and CDDday (Fig. 4) show their own characteristics and may not be classified into the above two categories. Abrupt changes and interannual oscillations will be detected, respectively.

Figure 5 shows the results of the Mann–Kendall abrupt change tests for the regional average annual and seasonal R95P, R20day, CWDday, and CDDday in the GBA. UF and UB are the forward and backward sequential statistics, respectively. The intersection of UF and UB curves denotes the abrupt change point. If the UF and UB curves are entangled and there is no obvious distance, the intersection points are not considered abrupt change points. The null hypothesis is rejected when any of the points exceeds the confidence interval $\pm 1.96$, which denotes an $\alpha = 0.05$ confidence level.

In JJA, abrupt changes from fewer to more values can be seen in 1991 for R95P and in 1993 for R20day, and R95P (R20day) has clearly been higher since 1991 (1993). In MAM, R95P shows three abrupt change points: from fewer to more in 1972 and 2009 and from more to fewer in 1994. R20day shows three abrupt change points: from fewer to more in 1965 and 2010 and from more to fewer in 1990. In DJF and SON, R95P, and R20day, there are no obvious abrupt change points. Annual R95P and R20day also show no obvious abrupt change points. Annually and seasonally, the abrupt change can be seen in the early 2010s for CWDday which has clearly been more and for CDDday which has clearly been fewer. In addition, CWDday in MAM exhibits abrupt change points from fewer to more in 1966 and from more to fewer in 1983.

Figure 6.1 and 6.2 show the Morlet wavelet analysis of the regional average annual and seasonal R95P, R20day, CWDday, and CDDday in the GBA. Annually and seasonally, the variations of R95P have a significant periodic oscillation of 3–5 years, which is relatively significant in DJF and MAM during 1980–1990s, in JJA during 2000s, and in SON during 1960s, 1980–1990s, and 2010s. The variations of R95P also have a significant periodic oscillation of 8–14 years, which is relatively significant in JJA and SON. The variations in R20day have a significant periodic oscillation of 3–5 years, which is relatively significant in DJF during the 1980–1990s, in MAM during the 1960–1970s, in JJA during the 1960s and 1990–2000s, and in SON during the 1960s, 1980–1990s, and 2010s. The variations in CWDday have a significant periodic oscillation of 3–5 years, which is relatively significant in DJF during the 1980–1990s, in MAM
during the 1970s, in JJA during the 1960s and 1990–2000s, and in SON during the 1970s. The variations in CDDday have a significant periodic oscillation of 3–5 years, which is relatively significant in all periods in DJF, in MAM during the 1970s, in JJA during the 1960s and 1980–1990s, and in SON during the 1960s. The variations in CWDday and CDDday also have significant periodic oscillations of quasi-8 years.

3.2 Response of extreme precipitation to abrupt climate change

The annual and seasonal average temperatures show increasing trends in the GBA (Fig. 7a, c, e, g, i). The climatic inclinations of the annual, DJF, MAM, JJA, and SON average temperatures are 0.021°C a⁻¹, 0.027°C a⁻¹, 0.016°C a⁻¹, 0.015°C a⁻¹, and 0.026°C a⁻¹, respectively (Table 1). Their confidence levels all reach a significance level of α = 0.05. The warming trend is the most obvious in winter and the weakest in summer. In the GBA, abrupt warming changes occur in 1995, 1989, 1998, 1995, and 1997 for the annual, DJF, MAM, JJA, and SON, respectively (Fig. 7b, d, f, h, j). The changes are the earliest in DJF and the latest in MAM.

The average annual and seasonal precipitation shows increasing trends in the GBA (Fig. 8a, c, e, g, i). The climatic inclinations of the annual, DJF, MAM, JJA, and SON precipitation are 5.517 mm a⁻¹, 0.972 mm a⁻¹, 1.928 mm a⁻¹, 2.515 mm a⁻¹, and 0.126 mm a⁻¹, respectively (Table 1).
The confidence levels reach a significant level of $\alpha = 0.05$ only in MAM and annually. For the average precipitation in the GBA, the annual, DJF, and MAM abrupt changes from fewer to more values can be seen in 2012 and in 1993 for JJA. In addition, the abrupt changes from fewer to more in 1968 and from more to fewer in 1991 can be seen in MAM (Fig. 8b, d, f, h, j).

In summary, annually and seasonally, abrupt warming changes of the average temperature in the GBA occurred in approximately 1995. The abrupt increasing change in the average precipitation occurred in 1993 for JJA and in 2012 for DJF, MAM, and annual precipitation. The analysis in Sect. 3.1 shows that most of the abrupt changes in extreme precipitation occur in the early 1990s and approximately 2010. Based on the main abrupt change characteristics of temperature, precipitation, and extreme precipitation, we divide the extreme precipitation change into three stages, 1961–1994, 1995–2009, and 2010–2018, to compare and analyze the difference in the average values of extreme precipitation and to determine the response degree of extreme precipitation to climate change.

Figure 9 shows the changes in climate and extreme precipitation in the GBA during three different stages, and Table 2 lists the specific differences between 2010–2018 and 1961–1994. During 1961–1994, the annual, DJF, MAM, JJA, and SON average temperatures are 20.4 °C, 12.4 °C, 20.5 °C, 26.9 °C, and 21.8 °C. During 1995–2009, these values are 20.4 °C, 12.4 °C, 20.2 °C, 27.0 °C, and 21.7 °C.
respectively. There are few changes during the 1961–1994 and 1995–2009 stages. However, during 2010–2018, these values are 21.1 °C, 13.4 °C, 20.9 °C, 27.4 °C, and 22.6 °C, which are 0.7 °C, 1.0 °C, 0.4 °C, 0.5 °C, and 0.8 °C higher than those during 1961–1994. In recent decades, the warming of temperature in the GBA has mainly manifested after 2010, with the most obvious effects in DJF and SON.

The annual, DJF, MAM, JJA, and SON average precipitations are 1811.2 mm, 149.6 mm, 581.2 mm, 791.0 mm, and 297.7 mm during 1961–1994; 1874.1 mm, 164.3 mm, 700.0 mm, 288.5 mm during 1995–2009; and 1966.2 mm, 184.9 mm, 635.2 mm, 865.6 mm, and 289.4 mm during 2010–2018, respectively. The annual and DJF precipitation in the latter stage are increasing compared with those in the former stage and increasing 155.0 mm and 35.3 mm during 2010–2018 compared with that during 1961–1994. The SON precipitation has little change in the three stages, and 2010–2018 is only 8.3 mm less than 1961–1994. The MAM precipitation increases significantly during 1995–2009 and decreases during 2010–2018, but the general trend is increasing. The MAM precipitation during 2010–2018 is 54.0 mm more than that during 1961–1994. The JJA precipitation decreases during 1995–2009 but increases significantly during 2010–2018. The JJA precipitation during 2010–2018 is 74.6 mm more than that during 1961–1994.

The average annual, DJF, MAM, JJA, and SON values account for 28.3%, 31.2%, 28.1%, 25.4%, and 34.3% of the total precipitation for R95P and 15.8%, 15.7%, 12.8%, 11.4%, and 17.0% of the total precipitation for R99P, respectively. The changes in annual and seasonal R95P and R99P are consistent with those in precipitation, but the annual R99P is the highest during 1995–2009. As shown in Table 2, the annual and seasonal R99P and R95P are increasing except for R95P in SON and R99P in MAM and SON during 2010–2018 and 1961–1994.

The changes in the annual and seasonal R10day, R20day, and SDII are consistent with those of precipitation, except for SDII in MAM. Compared with the former stage, the values in the latter stage are increasing. The average annual R10day, R20day, and SDII during 2010–2018 are 5.0 days, 2.3 days, and 0.3 mm more than those during 1961–1994. And during 2010–2018, R10day, R20day, and SDII are 1.2 days, 0.6 days, and 0.6 mm more than those during 1961–1994 in DJF, respectively. In SON, the average values in the three stages are basically unchanged for R10day,
In MAM, R10day, R20day, and SDII all increase significantly during 1995–2009 and decrease during 2010–2018. The general trend is increasing for R10day and R20day and decreasing slightly for SDII. In JJA, the average values decrease slightly during 1995–2009 and increase significantly during 2010–2018 for R10day, R20day, and SDII, and the average R10day, R20day, and SDII during 2010–2018 are 2.7 days, 1.3 days, and 0.8 mm more than those during 1961–1994, respectively.

The changes in RX1day and RX5day have their own characteristics, which are affected by both temperature and precipitation. The annual RX1day shows a slight decrease that is only 1.0 mm less during 2010–2018 than that during 1961–1994. However, the annual RX5day shows a significant increase that is 6.6 mm more during 2010–2018 than that during 1961–1994. In DJF, RX1day and RX5day have the same characteristics as precipitation, and both of them increase in the latter stage compared with the former stage. The average RX1day and RX5day during 2010–2018 are 4.9 mm and 13.3 mm more than those during 1961–1994.

In MAM, RX1day and RX5day in the latter stage decrease compared with those in the former stage, and the average RX1day and RX5day during 2010–2018 are 3.6 mm and 16.5 mm less than those in 1961–1994. In JJA, RX1day and RX5day have the same characteristics as precipitation and slightly decrease during 1995–2009 and significantly increase during 2010–2018, and the average RX1day and RX5day during 2010–2018 are 1.2 mm and 16.5 mm more than those in 1961–1994.

In SON, the average values are also basically unchanged in the three stages for RX1day but slightly increase in the latter stage compared with the former stage for RX5day, and the average RX5day during 2010–2018 is 4.5 mm more than that during 1961–1994.

In DJF, MAM, and SON, the changes in CWDday are consistent with those in precipitation, and the values increase in the latter stage compared with the former stage. The average CWDday during 2010–2018 are 1.1 days, 1.5 days, and 0.4 days more than that during 1961–1994 in DJF, MAM, and SON, respectively. In JJA, the average CWDday decreases significantly during 1995–2009 and increases significantly during 2010–2018, and the general trend is to decrease. The average CWDday during 2010–2018 are 0.8 days and 0.7 days less than that during 1961–1994 in DJF and JJA, respectively.

Annually and seasonally, the average values of CDDday are the highest during 1995–2009, except MAM. The average annual CDDday in 2010–2018 is 1.2 days less than that in 1961–1994. In DJF and JJA, the average CDDday increases during 1995–2009 and decreases during 2010–2018, and the general trend is decreasing. The average CDDday during 2010–2018 are 0.8 days and 0.7 days less than those during 1961–1994 in DJF and JJA, respectively.

Fig. 6 The Morlet wavelet analysis of the regional average annual and seasonal R95P (Fig. 6.1 a, c, e, g, i), R20day (Fig. 6.1 b, d, f, h, j), CWDday (Fig. 6.2 a, c, e, g, i), and CDDday (Fig. 6.2 b, d, f, h, j) in R20day, and SDII. In MAM, R10day, R20day, and SDII all increase significantly during 1995–2009 and decrease during 2010–2018. The general trend is increasing for R10day and R20day and decreasing slightly for SDII. In JJA, the average values decrease slightly during 1995–2009 and increase significantly during 2010–2018 for R10day, R20day, and SDII, and the average R10day, R20day, and SDII during 2010–2018 are 2.7 days, 1.3 days, and 0.8 mm more than those during 1961–1994, respectively.
In MAM, the value of CDDday decreases in the latter stage compared with the former stage, and the average CDDday during 2010–2018 is 2.3 days less than that during 1961–1994. In SON, the average CDDday increases during 1995–2009 and decreases during 2010–2018. The general trend is increasing, and the average CDDday is 0.2 days more in 2010–2018 than that in 1961–1994.

4 Conclusions and discussions

(1) During the period of 1961–2018, compared with the warming trend in China, the GBA was a relatively significant region. Precipitation has increased significantly in the GBA, which is one of the most significant areas in China. Warming in the GBA was mainly manifested after 2010 and the most obvious in winter and autumn. Annually and seasonally, abrupt warming changes in the average temperature occurred around 1995. Abrupt increases in the average precipitation occurred in 1993 or 2012.

(2) In summer, R95P, R99P, RX5day, R10day, R20day, and SDII had significant increasing trends, while the changes in RX1day, CWDday, and CDDday had no obvious trends. In spring, CWDday increased significantly, CDDday decreased significantly, and there was no significant trend for other extreme precipitation events. In winter and autumn, the nine indices all had
Fig. 8  Same as Fig. 7 but for the regional mean PRE in the GBA.

Table 2  Changes in climate and extreme precipitation in the GBA during 2010–2018 and 1961–1994

|   | TM  | PRE | R95P | R99P | RX1day | RX5day | R10day | R20day | SDII | CWDday | CDDday |
|---|-----|-----|------|------|--------|--------|--------|--------|------|--------|--------|
| Unit | °Ca⁻¹ | mma⁻¹ | mma⁻¹ | mma⁻¹ | mma⁻¹ | day⁻¹ | mma⁻¹ | day⁻¹ | mma⁻¹ | day⁻¹ | day⁻¹ |
| ANN  | 0.7  | 155.0 | 58.8  | 10.5  | -1.0  | 6.6   | 5.0   | 2.3    | 0.3  | 0.5    | -1.2  |
| DJF  | 1.0  | 35.3  | 16.4  | 8.2   | 4.9   | 13.3  | 1.2   | 0.6    | 0.6  | 1.1    | -0.8  |
| MAM  | 0.4  | 54.0  | 11.5  | -6.0  | -3.6  | -16.5 | 1.5   | 0.7    | -0.3 | 1.5    | -2.3  |
| JJA  | 0.5  | 74.6  | 33.4  | 14.7  | 1.2   | 16.5  | 2.7   | 1.3    | 0.8  | -0.6   | -0.7  |
| SON  | 0.8  | -8.4  | -2.5  | -6.4  | 0.4   | 4.5   | -0.4  | -0.2   | -0.003 | 0.4   | 0.2   |
no significant trends. Annually, R10day, R20day, and CWDday had significant increasing trends, CDDday had a significant decreasing trend, but R95P, R99P, RX1day, RX5day, and SDII had no significant trends.

3) The trends and interannual variations in R95P, R99P, RX1day, and RX5day were basically consistent. For these extreme precipitation events, the abrupt change point from fewer to more values occurred in 1991 in summer. Three abrupt change points, from less to more in 1972 and 2009 and from more to fewer in 1994, occurred in spring. No obvious abrupt change point occurred in winter and autumn. Annually, no obvious abrupt change point occurred. In addition, the annual and seasonal variations in these extreme precipitation events had significant periodic oscillations of 3–5 years and 8–14 years.

4) The trends and interannual variations in R10day, R20day, and SDII were basically consistent. For these extreme precipitation events, the abrupt change point from fewer to more values occurred in 1993 in summer. Three abrupt change points occurred in spring: from fewer to more in 1965 and 2010 and from more to fewer in 1990. No obvious abrupt change point occurred in winter, autumn, and annually. Annually and seasonally, the variations in these extreme precipitation events had significant periodic oscillations of 3–5 years.

5) Annually and seasonally, abrupt changes occurred in the early 2010s for CWDday which clearly increased and for CDDday which clearly decreased. In addition, CWDday exhibited abrupt change points from fewer to more in 1966 and from more to fewer in 1983 in spring. The variations in CWDday and CDDday had significant periodic oscillations of both 3–5 years and quasi-8 years.

6) During the periods 1961–1994, 1995–2009, and 2010–2018, the changes in the annual and most seasonal R95P, R99P, R10day, R20day, and SDII were consistent with those of precipitation. The values in the latter stage are increasing compared with those in the former stage. The changes in RX1day, RX5day, CWDday, and CDDday had their own characteristics.

China is vigorously building the Guangdong-Hong Kong-Macao Greater Bay Area, and as one of the regions with the most significant increase in precipitation in China, it is necessary to conduct further research on its extreme precipitation. To a certain extent, this paper reveals the annual and seasonal variation characteristics of different types of extreme precipitation in the Guangdong-Hong Kong-Macao Greater Bay Area. On this basis, it is hoped that future research can improve the accuracy of regional precipitation prediction from the perspective of model improvement and integration.

Acknowledgements The authors thank the editor and anonymous reviewers for their careful reviews and valuable comments, which led to substantial improvement of this work. The authors are grateful to the China Meteorological Administration for the observation dataset of CN05.1.

Author contribution Conceptualization: Zhigang Wei. Methodology: Zhigang Wei, Xianru Li. Formal analysis and investigation: Zhigang Wei, Xianru Li. Writing—original draft preparation: Zhigang Wei, Xianru Li. Writing—review and editing: Xianru Li, Huan Wang, Li Ma, Shitong Guo. Funding acquisition: Zhigang Wei.

Funding This work was jointly funded by the National Key R&D Program of China (2017YFC1502301); the major projects for talent team introduction of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), China (GML2019ZD0601); and the National Natural Science Foundation of China (41875089).

Availability of data and material The gridded 0.25°×0.25° observation dataset of CN05.1 was provided by the China Meteorological Administration. Wavelet software is provided by C. Torrence and G. Compo and is available at the URL: http://paos.colorado.edu/research/wavelets/.

Code availability NCAR Command Language (NCL) was used to process the data and plot the figures.

Declarations

Ethics approval and consent to participate We think ethics approval and consent to participate are not applicable for this study.

Consent for publication The work described has not been published before and is not under consideration for publication elsewhere.

Conflict of interest The authors declare no competing interests.

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