Responses of extreme high temperatures to urbanization in the Beijing–Tianjin–Hebei urban agglomeration in the context of a changing climate

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 42075023

Abstract
Extreme high-temperature event is one of the most urgent climate issues faced by coordinated development of the Beijing–Tianjin–Hebei region (BTH) in the future due to global warming and urbanization. Based on the homogenized daily temperatures from 174 meteorological observation stations, six extreme hot events were detected. The results revealed the spatiotemporal characteristics of the extreme high temperature in the BTH. The acquired evidence showed the maximum daily minimum temperature (TNx), high-temperature days (SU35), hot night days (TR25), and heatwave spell durations (HWDI) have significantly increased, while the daily temperature range (DTR) has significantly decreased (p < 0.01) during 1961–2018. The SU35, TR25 and HWDI in 2010s were 68%, 2.8 times and 2.1 times higher than that in 1980s, respectively. Moreover, since 1961, the high-temperature season in the BTH has been getting longer at a rate of 7.4d/10a. The study also revealed the contribution of urbanization on high-temperature indices depends on city size and location in the BTH. The magnitudes of the indices change in the downtown area of Beijing, Tianjin and Shijiazhuang ranked top in the 13 cities of the BTH, which are closely related to the urban development. The mean contribution of urbanization on maximum daily maximum temperature (TXx), TNx, SU35 and TR25 was 68%, 45% and 27% in Beijing, Tianjin and Shijiazhuang, respectively. The socio-economic driving factors have an important impact on the change rates of the extreme high-temperature indices, which means that controlling population, city size and reducing energy consumption could effectively alleviate the urban heat island (UHI) effect and slow down the high-temperature events in the BTH. In the future, it is vital to further study and investigate the mechanism of the extreme high-temperature changes through numerical simulations and to research their impact and response in this region.

KEYWORDS
Beijing–Tianjin–Hebei, extreme high temperature, spatiotemporal changes, urbanization
1 | INTRODUCTION

With global warming, the high-temperature extremes show increasing occurrence characterized by long duration, high intensity, large spatial extent and catastrophic impacts in recent decades (Alexander et al., 2006; Donat et al., 2013; Q. Su & Dong, 2019; Sun et al., 2014; X. Yang et al., 2017). Due to the urban heat island (UHI) effects, referred to as the temperature rise in urban relative to surrounding areas (Arnfield, 2003), the urban high-temperature heat stress has been significantly amplified (Bai et al., 2018; Kalnay & Cai, 2003; Liao et al., 2018; Perkins, 2015; Steven & Matthew, 2010; L. Zhao et al., 2014), and extreme high-temperature disaster risks in urban areas have been on the rise (Tong et al., 2020; Gabriel & Endlicher, 2011; Hajat & Kosatky, 2010; Yin et al., 2013; Zhang et al., 2015), which makes extreme high temperatures, referred as high-temperature events with a probability of occurrence usually less than 10%, among the most urgent climate issues that have to be dealt with by urban development in the future.

The high-temperature extremes show increasing occurrence, and heatwaves have become more frequent and severe in China during recent decades as the global mean temperature rises (Y. Chen & Li, 2017; Y. Li et al., 2017; Luo & Lau, 2017; Sun et al., 2016; You et al., 2017), leading to severe damage to human society and ecosystems (Basara et al., 2010; Patz et al., 2005; Q. Su & Dong, 2019; Tan et al., 2010; Wei et al., 2021; Zhai et al., 2018). Urbanization plays an important role in regional climate change through altered land–atmosphere interactions over urban areas (Liang & Oliver, 2016; L. Zhao et al., 2014; D. Zhou et al., 2016). The evidence of some typical high-temperature events in summer shows that the intensity of UHI during extreme high-temperature days is greater than that in non-high temperature days, and the influence on high-temperature events of UHI is also amplified (D. D. Li & Bou-Zeid, 2013; Z. X. Wu et al., 2019; X. C. Yang et al., 2015; Zhou et al., 2011). Urbanization is augmenting hot conditions and the duration of heatwaves in urban areas compared with rural regions (J. C. Ding et al., 2001, 2002; Sun et al., 2014).

As one of the three megacity clusters in China, the BTH urban agglomeration is not only one of the regions with the fastest urbanization rates, but it is also considered as the most typical region where human activities affect natural systems (Fang et al., 2018; Ge et al., 2017; Xia & Zhang, 2018). In recent years, the BTH urban agglomeration has received considerable attention because of the recently issued government policy ‘To build a world-class agglomeration of cities with the capital as the core’ (Y. Zhang et al., 2017). Some studies have previously pointed out that extreme high-temperature events show a significant upward trend in the area (Y. Chen & Li, 2017; Sun et al., 2014; Zhai et al., 2018) and that the BTH heatwave and UHI have a synergistic effect (Liang et al., 2016; Y. H. Liu et al., 2017; D. Zhou et al., 2016). The extreme indices related to minimum temperature were more significantly affected by urbanization than that related to maximum temperature, which is because the stronger UHI at night slows down the cooling of urban area and makes the extreme value of minimum temperature increase significantly (Y. Q. Zhou & Ren, 2011; Q. X. Li & Huang, 2013; Si et al., 2014; B. T. Zhou et al., 2014). The UHI influence on the spatial pattern of extreme high-temperature events depends on city size (Z. Q. Xie et al., 2015). The main significant difference between large and medium-size cities exists in the daily maximum temperature (N. Zhao et al., 2019). In addition, it was found that the frequency and intensity of extreme high temperatures can significantly increase in the future (Kang & Eltahir, 2018; Y. Shi et al., 2019; Song et al., 2015; Yu et al., 2018).

Previous studies on the extreme high-temperature events of the BTH have focused on individual case studies, putting emphasis on the UHI effect (Huang et al., 2012; Y. H. Liu et al., 2017; P. Yang et al., 2013). Much work has been done to quantify the effects of urbanization on long-term mean temperature trends (Hua et al., 2008; Y. Li et al., 2017; G. Y. Ren et al., 2008; Wang et al., 2013). However, few studies were found to investigate the changes in the daily extreme high-temperature indices and quantify the effects of urbanization on extreme high temperature in different size city of the BTH. It is almost unclear whether or to what extent urbanization has influenced long-term extreme high temperature changes in such a large urban agglomeration. Understanding the spatial and temporal changes in the intensity, frequency, and duration of extreme high-temperature events in the BTH is very important for developing effective and appropriate countermeasures against possible risks caused by such extreme high-temperature events.

Accordingly, the primary objectives of this study are to reveal the characteristics of the refined spatiotemporal changes of extreme high temperatures, to identify the contribution of urbanization on extreme high temperatures, and hopefully to provide scientific understanding for adapting to and mitigating the extreme high-temperature disasters in the BTH urban agglomeration. A brief description of the study, data and methods is given in Section 2, changes of extreme high-temperature indices and urbanization effect on high temperature in Section 3, and conclusion and discussion in Section 4.
2 | DATA AND METHODS

2.1 | Study area

The BTH is located at 36.07°–42.65° N, 113.46°–119.79° E, with an area of 216,000 km² and a population of 110 million people. It mainly includes 3 megacities (Beijing, Tianjin and Shijiazhuang), 10 medium cities (Baoding, Tangshan, Langfang, Handan, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Xingtai and Hengshui) and many small- and medium-sized towns in the south-central as well as mountainous areas in the north of the Hebei province (Figure 1). According to the circular of China’s State Council on adjusting the standards for the division of urban scale, cities with more than 1 million resident population were studied as big city, the others as medium cities in this study. Located at the Northern China Plain and surrounded by the Bohai Sea from the east, the Taihang Mountain from the west, the Yanshan Mountain from the north, and the Yellow and Ji rivers from the south, the terrain is high in the northwest and low in the southeast. The Yanshan and Taihang mountains form an arc mountain range from the east to the west until the south, and the altitude greatly varies in the Hebei Plain with a complicated geographical environment, which is in the east and south of the mountains. The BTH is located at the northern edge of the monsoon and sensitive to climate changes and fragile ecology because of its special geographical location and terrain.

2.2 | Data

The daily temperature data in 174 meteorological stations of the BTH from 1961 to 2018 were obtained from the China Surface Climate Data Daily Dataset (V3.0) of the National Meteorological Information Center, China Meteorological Administration (CMA; http://data.cma.cn/). The dataset has been controlled for quality and homogenized using the method described by W. Xu et al. (2013). Among these data, the metadata of the stations were used to describe the historical evolution information of each meteorological station as a reference for judging the temperature series inhomogeneity and the correction position of the change point. The RHtests method combined with the metadata has been used to remove the inhomogeneity and improve the data quality of temperature series (Cao et al., 2017; Q. X. Li et al., 2009).

Previous studies classified meteorological stations into urban and rural stations based on different methods (e.g., population, satellite-observed night-time light intensity and land cover data). To classify the meteorological stations, we chose the annual land use dataset of China with a resolution of 1 km (X. L. Xu et al., 2018). Stations with 33% or more built-up area in the buffer zone are classified as urban stations, otherwise they are classified as rural stations (G. Ren & Zhou, 2014). In the present study, based on the classification data of land use and urban buildings in the BTH in 2015 (Wang et al., 2013), 110 and 64 meteorological stations are defined as urban stations, respectively, among the urban stations, there are 13 sites with more than 1 million resident population, which were studied as downtown area.

The socio-economic data of 13 cities during 1981–2018 in the BTH, including the gross domestic product (GDP), population (POP), built-up area (BA) and vehicle ownership (VP), are from the local Bureau of Statistics. As for the urban impervious area (IA) data, they are from the surface coverage dataset, which was developed by Tsinghua University (Gong et al., 2019).

2.3 | Method

This study refers to the extreme temperature indices of ETCCDI (N. Zhang, Zhu, & Zhu, 2011a) and the specifications for Surface Meteorological Observation (CMA, 2007). Six extreme high-temperature indices, such as the maximum value of daily maximum temperature (TXx), the maximum value of daily minimum temperature (TMin), etc., are calculated.
temperature (TNx), daily temperature variations (DTR), SU35, TR25 and heatwave spell duration index (HWDI) of the warm season (May–September) were used to characterize the extreme high-temperature changes in the BTH urban agglomeration, as shown in Table 1.

To quantify the extent to which urbanization affects extreme high temperature, we use the method described by Z. X. Wu et al. (2019) to calculate the contribution of urbanization to extreme high-temperature index. The calculation formula is as follows:

\[ U_e = \left( \frac{T_u - T_r}{|T_u|} \right) \times 100\% , \]

where \( U_e \) is the contribution of urbanization to extreme high-temperature index, \( T_u \) and \( T_r \) are change tendency of extreme high-temperature index for urban stations and rural stations, respectively.

### RESULTS

#### Changes of extreme high-temperature indices

The evidence shows the increasing rate of annual average surface temperature at 0.33°C/10a in North China is the second highest in all Chinese eight regions during 1961–2018 (Song et al., 2019). As the central part of North China, the BTH experienced the same warming trend. The average surface temperature (Tm), average maximum surface temperature (Tmax) and average minimum surface temperature (Tmin) in the warm season significantly increased at a rate of 0.27°C/10a, 0.14°C/10a and 0.40°C/10a, respectively (\( p < 0.01 \), \( p \) value is the probability of failing to reject the null hypothesis.) and the warming rate was significantly higher than that of annual average surface temperature in North China (0.33°C/10a) and whole China (0.18°C/10a) during the same period (Song et al., 2019). The warming magnitude of the Tmin exceeding twice that of the Tmax is the highest in Chinese urban agglomerations, and it might have been more significantly related to the UHI effect at night in the BTH (Si et al., 2014; Y. Q. Zhou & Ren, 2011). That is because urban surfaces with low albedo absorb and store more radiation energy in the daytime and release the stored energy at night, thereby increasing night-time temperatures (Liang & Oliver, 2016; Y. Q. Zhou & Ren, 2014).

| Abbreviation | Name                           | Description                                               | Unit     |
|--------------|--------------------------------|-----------------------------------------------------------|----------|
| TXx          | Maximum value of daily maximum temperature | Seasonal maximum of daily maximum temperature            | °C       |
| TNx          | Maximum value of daily minimum temperature | Seasonal maximum of daily minimum temperature            | °C       |
| DTR          | Daily temperature range         | Seasonal mean difference between daily maximum temperature and daily minimum temperature | °C       |
| SU35         | Number of hot days             | Seasonal count of days when daily maximum temperature ≥ 35°C | d        |
| TR25         | Number of hot nights           | Seasonal count of days when daily minimum temperature ≥ 25°C | d        |
| HWDI         | Heatwave spell duration index  | Seasonal count of days with at least three consecutive days when TX ≥ 35°C | d        |

3.1.1 TXx, TNx and DTR

TXx and TNx are the indicators reflecting the intensity of extreme high-temperature events. From 1961 to 2018, the average TXx in the BTH showed an increasing trend, as it increased by 0.12°C every 10 years (Figure 2); however, it failed the significance test. This is consistent with the findings of Tong et al. (2020). The largest TXx in 2002 was 36.6°C, followed by that in 2017, 2000, 2018 and 2014, where it reached 36.0, 35.8, 35.7 and 35.7°C, respectively. From the regional distribution of the change tendency rate (Figure 3a), it can be seen that the TXx increase rate in the north of the BTH was greater, where Tianjin Tanggu, Beijing Tongzhou, Beijing Changping had the largest values, reaching 0.42°C/10a, 0.41°C/10a and 0.40°C/10a, respectively. Meanwhile, the TXx values in Xingtai and Handan in the south showed a decreasing trend. This may be related to the influence of irrigation in the southern BTH. Irrigation has a significant cooling effect on the daily
maximum temperature, which partially offsets the effect of urbanization (W. J. Shi et al., 2014).

As for the regional average TNx, it showed a significant upward trend ($p < 0.01$), with a temperature increase rate of 0.37°C/10a, and its maximum value was 24.3°C in 2016, followed by 23.9°C in 2017 and 23.8°C in 2014. It shows that the central part of the BTH was the area with the most significant TNx warming, where the temperature increase rate of Baoding Zhuozhou, Tianjin Xiqing, Tianjin Downtown reached 0.59°C/10a, 0.58°C/10a and 0.56°C/10a, respectively, while that in Chengde and Xingtai was relatively insignificant (Figure 3b).

It should be mentioned that, even after 1998, the TXx and TNx still increase significantly without a warming hiatus. The annual mean temperature in China had a cooling trend during the recent global warming hiatus period (Y. K. Xie et al., 2017), while TXx and TNx reached their decadal maximum values in 2000s and 2010s respectively, which were 0.82 and 1.37°C higher than those in 1980s (Table 2). It may be related to the rapid development of BTH after the successful bid for the 2008 Beijing Olympic Games (Jiang & Qian, 2008).

The DTR is one of the most important indicators for measuring the regional temperature changes (Braganza...
et al., 2004; Lauritsen & Rogers, 2012). Tmin warm at a faster rate than Tmax resulted in the significant decrease of DTR at a rate of 0.26°C/10a (p < 0.05) during 1961–2018 in the BTH, which is higher than that of the national average (Tang et al., 2005). This may be because the IA of the BTH rapidly increased (Table 2), where the impervious layer lowered the reflectivity and high heat capacity, thus leading to a decrease in the daily difference (Gallo et al., 1996; D. A. Stone & Weaver, 2003). It further indicates that the contribution of urbanization to the DTR is the largest in the region (Wang et al., 2013). It can be seen from the regional distribution of the DTR change trend rate in the BTH from 1961 to 2018 that, except for Chengde, the entire region showed a consistent decreasing trend, where the most significant areas of the DTR reduction were located in the south of the BTH (Figure 3c). Among them, Baoding Zhuozhou, Xingtai Julu and Xingtai downtown had the largest reductions, reaching 0.58°C/10a, 0.55°C/10a and 0.42°C/10a, respectively. Many natural factors, such as solar radiation, cloud, precipitation, water vapour content and the development of urbanization, the change of underlying surface and emission of air pollutants have an impact on the change of the maximum and minimum temperature. Therefore, the causes of spatial distribution of DTR change trends in the BTH are complex.

### 3.1.2 SU35, TR25, HWDI

High temperature and heatwave events have a significant impact on human health, labour productivity, water supply, power supply and economic development in China (Qin et al., 2015; Y. N. Su et al., 2018; Tang et al., 2010; Ye & Zhang, 2018). From 1961 to 2018, the SU35 in the warm season of the BTH insignificantly increased at a tendency rate of 0.9d/10a (Figure 4), greater than in China and North China (H. B. Shi, 2012; J. Y. Zhang and Cheng (2020). However, it is worth noting that before the mid-1990s, the number of SU35 fluctuated around the average value of 1961–1995 (7 days). Since the late 1990s, the SU35 often exceeded 10 days (the average value of 1996–2018 was 11 days). The SU35 in the 2010s was 68% higher than that in 1980s of the last century (Table 2). The main reason for this change might be related to the rapid expansion of the BTH, and it was more prominent in the number of SU35 (G. H. Zhang et al., 2012). Concerning the regional distribution of the SU35 tendency rate from 1961 to 2018 (Figure 3d), Beijing and Tianjin were the centres with the fastest increase in the number of SU35. Beijing Tongzhou, Beijing Changping and Tianjin Xiqing increased at a rate of 2.14d/10a, 2.03d/10a and 1.92d/10a, respectively, while the regional rate was 0.88 d/10a. The number of SU35 in southern Hebei decreased except in the region around Shijiazhuang in the past 60 years. This may be related to the irrigation cooling effect on the SU35 in the irrigated sites of southern BTH where the land cover is cropland (W. J. Shi et al., 2014) because higher sensible heat fluxes on summer days can induce larger cooling effects on hot days (Lobell et al., 2008). The difference between big cities and other regions was also very obvious (Figure 3d), which means UHI had significant effect on extreme climate at small scale (Tong et al., 2020).

In addition, since 1961, the high temperature starting time of the BTH has been advanced by 1.0 day every
10 years, and the end date has been delayed by 6.4 days every 10 years (Figure 5), which indicates that the high-temperature season in the BTH has been getting longer at a rate of 7.4d/10a.

Meanwhile, the TR25 in the BTH significantly increased by 1.49 days per decade ($p < 0.01$) during 1961–2018 (Figure 4). There was apparently an abrupt change in the mid-1990s. Before the mid-1990s, the
The number of TR25 fluctuated around the average value of 1961–1995 (2.5 days). Since the mid-1990s, the number of TR25 often exceeded 10 days (the average value for 1996–2018 was 7.5 days). The TR25 in 2010s was 2.8 times higher than that in 1980s of the last century (Table 2). It could be because the growth rate of urbanization changed significantly after the mid-1990s and was around three times that of 1980s in the BTH (Z. X. Wu et al., 2019). Regarding the regional distribution of the TR25 change tendency rate in the BTH from 1961 to 2018 (Figure 3e), the number of TR25 in the central and southern BTH significantly increased, and the centre was Tianjin, where Tianjin Downtown and Tianjin Xiqing increased to 4.46d/10a and 3.95d/10a, respectively. However, the increase in the number of hot nights in the north was relatively small. The change trend of the TR25 is quite different from the SU35 in southern BTH. Previous studies over North China show...
that urbanization effect on maximum-related temperature indices is generally much weaker than that on minimum-related indices (Si et al., 2014; Wang et al., 2013). It could be because urbanization weakened the irrigation cooling effect on TR25 in southern BTH.

Significant positive trends in the frequencies of heatwaves prevailed in most of China (Su et al., 2016; J. Y. Zhang & Cheng, 2020). From 1961 to 2018, the HWDI of the BTH increased by 0.56 per day every 10 years. Similar to the changes of the SU35 and TR25, the HWDI frequently exceeded 6 days after 1995 (Figure

**FIGURE 6** The $T_{in} - T_{r}$ of TXx, TNx, SU35 and TR25 in 13 cities of the BTH (red solid triangle represents significantly positive difference between urban and rural; blue solid triangle represents significantly negative difference between urban and rural at level 0.05). BTH, Beijing–Tianjin–Hebei region; TNx, maximum daily minimum temperature; TR25, hot night days; TXx, maximum daily maximum temperature; SU35, high-temperature days
4). The HWDI in 2010s was 2.1 times higher than that in 1980s of the last century (Table 2).

The regional distribution of its change rate showed that Beijing and Tianjin had the most significant increase in the HWDI (Figure 3f). Among them, Beijing Tongzhou, Tianjin Xiqing and Beijing Changping had the largest increases, reaching 1.54d/10a, 1.49d/10a and 1.35d/10a, respectively, while the regional HWDI change rate was 0.56d/10a. Shijiazhuang also experienced a significant increase, especially when it was compared with the region located in the same latitude. The HWDI in the southern part of the region decreased.

### 3.2 Urbanization effect on high temperature

The increase of extreme high-temperature event is related to the city size and spatial structure (B. Stone et al., 2010). In order to analyse the urbanization effect on high temperature, we calculated the $T_{u} - T_{r}$ of each extreme high-temperature index from 1961 to 2018 in 13 cities of the BTH, respectively (Figure 6). It clearly indicates the difference of each extreme high-temperature index change between urban and rural areas in different city sizes. The increasing tendency of the TXx, TNx, SU35 and TR25 in the urban area of megacities such as Beijing, Tianjin and Shijiazhuang was obviously greater than that in the rural area. Among them, the urban–rural differences of increasing rate in Beijing were the most significant ($p < 0.01$) with 0.28°C/10a, 0.23°C/10a, 1.17d/10a and 1.01d/10a, respectively. The mean contribution of urbanization to those indices was 68%, 45% and 27% in Beijing, Tianjin and Shijiazhuang, respectively. But urbanization on these extreme high-temperature indices in medium-sized cities tended to have relatively small and no consistent effect. Especially, urbanization in medium cities of southern BTH tended to have a negative effect on SU35. It is because the significant difference of urbanization effect between large and medium-size cities lay in the daily maximum temperature (N. Zhao et al., 2019).

By comparing the magnitudes of extreme high-temperature index change in the downtown area of 13 cities (Table 3), the change tendency of the TXx, TNx, SU35 and TR25 in the Beijing and Tianjin downtown areas was the most significant ($p < 0.01$), of which TXx ranked first in Beijing downtown, TNx and TR25 ranked first in Tianjin downtown. The change tendency of TNx, SU35 and TR25 in the Shijiazhuang downtown area was also more prominent in 13 downtown areas ($p < 0.01$). The city of Tangshan, which is close to Beijing and Tianjin, also had larger increases in the TXx, TNx and TR25 ($p < 0.01$). Meanwhile, there were differences in the changes in the extreme high-temperature indices in different downtown areas of other medium cities. In addition to the effects of climate change and urbanization, the local atmospheric circulation and local urban climate background, which were determined by the special geographical locations of the cities, also affected the variation of their extreme high temperatures. Thus, the mechanism of the extreme high-temperature changes in the cities still needs to be further studied.

| City      | TXx (°C/10a) | TNx (°C/10a) | SU35 (d/10a) | TR25 (d/10a) |
|-----------|--------------|--------------|--------------|--------------|
| Beijing   | 0.36**       | 0.36**       | 1.98**       | 1.38**       |
| Tianjin   | 0.32**       | 0.57**       | 1.87**       | 4.21**       |
| Shijiazhuang | 0.11       | 0.42**       | 1.91**       | 2.63**       |
| Tianjin Xiqing | 0.24**     | 0.50**       | 0.50         | 1.42**       |
| Beijing Changping | 0.07     | 0.41**       | 0.20         | 1.22**       |
| Baoding   | 0.04         | 0.32**       | 0.19         | 0.28         |
| Cangzhou  | −0.03        | 0.31**       | 2.92**       | 2.61**       |
| Xingtai   | 0.09         | 0.42**       | −0.90        | 1.50**       |
| Chengde   | 0.19*        | 0.15**       | 0.06         | 0.03         |
| Zhangjiakou | 0.24**     | 0.39**       | 0.16         | 0.04         |
| Langfang  | 0.15         | 0.46**       | 0.53         | 1.21**       |
| Hengshui  | −0.12        | 0.21**       | 0.57         | 1.65**       |
| Qinhuangdao | 0.27**    | 0.47**       | 0.36         | 0.25**       |

Abbreviations: TNx, maximum daily minimum temperature; TR25, hot night days; TXx, maximum daily maximum temperature; SU35, high-temperature days.

* $p < 0.05$; ** $p < 0.01$.  

TABLE 3 The change tendency of the extreme high-temperature indices in the downtown area of 13 cities in the BTH
A recent study revealed the economic scale, population, power consumption and the number of vehicles were positively correlated with UHI in the BTH (Y. H. Liu et al., 2017). In order to identify the UHI contribution to high-temperature indices, the $T_{u}-T_{r}$ was used to remove the long-term change trend of global warming in the study. We calculated the correlation coefficients among $T_{u}-T_{r}$ and the social-economic indicators, which can describe the development level of urban clusters after the 1980s. During the last four decades, the social-economy of the BTH developed very fast. From 2011 to 2018, regional GDP, POP, BA, VP and IA increased by 55 times, 44%, 181%, 31 times and 4 times, respectively, in comparison with the 1980s (Table 2). As seen in Table 4, from 1981 to 2018, the TR25 had the highest positive correlation with all social-economic indicators, where most of them passed the 0.01 confidence test. The SU35 and HWDI were significantly and positively correlated with the GDP, POP, VP and IA. Both the TXx and TNx were also positively correlated with social-economic indicators, while the DTR was negatively correlated with them, but failed in the confidence test. The result further indicates that the extreme high-temperature index changes in the BTH cluster were closely related to urban development.

## Discussion and Conclusions

### 4.1 Discussion

The special geographical location, climate background and rapid urbanization of the BTH have made the region warm faster (Qin et al., 2015; Yan et al., 2020). Our results show the change magnitudes of the most extreme high-temperature indices in the BTH are higher than those of the national average (Y. Q. Zhou & Ren, 2014). Compared with the Yangtze River Delta and the Pearl River Delta, the changing rates of TNx, TR25 and DTR are the most significant, but the increasing rates of TXx and SU35 are less than those of the Yangtze River Delta (Nie et al., 2011; Tang et al., 2005; K. Wu & Yang, 2013; X. Yang et al., 2017; N. Zhao et al., 2019).

Previous studies over North China show that urbanization effect on maximum-related temperature indices is generally much weaker than that on minimum-related indices (Si et al., 2014; Wang et al., 2013; X. Yang et al., 2017; X. Zhang, Alexander, et al., 2011b; Zhao et al., 2019). Our results confirm the increasing magnitudes of Tmin, TNx and TR25 much more exceeded that of the Tmax, TXx and SU35. It might have been more significantly related to the UHI effect at night in the BTH. We also found that urbanization had a great impact on the maximum temperature in Beijing in the last 10 years, which was inconsistent with a previous study (Wang et al., 2013). It may be because our study used the latest observation data, which represent the effect of recent faster urbanization. The extreme high-temperature indices reached their decadal maximum values in the 21st century without a warming hiatus after 1998. It may be related to the rapid development of BTH after the successful bid for the 2008 Beijing Olympic Games. Zhang et al. (2015) also indicated that the urban annual high-temperature days were significantly increasing in each area of the BTH after 1997. Compared with the cities that have been in a relatively stable state, the trend of extreme high-temperature increase is more significant in cities with rapid development stage (Sen & Yuan, 2009). Furthermore, the study firstly revealed that the high-temperature event started earlier and ended
later, and the high-temperature season has been getting longer in the BTH. Therefore, our study strongly encourages the implementation of mitigation and adaptation strategies in order to combat the adverse effect of urbanization.

Mishra and Lettenmaier (2011) pointed out that the change of extreme temperature index related to minimum temperature is mainly affected by climate change, while the change of index related to maximum temperature is more closely related to urbanization. The UHI effect caused by rapid urbanization increased the frequency of extreme high-temperature events in summer (Sun et al., 2014), and the number of days of high temperature in urban sites was slightly higher than that in non-urban sites (Mishra et al., 2015). Our study indicates that the urban–rural differences of increasing rate of the TXx, TNx, SU35, TR25 and HWDI in megacities such as Beijing, Tianjin and Shijiazhuang were very significant. It means that carefully managing local population density, city size and reducing energy consumption can effectively alleviate the UHI effect and slow down the high-temperature events in the BTH. This could provide a reference for the coordinated development of the BTH in the future.

Starting from the sixth assessment report, the Intergovernmental Committee on Climate Change (IPCC) will pay more attention to regional climate change issues, especially to the climate change and urban sustainable development issues (Zhai et al., 2018). Under the business-as-usual scenario of greenhouse gas emissions, North China Plain is likely to experience deadly heatwaves (Kang & Eltahir, 2018). Unlike previous studies, it is found the spatial distributions of change tendency of those high-temperature indices in the BTH are quite different. Especially, TXx and SU35 showed decreasing trends in southern BTH. It is possibly related to the irrigation cooling effect (Tong et al., 2020). Extreme high temperature in urban agglomerations is the result of climate change, urbanization, local climate and atmospheric circulation, and the mechanism is more complex. Numerical simulation is an effective way for explaining extreme high-temperature changes (F. Chen et al., 2014; Grossman-Clarke et al., 2010; D. Li & Bou-Zeid, 2013; N. Zhang, Zhu, & Zhu, 2011a). Next, we need to use the regional climate model coupled with the urban canopy model to conduct a collective simulation of the extreme high temperature in the BTH so as to reveal the physical mechanism of its change. Thus, further research regarding the risks and countermeasures of the extreme high temperature in the BTH in the future could provide scientific support for the sustainable development of this region.

4.2 | Conclusions

This study examined the spatiotemporal characteristics of six extreme high-temperature indices in the Beijing–Tianjin–Hebei region (BTH) urban agglomeration, and it revealed the urbanization impact on the extreme high-temperature changes. The major conclusions are as follows:

1. The maximum daily maximum temperature (TXx), maximum daily minimum temperature (TNx), high-temperature days (SU35), hot night days (TR25) and heatwave spell durations (HWDI) showed an increasing trend at rates of 0.12°C/10a, 0.37°C/10a, 0.9d/10a, 1.49d/10a and 0.56d/10a, respectively during the last 60 years in the BTH. Especially, they still significantly changed after 1998 without a warming hiatus. The SU35, TR25 and HWDI in 2010s reached the decadal highest, which were 68%, 2.8 times and 2.1 times higher than that in 1980s, respectively. Moreover, the high-temperature season in the BTH has been getting longer at the rate of 7.4d/10a since 1961.

2. Urbanization had a significant impact on high-temperature extremes in the BTH. The increasing tendency of the TXx, TNx, SU35, TR25 and HWDI in the urban areas of megacities was significantly greater than that in the rural areas. The megacities also exhibited their effect on their surrounding areas. The mean contribution of urbanization to those indices was 68%, 45% and 27% in Beijing, Tianjin and Shijiazhuang, respectively.

3. The contribution of urbanization on high-temperature indices depends on city size and location. The change magnitudes of these indices in the downtown area of Beijing, Tianjin and Shijiazhuang ranked top in the 13 cities of the BTH. Especially, the increasing rates in Beijing downtown area were about twice than that in the rural area. The urbanization effects on TR25, SU35 and HWDI had significant and positive correlations with social-economic indicators, especially for TR25.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (42075023). Many thanks to Dr Qufeng Liu, who helped draw the figures. We thank Editor-in-Chief, Associate Editor and two anonymous reviewers who all made very valuable suggestions for improvement of this manuscript.

AUTHOR CONTRIBUTIONS

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**How to cite this article:** Wang, Y., Ren, Y., Song, L., & Xiang, Y. (2021). Responses of extreme high temperatures to urbanization in the Beijing–Tianjin–Hebei urban agglomeration in the context of a changing climate. *Meteorological Applications*, 28(5), e2024. [https://doi.org/10.1002/met.2024](https://doi.org/10.1002/met.2024)