Changes of extreme high temperature and heavy precipitation in the Guangdong-Hong Kong-Macao Greater Bay Area

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ABSTRACT

The changes of extreme high temperature and heavy precipitation events in the Guangdong-Hong Kong-Macao Greater Bay Area from 1961 to 2019 are analyzed in this paper. Based on the high-resolution climate projection simulations, this study also projects the future risks of heat and flood disasters. The results indicate that hot days, hot nights, heat wave durations, extreme daily maximum and minimum temperature have increased significantly at the rates of 3.6 d/10a, 6.0 d/10a, 2.1 d/10a, 0.23 \textdegree C/10a and 0.21 \textdegree C/10a, respectively. The heavy and very heavy precipitation days, extreme precipitation amount, maximum 1-day and 5-day precipitation amount have increased by 0.6 days, 0.2 days, 12.5 mm, 0.7 mm and 3.5 mm per 10 years, respectively. All the extreme indices will keep increase at similar rates. In the mid-21\textsuperscript{st}, the area with highest heat and flood risks shows an increase by a factor of 10, mainly located in Guangzhou, Foshan, Dongguan, Shenzhen, Hong Kong and the northern part of Zhongshan. The area proportions of the highest two risk levels of heat and flood disasters will be as high as 66\% and 60\%, respectively. Considering both high climate risks and urbanization developments, it is necessary to improve the resistance to extremes and enhance the resilience of society to these extreme disasters.

1. Introduction

In recent decades, China has experienced rapid urbanization. Both the global climate change and urbanization have contributed to the increases of extreme high temperature and heavy precipitation events in major urban agglomerations of China (Wu and Yang\textsuperscript{2013}; Qin et al.\textsuperscript{2015}; Song et al.\textsuperscript{2014}; Sun et al.\textsuperscript{2014}; Sun et al.\textsuperscript{2016};...
Jiang et al. 2018; Yu et al. 2018), which has threatened the sustainable development of cities and even regions. In the future, extreme weather and climate events will be among the most pressing issues that the development of urban agglomerations has to face, and they will attract more and more attention (IPCC 2014; Bai et al. 2018; Zhai et al. 2019).

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is one of China’s three mega-cities. It is one of the regions with the highest population density and economic output within China and even the world. The extreme high temperature and heavy precipitation events in the GBA have severely affected the social and economic development, and people’s lives and property as well (Zhu et al. 2015; Shi et al. 2015; Zhang et al. 2016). The increasing trend of high temperature events in the GBA is obviously stronger than that in other areas of South China since the 1990s (Luo and Lau 2017). For example, on July 7, 2014, due to an extreme high-temperature event, the power grid load in Guangdong reached a record high, becoming the first provincial power grid in China that exceeds 90 million kilowatts (National Climate Center (NCC) 2015). During recent decades, the number of precipitation days has decreased but the precipitation intensity has increased in the Pearl River Basin where the GBA is located (Zhao et al. 2014; Zhang et al. 2017). Both the frequency of extreme 1–3-hour precipitation and the contribution of extreme precipitation to the annual total precipitation in Hong Kong have increased significantly (Wong et al. 2011). The increasing short-duration extreme precipitation has led to severe waterlogging in the cities of GBA (Chen et al. 2017). For example, on May 7, 2017, the 3-hour rainfall in the Zengcheng District of Guangzhou reached 586 mm, causing severe urban waterlogging (Zhang et al. 2019). A clear understanding of the climate risks associated with extreme high temperatures and heavy precipitation is very important for the implementation of the strategic objectives of the "Guangdong-Hong Kong-Macao Greater Bay Area Development Planning Outline". However, there have been few studies on extreme high-temperature and heavy precipitation events in the GBA, especially on future climate risks. Based on the daily observation data from 31 meteorological stations during 1961–2019 and future projection data to the end of 21st century from the high-resolution regional climate model (RCM) of RegCM4, this study systematically studied the past spatiotemporal changes of extreme high temperature and heavy precipitation events and projected the future changes in the GBA. It aims to reveal the future climate risks associated with extreme high temperature and heavy precipitation in the GBA, and provide scientific support for the GBA to better adapt to climate change and enhance the resilience of the society.

2. Data and methods

2.1. Study area

The GBA is located in the southern coast of China and composed of nine cities in Guangdong Province—Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zuhai, Zhongshan, Jiangmen and two special administrative regions of Hong Kong and Macao (Figure 1). The area of GBA is 56,000 square kilometers, the population is more than 70 million, and the regional GDP accounts for 12% of that
in China. As the GBA is facing the sea on the south and surrounded by mountains on the other three sides, the local climate is deeply affected by the systems from both land and sea, and thus the natural ecology is diverse and complex. The GBA belongs to the subtropical monsoon climate with an average annual temperature of 22.2°C and precipitation of 1873.9 mm. Various meteorological disasters including heat and flood with high frequencies seriously affect the GBA region. The economic losses from meteorological disasters can account for more than 80% of the total losses from natural disasters in GBA (Zhou et al. 2019).

2.2. Data

The daily observation at 31 meteorological stations in the GBA during 1961–2019 (Figure 1) used in this article are obtained from the "Dataset of daily climate data from Chinese surface stations (V3.0)" (Ren et al. 2012). The climatology refers to the 30-year mean during 1981–2010.

The climate change projection data come from five dynamical downscaling simulations under the Representative Concentration Pathway 4.5 (RCP4.5) from 1979 to 2099 by using the 25-km-resolution RCM of RegCM4.4 (Han et al. 2017, 2019; Gao et al. 2018). Biases in RCMs’ simulated results are corrected by using the method of quantile delta mapping (Cannon et al. 2015; Tong et al. 2017; Han et al. 2018; Tong et al. 2020). Simulations from five CMIP5 (Coupled Model Intercomparison Project phase 5) global models (CSIRO-Mk3–6-0, EC-EARTH, HadGEM2-ES, MPI-ESM-MR, and NorESM1-M) are used to drive the RCM.

The gridded observational dataset of CN05.1 with a resolution of 0.25° × 0.25° (Wu and Gao 2013) is employed to validate the RCM simulations. The RCM outputs are bilinearly interpolated to the CN05.1 grid.

The socio-economic projection data includes population density (POP), gross domestic product (GDP), and percentage of crop land (CROP) under the SSP2 (Shared Socioeconomic Pathways) scenario. The POP data come from the Inter-Sectoral Impact Model Intercomparison Project with a spatial resolution of 1/24° × 1/
The GDP data come from the Potsdam Institute for Climate Impact Research with a spatial resolution of 1/12° × 1/12° (Geiger et al. 2017; Murakami and Yamagata 2019). The CROP data come from the Land-Use Harmonization datasets with a spatial resolution of 0.25° × 0.25° (Hurtt et al. 2020). All datasets are interpolated to the CN05.1 grid of 0.25° × 0.25° by applying the conservative interpolation method.

The SSP2-RCP4.5 scenario represents the medium-low radiative forcing scenario with modest mitigation, which is a more plausible pathway considering countries’ current and pledged climate policies (Hausfather and Peters 2020).

2.3. Methods

2.3.1. Climate extreme indices

The daily maximum and minimum temperatures as well as daily precipitation are used to calculate the climate extreme indices. Eleven extreme indices are employed, which are mainly defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Sillmann et al. 2013) or localized indices by changing the threshold in the definition, including six temperature indices (SU35, TR25, HWDD, TXx, TNx and DTR) and five precipitation indices (R25, R50, R95p, Rx1day and Rx5day). All indices are defined in Table 1. These extreme indices have already been widely used in China and have been proven to be robust and reliable (Wong et al. 2011; Wang et al. 2012; Zhao and Guo 2015; Zhou et al. 2016).

Theil-Sen trend analysis is used to estimate the linear trends. The uncertainty in trend estimation is calculated through the method of bootstrap simulation proposed by Wilcox (2010). To maintain consistency, the significance test result is also derived from the bootstrap simulation, instead of the Mann–Kendall test which is traditionally used. Trends estimated with p-values less than 0.05 are considered statistically significant.
significant. The uncertainty is shown as “trend [lower bound–upper bound]” with the 95% confidence intervals. For example, 0.22 [0.17–0.30]°C/10a means that the 95% confidence intervals in the trend of 0.22 °C/10a range between 0.17 and 0.30 °C/10a. The trend calculation is based on the package ‘WRS’ in R language (https://dornsife.usc.edu/labs/rwilcox/software/). The running slope difference test is used to detect trend turnings, which checks for the statistical significance in the difference of the slopes of two time series (Zuo et al. 2019). Only the trend turnings with p-values less than 0.05 are considered statistically significant.

In this study, the average of the five future projection simulations with equal weights is taken as the ensemble mean (ensR), as suggested by the IPCC assessment reports. All future projections are reported as the changes from the reference period (1986–2005) to the future periods, in particular the mid-21st century period (2046–2065) over the GBA.

2.3.2. Evaluation method

To investigate how well the ensR can reproduce the mean climate and climate extremes in the GBA during the reference period, the root-mean-square error (RMSE), normalized RMSE relative to observation (nRMSE), and spatial correlation (SCOR) were calculated between the observations of CN05.1 and the ensR over the whole GBA region with a total grid number (m) of 78.

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RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (ensR_i - OBS_i)^2}
\]

\[
nRMSE = RMSE / \left(\frac{1}{m} \sum_{i=1}^{m} OBS_i\right)
\]

2.3.3. Calculation of heat and flood disaster risks

The heat and flood disaster risks are assessed by using the method and parameter sets proposed by Wu et al. (2011a). This method has been used to assess future disaster risks over China and subregions (Wu et al. 2011b; Dong et al. 2014; Xu et al. 2014; Yin et al. 2018; Wu et al. 2019). In this method, the risk is presented as the product of hazard and vulnerability (including both vulnerability and exposure), that is, risk = hazard × vulnerability, which can be calculated based on the normalized hazard factors and vulnerability indices (0–1) over each grid of the GBA region. According to the normalized value of the risk level, the disaster risks are divided into five levels, namely, 0–0.02 (I), 0.02–0.05 (II), 0.05–0.1 (III), 0.1–0.2 (IV) and 0.2–1.0 (V) by the values of 20th, 40th, 60th and 80th percentiles based on the empirical distribution of historical risk indices. When the normalization is conducted, 1.0 is regarded as the maximum value in all grids and all time periods.

Extreme climate indices are considered as the hazard factors. For the index of heat hazard, the normalized SU35 and TR25 are added up with equal weight. For the
index of flood hazard, the normalized R25, Rx1day and the reciprocal value of the terrain elevation are added up with the weights of 0.4, 0.5 and 0.1, respectively.

Vulnerability indices are the sum of normalized POP, GDP, and CROP by using weights in Wu et al. (2011a) based on the experts grading method. The vulnerability to the heat hazard $V_H$ is calculated by using the formula $V_H = 0.4833 \times N_{POP} + 0.2389 \times N_{GDP} + 0.2778 \times N_{CROP}$, and the vulnerability to the flood hazard $V_F$ is calculated by using the formula $V_F = 0.3444 \times N_{POP} + 0.3833 \times N_{GDP} + 0.2722 \times N_{CROP}$, where $N_{POP}$, $N_{GDP}$, and $N_{CROP}$ refer to the normalized POP, GDP and CROP, respectively.

3. Results

3.1. Observed climate changes

3.1.1. Annual mean temperature and precipitation

Based on the observation of daily temperature and precipitation from 31 meteorological stations, the area-weighted averages of annual mean temperature and precipitation in the GBA are calculated. The observation shows a warming and wetting tendency in the GBA in past 60 years (Figure 2). From 1961 to 2019, the annual mean temperature has significantly ($p < 0.01$) increased by the rate of 0.22°C/10a, which is higher than that in the southern China (Committee of South China Regional Climate Change Assessment Report 2013). The 95% confidence intervals in the trend range from 0.17 to 0.30°C/10a. The annual precipitation has increased by the rate of 29.3 mm/10a (but not statistically significant).
The annual temperature and precipitation also show large interannual and interdecadal variations. The interannual variations in temperature and precipitation are $0.52 \, ^\circ\mathrm{C}$ and $0.16$, respectively, which are indicated by the standard deviation and normalized standard deviation relative to climatological normal. The interdecadal variations in temperature and precipitation are $0.39 \, ^\circ\mathrm{C}$ and $0.04$, respectively, which are calculated based on smoothed time series by the 9-year running mean method.

Significant trend turnings of annual temperature can be detected in around 1976, 2001, and 2010. Specifically, there is an insignificant negative trend ($-0.29 \, ^\circ\mathrm{C}/10\text{a}$) in 1961–1976, a significant positive trend ($p < 0.01; 0.41 \, ^\circ\mathrm{C}/10\text{a}$) in 1976–2001, an insignificant negative trend ($-0.32 \, ^\circ\mathrm{C}/10\text{a}$) in 2001–2010, and a significant positive trend.

Figure 3. (a, c, e) Time series of area-averaged changes and (b, d, f) spatial distributions of linear trends in (a–b) SU35, (c–d) TR25 and (e–f) HWDI during 1961–2019 over the GBA. In Figures 3a, c and e, the dashed red lines indicate linear trends, the thick solid black lines indicate smoothed time series by 9-year running mean, and the vertical dashed lines indicate the years of trend turning.
(\(p < 0.01; 1.08 ^\circ C/10a\)) in 2010–2019 (Figure 2a). The turning points and magnitudes of the trends may vary due to the choices of the test methods and the initial points of the time series. However, the running window trend analysis, which calculates the trends in all the running windows with widths no less than 10 years, shows that the decadal characteristics in annual temperature are quite robust, with slight trends before the 1970s, strong positive trends between the 1980s and 1990s, negative trends in the 2000s and again positive trends after the 2010s (Figure 2c). These characteristics are generally consistent with those in global and China’s mean temperature (National Climate Center (NCC) 2020). For interdecadal variabilities in annual precipitation, relatively large negative anomalies appear before 1970 and between 1985–1995, and these characteristics are quite similar to those heavy precipitation indices discussed later in section 3.1.3.

### 3.1.2. Extreme high temperature

The area-averaged climatological normal of SU35 in the GBA is 14.8 days, with the maximum value (29.4 days) occurring in 2014. The past ten years (2010–2019) is the hottest decade with the highest total number of SU35 since meteorological records began in 1961. For the past ten years, the mean value of SU35 is 23.3 days, which is 57% more than the climatological normal. From 1961 to 2019, the SU35 has significantly \( (p < 0.01) \) increased by the rate of 3.6 d/10a (Figure 3a). The 95% confidence intervals in the trend range from 2.8 to 4.3 d/10a. Figure 3b shows the spatial distribution of linear trends of the SU35, which increases in all regions of the GBA. The maximum value (7.6 d/10a) appears in the Huadu District of Guangzhou. The trends in coastal cities are relatively small, with values of 0.2 d/10a, 0.3 d/10a and 0.8 d/10a in Hong Kong, Macao and Shenzhen, respectively. This may be related to the intensities of heat islands in different cities (Yang et al. 2019).

The area-averaged climatological normal of TR25 in the GBA is 75.9 days, with the maximum value (100.4 days) occurring in 2016. From 1961 to 2019, the TR25 has significantly \( (p < 0.01) \) increased by the rate of 6.0 d/10a (Figure 3c). The 95% confidence intervals in the trend range from 4.7 to 8.0 d/10a. Most regions in the GBA, except Macao and the Conghua District of Guangzhou, show an increase in the TR25. The maximum value (16.0 d/10a) appears in Shenzhen (Figure 3d).

The area-averaged climatological normal of HWDI in the GBA is 7.4 days, with the maximum value (16.9 days) occurring in 2015. From 1961 to 2019, the HWDI has significantly \( (p < 0.01) \) increased by the rate of 2.1 d/10a (Figure 3e). The 95% confidence intervals in the trend range from 1.5 to 2.8 d/10a. The whole area shows consistent increases in HWDI. The maximum value (5.0 d/10a) appears in the Huadu District of Guangzhou (Figure 3f).

The area-averaged climatological normal of TXx in the GBA is 36.8 °C, with the significant \( (p < 0.05) \) linear trend being 0.23 °C/10a during 1961–2019 (Figure 4a). The 95% confidence intervals in the trend range from 0.13 to 0.33 °C/10a. Figure 4b shows the spatial distribution of linear trends of the TXx. Most regions in the GBA, except the Fengkai and Huaiji Countries in Zhaoqing, show an increase in the TXx, with the maximum value being 0.49 °C/10a in the Panyu District of Guangzhou.
The area-averaged climatological normal of TNx in the GBA is 28.2°C, with the significant ($p < 0.01$) linear trend being 0.21°C/10a during 1961–2019 (Figure 4c). The 95% confidence intervals in the trend range from 0.16 to 0.26°C/10a. Most regions in the GBA, except the Conghua District of Guangzhou, show an increase in the TNx, with the maximum value being 0.44°C/10a in the Shunde District of Foshan (Figure 4d).

The DTR reflecting the regional temperature change range is one of the important indicators to measure climate changes, which also relates to human comfort (Braganza et al. 2004; Lauritsen and Rogers 2012). From 1961 to 2019, the DTR has slightly decreased by the rate of 0.05°C/10a (not statistically significant; Figure 4e).
The regions with pronounced decreases are mainly located in the east of the Pearl River Estuary, with the maximum value being 0.39 °C/10a in Shenzhen (Figure 4f), which may be related to its rapid development in recent decades. The urbanization effect on the decrease of the DTR in the GBA during 1961–2008 can be as large as 37% (Ren and Zhou 2014).

Except the DTR, the decadal characteristics in temperature indices, which show only one potential trend turning point within the 1970s, are not similar to those in annual mean temperature. The significant trend turnings can only be detected in temperature indices related to daily maximum temperature, including SU35, HWDI and TXx. The turning points are around 1974–1976, before which there are negative trends in SU35, HWDI and TXx, with the rates being −3.6 days ($p < 0.05$), −1.5 days
(not statistically significant) and $-0.46\, ^\circ C$ (not statistically significant) per 10 years, respectively, and after which there are significant positive trends ($p < 0.01$), with the rates being 4.6 days, 2.9 days and $0.33\, ^\circ C$ per 10 years, respectively. There are also slight or negative trends in TR25 and TNx before the 1970s. However, the differences between the slopes of two time series before and after those potential turning points cannot pass the significance test.

3.1.3. Extreme heavy precipitation

The area-averaged climatological normal of R25 in the GBA is 22.6 days, with the maximum value (32.7 days) occurring in 2016. From 1961 to 2019, the R25 has increased by the rate of 0.6 d/10a (not statistically significant; Figure 5a). Figure 5b shows the spatial distribution of linear trends of the R25. Most regions in the GBA, except the Sihui Country of Zhaoqing and Macao, show an increase in the R25. The top two values of the trends (1.56 d/10a and 1.23 d/10a) appear in the downtown area and the Panyu District of Guangzhou.

The area-averaged climatological normal of R50 in the GBA is 8.4 days, with the maximum value (12.1 days) occurring in 2001. From 1961 to 2019, the R50 has increased by the rate of 0.2 d/10a (not statistically significant; Figure 5c). Figure 5d shows the spatial distribution of linear trends of the R50. Most regions in the GBA,
except Jiangmen and Macao, show an increase in the R50, with the maximum value being 0.59 d/10a in Guangzhou.

During recent six decades, the R95p has slightly increased by the rate of 12.5 mm/10a (not statistically significant). Most regions in the GBA show an increase in the R95p, with the maximum value being 50.3 mm/10a in the Zengcheng District of Guangzhou (Figures 5e–5f).

The area-averaged climatological normal of Rx1day in the GBA is 147.0 mm, with the maximum value (204.3 mm) occurring in 2008. From 1961 to 2019, the Rx1day has slightly increased by the rate of 0.7 mm/10a (not statistically significant; Figure 6a). The spatial distribution of linear trends shows that most regions in the GBA present an increase in the Rx1day, with the maximum trend (9.1 mm/10a) in the Huadu District of Guangzhou (Figure 6b).

The area-averaged climatological normal of Rx5day in the GBA is 257.8 mm, with the maximum value (353.4 mm) occurring in 2008. From 1961 to 2019, the Rx5day has slightly increased by the rate of 3.5 mm/10a (not statistically significant; Figure 6c). The spatial distribution of linear trends of the Rx5day is quite similar to that of Rx1day, with the maximum (13.8 mm/10a) in the Huadu District of Guangzhou (Figure 6d).

### 3.2. Projected climate changes

#### 3.2.1. Evaluation

We investigated how well the RCM ensemble can reproduce the mean climate and climate extremes in the GBA during the reference period. Table 2 shows the RMSE, nRMSE, and SCOR calculated between the observations and the ensR over the whole GBA region. The spatial patterns are all well simulated by the ensR, with the values of SCOR higher than 0.91. The biases are also acceptable, with the RMSEs in annual temperature at surface (TAS), TXx, and TNx being 0.5 °C, 0.3 °C and 0.2 °C, respectively, and nRMSE in other variables less than 14%, except two hot-day indices of SU35 and HWDI (26.0% and 25.7%).

#### 3.2.2. Changes in mean climates

The annual mean temperature will continue to rise in future, with the rate being 0.19 °C/10a ($p < 0.01$), mainly due to external forces such as anthropogenic greenhouse gas emissions. The 95% confidence intervals in the trend range from 0.17 to 0.21 °C/10a. The rates of temperature increases are similar in different seasons, with
the value in summer being a little bit higher (0.20 °C/10a). By 2050, the magnitude of annual temperature rise will reach 1.3 °C, and it will be 1.9 °C by 2099 (Figure 7a). The projected precipitation change shows clear interdecadal variations and also a significant increasing trend with the rate being 20 mm/10a (percentage change being 0.8%/10a; \( p < 0.01 \)). The 95% confidence intervals in the trend range from 6 to 32 mm/10a. The change in annual precipitation shows increases in all future periods, with the magnitude not exceeding 200 mm before 2080, and up to 300 mm after 2080. The annual change in precipitation is contributed mostly by the precipitation change in March-April-May (about 65%), then the June-July-August (about 28%), so
the changes in March-April-May and June-July-August show nearly synchronous interdecadal changes with that of the annual mean (Figure 7b).

In the mid-21st century, the mean annual temperature shows increases over all grids in the GBA, with the magnitudes between 1.3–1.5 °C and the average value being 1.41 °C. The ensR presents the most pronounced warming over the coastal area of Hong Kong, Zhuhai and Huizhou, with the magnitudes within the range of 1.48–1.5 °C. Most of the low values of increasing appear at the regions with higher elevation, with the magnitudes less than 1.38 °C (Figure 7c).

In the mid-21st century, the mean annual precipitation also shows increases over all regions in the GBA with the magnitude up to more than 140 mm. The ensR presents the largest precipitation increases over almost all the coastal area, in which

Figure 8. (a) Time series of area-averaged changes and (b) their SNRs during 2021–2099 and (c–e) spatial distributions of changes in temperature extremes during 2046–2065: (c) SU35 (units: d), (d) HWDI (units: d), (e) TR25 (units: d) (In Figure 8a, the values are smoothed by a 9-year running mean; the dashed lines indicate linear trends. In Figures 8c and d, the agreement on the sign of the change was found everywhere, and therefore these data are not shown).
both the climatological mean (more than 2000 mm) and percentage change (more than 10%) are the largest within the GBA (not shown), indicating quite large absolute and relative precipitation change. The average increase in the whole GBA is 98.7 mm (Figure 7d).

The uncertainties of projected changes are also analyzed quantitatively. Two criteria are used (Han et al. 2020): more than 80% of the ensemble members agree on the sign of change; the signal-to-noise ratio (SNR), which is a ratio between the ensemble mean change and the standard deviation of members’ changes (inter-model spread), is larger than 1. All five members show positive annual temperature changes over the whole GBA, and more than 80% of the members project increasing annual precipitation over a large part of the GBA (Figures 7c–7d). For uncertainties in the magnitudes of the changes, the SNR values for area-averaged temperature changes are mostly larger than 3, with the maximum value exceeding 8 around the 2030s; while the SNR values for precipitation changes are mostly smaller than 1, indicating large model uncertainties in projected values of precipitation changes but small uncertainties in temperature change magnitudes.

### 3.2.3. Changes in extreme high temperature

In future, both extreme high-temperature events and heavy precipitation events show increases. There are significant increasing trends in heat duration indices of SU35, TR25 and HWDI ($p < 0.01$). The estimated linear trends are 3.6 [3.2–3.8], 6.8 [6.3–7.4] and 2.9 [2.6–3.1] d/10a, respectively. By 2050, the SU35, TR25, and HWDI show increases by about 15 days, 50 days and 12 days, respectively; by 2099, the increases will reach about 27, 65 and 22 days (Figure 8a). In the mid-21st century, the SU35, TR25 and HWDI show increases over all regions in the GBA with the magnitudes up to more than 30 days, 70 days and 25 days (Figures 8b–8d), respectively. Although the absolute values of the increases in TR25 (40–70 days) are larger than those in SU35 and HWDI (10–30 days), compared to the reference period, the relative changes in SU35 and HWDI are larger, with the SU35 increasing by a factor of about 3–8 and the HWDI increasing by a factor of about 5–20, while the TR25 increases by a factor of no more than 5 over most regions. The maximum absolute increases in SU35 and HWDI appear in the central area of the GBA, mainly in Guangzhou and Dongguan, with the projected SU35 and HWDI about 3 and 6 times the climatological mean of the reference period, respectively (Figures 8c–8d). The spatial distribution of TR25 is quite different from that of SU35, with maximum values in east and west sides of the GBA, mainly in Huizhou, Jiangmen and Zhaoqing, and medium increases around Guangzhou (Figure 8b).

There are significant increasing trends in heat intensity indices of TXx and TNx ($p < 0.01$), with the estimated linear trends being 0.24 [0.21–0.27]°C/10a and 0.20 [0.18–0.22]°C/10a, respectively. By 2050, the TXx and TNx show increases by about 1.6 °C and 1.5 °C, respectively; by 2099, the increases will reach about 2.3 °C and 2.0 °C (Figure 9a), respectively. In the mid-21st century, both the TXx and TNx show increases over all regions in the GBA with the magnitudes up to more than 1.9 °C (Figures 9c–9d). The maximum increases in TXx appear in the coastal area and part of the central area of the GBA, mainly in Guangzhou and Foshan (Figure 9c). For
the increase of the TNx in the mid-21st century, the maximum increases only appear in Foshan (Figure 9d). Compared to the reference period, the area-averaged DTR will decrease over most periods of the 21st century, especially the periods of 2040s–2060s and 2090s; however, there is no significant trend in the DTR changes, and the decreasing magnitudes are less than 0.1°C (Figure 9a). In the mid-21st century, the DTR shows decreases over most regions in the GBA, except part of the coastal area, with the decreasing magnitudes less than 0.12°C (Figure 9b). The change rates of DTR are quite different between the past and future changes, partly because the urban development is not considered in current simulations on future climate projection.
Figure 10. (a–b) Time series of area-averaged changes and (c–d) their SNRs during 2021–2099 and (e–i) spatial distributions of changes in precipitation extremes during 2046–2065: (e) R25 (units: day), (f) R50 (units: days), (g) Rx1day (units: mm), (h) Rx5day (units: mm), (i) R95p (units: mm). (In Figure a and b, the values are smoothed by a 9-year running mean; the dashed lines indicate linear trends. In Figures 10e–i, marked areas indicate that 80% or more of the ensemble members agree on the sign of change.)
Except for the DTR, the changes of all the other temperature indices can pass the threshold on the agreement over all regions of the GBA, and the SNR values are greater than 1. The SNR values for area-averaged SU35, TR25, TXx and TNx changes are around 2–4, and the values for HWDI are higher, which are around 4–6 (Figures 8b and 9b). The results indicate low uncertainties in the change sign and change magnitudes of heat temperature indices but high uncertainties in the DTR changes.

Equally weighted on the increases in daytime and nighttime heat events, the heat hazard shows increases mostly over the central part of the GBA (not shown), which trends to induce higher heat disaster risk discussed in the following section.

3.2.4. Changes in extreme heavy precipitation

Similar to the annual precipitation, the changes of extreme precipitation in future show distinct interdecadal fluctuations, and the phases are also similar (Figure 10a).
There are also significant increasing trends in R25 and Rx1day with the rates being 0.2 [0.0–0.4] d/10a ($p < 0.05$) and 1.9 [0.7–3.2] mm/10a ($p < 0.01$), respectively. The R25 changes fluctuate within 2.5 days before mid-21st century, followed by a slight increase with the maximum increase reaching about 4 days to the end of the 21st century. The projected Rx1day shows similar features to those of R25: the magnitude of increase fluctuates within 25 mm until the 2080s, and then reaches 35 mm till the end of the 21st century. For other duration or intensity indices, they also show similar temporal features. The estimated linear trends in R50, R95p and Rx5day are 0.1 [0.0–0.2] d/10a ($p < 0.05$), 11.7 [3.2–19.1] mm/10a ($p < 0.01$) and 3.3 [1.1–5.1] mm/10a ($p < 0.01$), respectively, with the maximum magnitudes of increases reaching 1.5 days, 190 mm and 45 mm to the end of the 21st century, respectively.

In the mid-21st century, all precipitation extremes show increases over most regions in the GBA except that the R25 decreases with small magnitudes over a large area of the southwestern GBA—Jiangmen (Figures 10b–10g). The magnitudes of increases reach 2 days, 1.5 days, 30 mm, 30 mm and 100 mm for R25, R50, Rx1day, Rx5day and R95p, respectively. The maximum increases in R50, Rx1day and Rx5day appear in the coastal area (Figures 10d–10f), while for R25 and R95p the maximum increases appear in both the coastal area and the northern mountainous area of the GBA (Figures 10c and 10g).

All the changes in precipitation indices can pass the threshold on the agreement over most regions of the GBA (Figures 10e–10i). However, only the SNR values for area-averaged Rx1day changes are greater than 1 over most future periods. The SNR values for Rx5day and R95p changes can exceed 1 in the 2020s, 2040s, 2070s and 2090s, while for R25 and R50 changes, the SNR values are mostly smaller than 1 (Figures 10c–10d). The results indicate low uncertainties in the change sign of precipitation indices, and the uncertainties in the change magnitudes are relatively lower for heavy precipitation amount indices than those for heavy precipitation frequency indices.

By weighted combining of the terrain and the increases in heavy precipitation days and amount, the flood hazard shows increases mostly over the coastal area of the GBA (not shown), which trends to induce higher flood disaster risk discussed in the following section.

There have been few studies focussing on future changes in mean climate and extreme climate over the GBA. Compared to previous studies on future climate projections over larger regions (e.g., Du et al. 2016; Lu et al. 2019; Han et al. 2020;
Zhang and Gao (2020), the conclusions of positive changes in mean temperature, mean precipitation and climate extremes are similar, which can also support the uncertainty analysis results in our study. It should be noted that the projection results are responses to future changes in external anthropogenic forcings (such as greenhouse gases) under certain emission scenario. Internal climate variations (such as decadal changes related to the Interdecadal Pacific Oscillation) will also influence the ‘real’ climate changes (Huang et al. 2020), yet the contribution of which in this region is still unknown.

### 3.2.5. Heat and flood disaster risks

Under the SSP2 scenario, the regional mean GDP will continuously increase to the end of the 21st century, with the values being about $2 \times 10^8$ CNY per km$^2$ around 2020, $5 \times 10^8$ CNY per km$^2$ around 2050 and $6.5 \times 10^8$ CNY per km$^2$ around 2099. Meanwhile, the regional mean POP will reach the peak value of $1.3 \times 10^8$ persons per km$^2$ around 2040 from the value of $1.2 \times 10^8$ persons per km$^2$ around 2020. To the end of the 21st century, the POP will drop back to the value of $0.9 \times 10^8$ persons per km$^2$. The regional mean CROP will also continuously increase to the end of the 21st century, being 15% around 2020 and 22% around 2099 (Figure 11a). The spatial distributions of GDP and POP are quite similar, and the patterns will not change in the future, both of which show higher values in the central part of the GBA. The croplands are located over almost all the plain area, mainly in the southwestern and central parts of the GBA (Figure 1). Due to less weight on CROP, both the heat and flood vulnerability indices show similar spatial patterns to those of the GDP and POP, with the maximum value over the central part of the GBA (Figures 11b and 11c).

In the mid-21st century, the regions with the highest heat risk (Grade V) are mainly distributed in the central part of the GBA except most areas in Zhaoqing and Huizhou as well as the western part of Jiangmen (Figure 11d), because both the hazard and vulnerability of heat disaster show similar patterns. The proportion of the area with the risk of Grade V increases the most, with the values being 3.7% in the reference period and 41.5% in the mid-21st century. The proportion of the regions with risk of Grade I decreases, with the similar magnitude to that of Grade V. In the meantime, the proportions of the area with risks of both Grade III and Grade IV increase while that of Grade II decreases, and all the magnitudes are quite small (Table 3).

In the mid-21st century, the area with the highest risk (Grade V) of flood disaster is mainly distributed in the central part of the GBA, mainly in Guangzhou, Foshan, Dongguan, Shenzhen, Hong Kong and the northern part of Zhongshan, which is quite smaller than the area with the heat risk of Grade V (Figure 11e). This is because the hazard and vulnerability of flood disaster show different spatial patterns, with medium values of flood hazard located in the central part of the GBA. The proportion of the area with the risk of Grade V increases the most, with the value being 2.6% in the reference period and 20.7% in the mid-21st century. The change magnitude is smaller than that of the area with the heat risk of Grade V, because the change of flood disaster is smaller. The total proportion of the area with risks of
Grades I and II decreases, with the similar magnitude to that of Grade V. In the meantime, the proportion of the area with the risk of Grade IV increases while that of Grade III decreases, and both the magnitudes are quite small (Table 3).

4. Conclusions and discussion

This study shows that the extreme high temperature and heavy precipitation events in the GBA have increased in the past 60 years. Under the background of global climate change in the future, the GBA will face greater risks of high temperature and flood disasters. Our conclusions and discussion are as follows.

Both the observation and projection simulations show a warming and wetting tendency and large interdecadal variations in the GBA from the past 60 years to the end of the 21st century. The linear trends in annual temperature are 0.22 [0.17–0.30]°C/10a and 0.19 [0.17–0.21]°C/10a in the past (1961–2019) and future (2021–2099), respectively, and the trends in annual precipitation are 29 mm/10a (insignificant) and 20 [6–32] mm/10a, respectively. For annual temperature, there are slight trends before the 1970s, strong positive trends between the 1980s and 1990s, negative trends in the 2000s, and again positive trends after the 2010s. The significant trend turning within the 1970s also exists in the observed SU35, HWDI, and TXx changes. For annual precipitation, it shows relatively large negative anomalies before 1970 and between 1985–1995, and similar interdecadal characteristics also exist in observed heavy precipitation indices changes.

From 1961 to 2019, the area-averaged SU35, TR25, HWDI, TXx and TNx in the GBA have increased significantly at the rates of 3.6 [2.8–4.3] d/10a, 6.0 [4.7–8.0] d/10a, 2.1 [1.5–2.8] d/10a, 0.23 [0.13–0.33]°C/10a and 0.21 [0.16–0.26]°C/10a, respectively; while the DTR has slightly and insignificantly decreased by the rate of 0.05°C/10a. It is projected that to the end of the 21st century, the SU35, TR25, HWDI, TXx and TNx show significant increases at the rates of 3.6 [3.2–3.8] d/10a, 6.8 [6.3–7.4] d/10a, 2.9 [2.6–3.1] d/10a, 0.24 [0.21–0.27]°C/10a and 0.20 [0.18–0.22]°C/10a, respectively, and by 2050 the magnitudes of the increases are 15 days, 50 days, 12 days, 1.6°C and 1.5°C relative to those in the reference period, respectively. The DTR shows decreases over most periods of the 21th century, however, the trend is small and not significant. The regions with most pronounced increase in heat extremes are located in the central part of the GBA, including Guangzhou and Dongguan. The values at these regions in the mid-21st century (2046–2065) will increase by three times for SU35 and six times for HWDI to the reference period. Then the proportion of the area with heat risks of Grades IV and V will be as high as 65.9%, with the value of 41.5% for the risk of Grade V mainly distributing in the central part of the GBA. Compared with the reference period, the area with the highest risk of heat disaster shows increases by a factor of 11 in the mid-21st century.

From 1961 to 2019, the R25, R50, R95p, Rx1day and Rx5day have insignificantly increased by 0.6 days, 0.2 days, 12.5 mm, 0.7 mm and 3.5 mm per 10 years, respectively. It is projected that to the end of 21st century, the R25, R50, R95p, Rx1day and Rx5day show significant increases at the rates of 0.2 [0.0–0.4] d/10a, 0.1 [0.0–0.2] d/10a, 11.7 [3.2–19.1] mm/10a, 1.9 [0.7–3.2] mm/10a and 3.3 [1.1–5.1] mm/10a,
respectively, and the regions with higher magnitudes of increases are located along the coastal area of the GBA in the mid-21st century. Considering both the extreme heavy precipitation changes as well as the economic and social development of the GBA, the projection shows that the area proportion with the flood risks of Grades IV and V is up to 59.8% in the mid-21st century. The regions with the highest flood risk (Grade V) are mainly located in Guangzhou, Foshan, Dongguan, Shenzhen, Hong Kong and the northern part of Zhongshan, and the area is 8 times that of the reference period.

Generally, there are small uncertainties in the future change signs of mean and extreme climate except the DTR. The model uncertainties in projected change magnitudes are small for mean temperature and heat temperature indices but large for mean precipitation. For projected precipitation change magnitudes, the model uncertainties are smaller in heavy precipitation amount indices than those in heavy precipitation frequency indices.

The high temperature events have great impacts on economic development, population health and urban environment in the GBA (Xie et al. 2015; Luo et al. 2016; Wang et al. 2017; Zhang et al. 2017). Although this study reveals the characteristics and future risks of high-temperature events in the GBA, the interaction mechanism between the development of urban agglomerations and extreme high-temperature events in the GBA needs further study. For future urban planning and construction in the GBA, full consideration should be given to adopting adaptive strategies to mitigate the impact of urban heat islands and high temperature events (Ren et al. 2011; Kong et al. 2017; Ng et al. 2012).

Previous studies have shown that the rate of sea level rise in the GBA is higher than the global and national averages (He et al. 2014; He et al. 2016; Wang et al. 2016). The storm surge also contributes to extreme high sea levels (Zhang et al. 2017). Considering the further influences of these factors, the flood risk in the GBA will be even greater in the future. Therefore, in the future, it is necessary to further study the strategies for adapting to extreme precipitation events and the risk management of urban waterlogging in the GBA, so as to mitigate the urban waterlogging problems (Wu and Xiang 2016; Chen et al. 2017).

Under the global climate change, the GBA will face high climatic risks related to extreme high temperature and heavy precipitation in the future, and the acceleration of urbanization would further increase the risks. It is necessary to improve the resistance to extreme weather and climate events, build a climate-friendly city, and increase the resilience of the society to respond to climate changes.

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