Characteristics and main influence factors of heat waves in Beijing–Tianjin–Shijiazhuang cities of northern China in recent 50 years

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Abstract
Heat wave is serious natural disaster that can harm human health and affect social economy, transportation and ecological environment. This paper investigates the long term trends of high temperature events in three major cities (Beijing, Tianjin and Shijiazhuang) of northern China during 1970–2019, and quantifies the contributions of main influencing factors to the variability of high temperature days. High temperature events in Beijing–Tianjin–Shijiazhuang cities mainly occur from June to July and account for 60–65% of the annual total, showing a significant upward trend in the interannual change. There is a trend of high temperature events starting early and ending late in recent 50 years, and this trend is intensified by the increasing urbanization. Due to geographical location and city scale, the frequency and intensity of high temperature events show difference among Beijing, Tianjin and Shijiazhuang cities. Variance analysis shows that climate warming contributes 20.2–25.5% to the variability of high temperature days, while urban heat island accounts for 14.7–24.2%, equal to the sum of the contributions from atmospheric circulation and solar activity.

KEYWORDS
climate warming, frequency, heat waves, intensity, urban heat island, variance analysis

1 INTRODUCTION
Since the beginning of the 21st century, heat waves have frequently occurred across the globe. China Climate Bulletin reports that in the summer of 2019, the high temperature days in most parts of China are 3.1 days more than usual (www.ncc-cma.net). During the same period, temperatures in many parts of Europe are unusual and exceed 40°C, and temperatures in parts of South Asia and the Middle East frequently go above 50°C. Heat waves not only harm human health but also have significant negative impact on social economy, transportation, and ecological environment (Wagner, 1999; Andereas et al., 2004; Wang et al., 2019). According to the report of the World Meteorological Organization, people affected by heat waves globally increases with 126 million from 2000 to 2016. The 2003 heat wave in Europe kills more than 70,000 people (Robine et al., 2008). There are at least 5,758 heat-wave-related illnesses reported in China in 2013 alone (Gu et al., 2016). From the perspective of disaster
prevention and mitigation, heat waves have long been one of the hot topics in urban meteorology research and climate change field (Black et al., 2015; Dong et al., 2016).

China is sensitive and susceptible to climate change. Since the middle of the 20th century, the intensity and frequency of extreme heats in China increase significantly (Wang et al., 2015; Qian, 2016; Hu et al., 2017; Cheng et al., 2019; Li et al., 2020). A number of factors have caused this growth trend, including human-induced reasons, multiyear variability and local urbanization of economic communities (Qian, 2016; Xia et al., 2016; Ma et al., 2017). For example, a positive feedback between the warming effect of urbanization and high temperature weather is reported as the main cause of high temperature events in Beijing–Tianjin–Shijiazhuang. According to Zhang (2019). Small-scale circulation can also affect extreme high temperatures (Na et al., 2019).

The circum-Beijing metropolitan region has been one of the fastest growing regions in the world over the last 30 years. It is of great importance in China’s development plan. There is little knowledge about the long-lasting heat wave events in the region, and few studies on quantitatively describing the contributions of main influence factors to heat waves. This study investigates the long-term change patterns and urban–rural differences of heat wave events in Beijing–Tianjin–Shijiazhuang cities, and explores to quantitatively describe the effects of regional climate warming and urban heat islands on urban heat waves.

2 | DATA AND METHODS

Urban development data including the urban population and the urban built-up area are from the National Statistical Yearbook (www.stats.gov.cn) and the Urban Construction Yearbook (www.mohurd.gov.cn). The temperature data comes from the normalized temperature data set (1970–2015) published by the China National Meteorological Information Center and temperature observations at stations during 2016–2019. These data are subjected to strict quality control and normalized. This study focuses on the three urban stations of Beijing, Tianjin and Shijiazhuang. According to Wang et al. (2013) and Bian et al. (2017), three or four rural stations are selected around each urban station based on a station selection plan that integrated the population, night light index, and land use data by remote sensing. Thus, 3 urban stations and 11 rural stations are used in this study. The basic information about the stations is shown in Table 1 and the distribution of the stations is presented in Figure 1.

Heat wave event in different regions is usually described according to different standards (You et al., 2017), but the main factors considered are the same, that is, first, the temperature is high, and then it needs to be maintained for a period of time. According to Huang et al. (2011), it is not a good choice to apply the same high temperature threshold to different regions due to the difference of geographical location. Russo et al. (2014) propose a new definition of a heat wave event, which can effectively characterize the duration and intensity of a heat wave event; especially it is comparable between different geographic environments and climate types. This definition has been adopted by

| Station name | Borough | Location | Elevation (m) | Population density (person·km^2) | Station type |
|--------------|---------|----------|---------------|----------------------------------|-------------|
| Beijing (BJ) | Beijing | 116.28°E, 39.92’N | 54.7 | 23,407 | Urban |
| Huairou (HR) | Beijing | 116.63’E, 40.32’N | 60.6 | 179 | Rural |
| Pinggu (PG) | Beijing | 117.10’E, 40.15’N | 29.4 | 445 | Rural |
| Miyun (MY) | Beijing | 116.87’E, 40.38’N | 73.1 | 214 | Rural |
| Fangshan (FS) | Beijing | 116.00’E, 39.70’N | 48.9 | 521 | Rural |
| Tianjin (TJ) | Tianjin | 117.20’E, 39.07’N | 3.8 | 23,905 | Urban |
| Wuqing (WQ) | Tianjin | 117.10’E, 39.40’N | 7.4 | 509 | Rural |
| Beichen (BC) | Tianjin | 117.12’E, 39.22’N | 5.2 | 711 | Rural |
| Jinghai (JH) | Tianjin | 116.92’E, 38.92’N | 6.5 | 438 | Rural |
| Shijiazhuang (SIZ) | HeBei | 114.42’E, 38.03’N | 81.0 | 10,946 | Urban |
| Gaocheng (GC) | HeBei | 114.81’E, 38.01’N | 53.5 | 927 | Rural |
| Yuanshi (YS) | HeBei | 114.53’E, 37.75’N | 66.4 | 621 | Rural |
| Pingshan (PS) | HeBei | 114.02’E, 38.25’N | 131.0 | 546 | Rural |
| Xingle (XL) | HeBei | 114.68’E, 38.35’N | 70.8 | 929 | Rural |
several research institutions (Ceccherini et al., 2015; Forzieri et al., 2016). Therefore, this paper refers to this method, and the definition is described as follows.

Daily high temperature threshold: for a given day \(d\), if the 90th percentile of the highest temperatures between \(d - 15\) and \(d + 15\) during the research period of 1970–2019 (a total of \(31 \times 50\) days) is above 33.5°C, it is defined as the daily high temperature threshold (Huang et al., 2011).

High temperature day: when the maximum temperature on a day is higher than the daily high temperature threshold, it is defined as a high temperature day.

Heat wave event: three consecutive days with the maximum temperature exceeding the daily high temperature threshold are recorded as a heat wave event. Similarly, if the maximum temperatures of 4 days in a row exceed the daily high temperature threshold, these 4 days are recorded as two heat wave events.

Heat wave magnitude index (HWMI): the sum of the maximum temperatures of 3 days for each heat wave event is calculated, and the results are normalized to a value between 0 and 1 for each heat wave event. This value is defined as the heat wave magnitude index.

3 | RESULTS AND ANALYSIS

3.1 | Urbanization

The urbanization indices of Beijing, Tianjin and Shijiazhuang cities are presented in Figure 2. It can be seen that Beijing is the largest city with the highest level of urbanization, followed by Tianjin, and then Shijiazhuang. In 2018, the urban built-up areas of Beijing, Tianjin and Shijiazhuang are 1,485, 1,103 and 291.8 km², respectively, and the corresponding urbanization rates are 86.5, 83.2 and 63.2%. From 1980 to 2000, the urbanization rate of Beijing increases by 5.6% every 10 years, while during 2001–2018 Beijing's urbanization rate accelerates significantly with an increasing of 9.8% every 10 years. Both Tianjin and Shijiazhuang show a rapid urbanization rate than Beijing during the same period (2001–2018), with an increasing rate of 15.3% and 17% every 10 years, respectively. According to the Shijiazhuang Urban Space Development Plan (www.sjzghj.gov.cn), Shijiazhuang's urban built-up area will increase to 755 km² and the urbanization rate will reach 91.5% by 2030. This means that the urbanization development of Shijiazhuang will be rapid in the next 12 years and may have a significant impact on the surrounding environment.

3.2 | Trend of high temperature days

Shijiazhuang has a significant higher value for daily high temperature threshold than Beijing and Tianjin, and the difference can reach 1.5–2°C in June and July. The high temperature threshold in the coastal city of Tianjin is lower than that of Beijing. In recent 50 years, the high temperature day in urban area starts at April 4 and ends at October 1, with a span of 6 months (Table 2). Shijiazhuang's high temperature day starts earlier than Beijing while Beijing earlier than Tianjin, but the end of high temperature day is the opposite. In recent 50 years, the average number of annual high temperature days in Beijing, Tianjin and Shijiazhuang is 10.5, 11.1 and 12.2 days, respectively. There is 60–65% of the total during June to July and about 20% in August. The highest probability of high temperature days occurs in late July, accounting for about 13%. Additionally, the high temperature day in rural area starts later and ends earlier than that in urban area.

The number of annual high temperature days in Beijing (BJ), Tianjin (TJ) and Shijiazhuang (SJZ) presents a significant upward trend (Figure 3a), with an average annual increase of 2.3–2.9% (growth rate: Beijing > Tianjin > Shijiazhuang). There is mostly a negative anomaly before the mid-1990s, and few high temperature days appear. After that, the number of high temperature days increase significantly and is currently in a strong positive anomaly period. The Mann–Kendall (MK) test on the sequence of high temperature days in Beijing reveals that the number of high temperature days has been increasing significantly since 1970 (Figure 3b).
significance level ($U_{0.001} = 2.56$) in the early 2000s. The intersection of the UF and UB curves in Figure 3b indicates that the number of high temperature events in Beijing abruptly increases in 1995 (similar results in Tianjin and Shijiazhuang). This time point is consistent with the mutation point of climate warming in Beijing (Zheng et al., 2011). According to You et al. (2011) and Shen et al. (2018), this phenomenon may be related to the combined effect of multiple signals including Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO), because PDO index also has a significant mutation in the same period. The mechanism of mutation in this period still needs to be further studied. Moreover, there is a trend of high temperature events starting early and ending late in recent 50 years, with an average advance (delay) of 3.8 (6.2) days for every 10 years (Figure 3c).

### 3.3 Heat wave frequency and HWMI

There is a strong consistency between the heat wave frequency and the number of high temperature days. In the years with more high temperature days, there are more heat wave events, and vice versa. In recent 50 years, the average annual heat wave frequencies in Beijing, Tianjin and Shijiazhuang are 2.28, 1.78 and 2.67, respectively (Figure 4). Before the mid-1990s, the heat wave events occur less frequently, and after that, there is an obvious jump process. From 1970 to 1995, the numbers of average annual heat wave events in Beijing, Tianjin and Shijiazhuang are 0.27, 0.34 and 0.88, respectively, and only 4 in extreme years (Shijiazhuang, 1987). However, from 1996 to 2019, these numbers in the three cities reach 4.45, 3.33 and 4.58, respectively, with an increase of 5–15 times. In some years, there are more than 10 heat wave events, such as 14 in 1999 and 13 in 2000 for Beijing. The heat wave frequency of urban stations is generally higher than that of rural stations. In the big scale cities of Beijing and Tianjin, there are only a few years when the difference of heat wave frequency between urban and rural stations is negative, yet in the small scale city of Shijiazhuang, such years become more. Moreover, in the year when the difference of heat wave frequency between urban and rural stations is negative, the frequency of heat wave events at urban stations is small, implying that this phenomenon mostly occurs in the years with less high temperature days. In recent 50 years, the average annual HWMI of Beijing, Tianjin and Shijiazhuang are 1.86, 1.45 and 2.10, respectively, and there are also obvious changes from small to large in the mid-1990s.

It is also found in Figure 4 that the number of average annual high temperature days in recent 50 years is ranked as Shijiazhuang > Tianjin > Beijing. Cities with low latitude are more likely to have high temperature events. The growth rate of high temperature events is ranked as Beijing > Tianjin > Shijiazhuang, indicating a close relationship with the city scale. Moreover, the annual heat wave frequency and HWMI are ranked as Shijiazhuang > Beijing > Tianjin, and their growth rates are ranked as Beijing > Shijiazhuang > Tianjin. Note

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**TABLE 2** The starting and ending times of high temperature day in Beijing, Tianjin and Shijiazhuang urban and rural stations in recent 50 years

| Station type           | Starting time | Ending time |
|------------------------|---------------|-------------|
| Beijing (urban/rural)  | Apr 29/May 2  | Sep 18/Sep 16 |
| Tianjin (urban/rural)  | Apr 30/May 4  | Sep 11/Sep 10 |
| Shijiazhuang (urban/rural) | Apr 4/Apr 15 | Oct 1/Sep 23 |
that the heat wave events in Beijing are more and the growth rate is faster than that in Tianjin, this is different from the distribution of high temperature days, and may be related to Tianjin being a coastal city.

4 | DISCUSSION

This paper analyzes the distribution patterns of heat waves in Beijing, Tianjin and Shijiazhuang cities of northern China in recent 50 years. On the whole, the trend of heat waves in these cities is consistent with that in other parts of China (You et al., 2011; Luo and Lau, 2017; Cheng et al., 2019). However, there are still differences in details. The increasing trend of annual high temperature days and heat wave frequency in Beijing, Tianjin and Shijiazhuang is stronger than that in the Pearl River Delta region, showing the local characteristics of such small probability events.

Regional climate warming is likely to be the main reason for the increasing frequency of high temperature
events. The warmest 24 years in China since the observation records appear in the latest 25 years (Li et al., 2020). This significant warming will undoubtedly affect heat wave events. As shown in Figure 5, the average annual temperature in Beijing is positively related with the annual maximum temperature and the number of high temperature days, with the correlation coefficients of 0.540 and 0.579, respectively, indicating the important influence of climate warming on local heat wave events.

Moreover, heat wave events are found to be associated with atmospheric circulation anomalies (Luo and Lau, 2017, 2018; Chen et al., 2019; Xu et al., 2019). Furthermore, urbanization can lead to changes in the increase of surface temperature (Tysa et al., 2019). There is a positive feedback relationship between urbanization warming effect and high temperature weather (Liu et al., 2018; He et al., 2019). Therefore, it is of great significance to quantify the contribution of urbanization factors (Wang et al., 2018). However, it is very skillful to choose which way to use. The simple urban–rural comparison method excessively depends on the station selection. For example, in a study of heat wave events in the Pearl River Delta of southern China, Luo and Lau (2017) think that the contribution of urbanization on heat wave

**FIGURE 4** Interannual variations of heat wave frequency and heat wave magnitude index in recent 50 years in (a) Beijing, (b) Tianjin and (c) Shijiazhuang urban and rural stations.
frequency is close to 50%, while Cheng et al. (2019) suggest that the urbanization impact is not obvious.

As a small probability event, high temperature weather has a large interannual variability and a variety of influencing factors. It is very difficult to exhaust all the influencing factors, and studies on the attribution to heat waves usually focus on single case (Luo and Lau, 2017; Chen et al., 2019). Therefore, this study also tries to quantify the relative contributions of several common influencing factors to the variability of high temperature days. Forbes et al. (2000) designed a multiple linear regression analysis to assess to what degree the observed variability may be attributed to various sources. This method is adopted here to quantify the relative contributions of several factors that mentioned in previous studies, such as climate warming, atmospheric circulation anomaly, urbanization effect and solar activity. Taking Beijing as an example, the following multiple linear regression equation is established with the observation data since 1970.

\[
Y = -34.4361 + 4.7340X_1 + 0.0309X_2 - 0.1101X_3 - 14.0175X_4,
\]

where \(Y\) is the number of high temperature days, \(X_1\) is the annual average temperature, representing the background of climate warming, \(X_2\) is the subtropical high pressure ridge point index of western Pacific in summer, representing the influencing factor of large-scale circulation (Luo and Lau, 2017; Xu et al., 2019), \(X_3\) is the F10.7 index, indicating the intensity of solar activity (data from China National Climate Center), and \(X_4\) is the intensity of urban heat island in Beijing, representing the impact of urbanization. These \(X_s\) represent several main factors influencing high temperature days. The multiple correlation coefficient of the above regression equation is 0.672 at a confidence level large than 0.99, indicating that the interannual variation of high temperature days can be well fitted. After establishing Equation (1), the normalized standard deviation (n.s.d.) of the time series is calculated as follows according to the method of Forbes et al. (2000).

\[
n.s.d. = \sqrt{\text{var}(Y)} / \bar{Y},
\]

where \(\text{var}(Y)\) is the variance of all available \(Y\), and the overbar on \(Y\) refers to the mean value of all available \(Y\). Then, the \(X_1\) in Equation (1) is removed and the n.s.d. is calculated again. The \(X_2\) and \(X_3\) are similarly removed, and the changes in n.s.d. are noted. At the end, when all these factors are removed, the n.s.d. is calculated again. Thus, the differences between these n.s.d. values can provide some measure of the \(Y\) (high temperature days) variability due to the \(X_1, X_2, X_3\) and \(X_4\). The results show that these four factors can explain 51.3% of the variability of high temperature days, and the other 48.7% of the variability is contributed by those influencing factors not included in the Equation (1). Among the 51.3% contribution, climate warming factor contributes 22.5%, followed by urban heat island factor, which contributes 14.7%, and this number is approximately the sum of the contributions of atmospheric circulation factor (9.4%) and solar activity factor (4.7%). It is clear that the urban heat island effect cannot be ignored.

The n.s.d. analysis results of Tianjin and Shijiazhuang are similar to that of Beijing. Figure 6 presents the
contributions of main influencing factors on the variability of high temperature days in these three cities. During 1970–2019, climate warming contributes 20.2–25.5%, while urbanization contributes 14.7–24.2%, and the contributions of atmospheric circulation and solar activity are 8.5–13.2% and 3.5–8.7%, respectively. These results show that the above four factors can explain 49.1–51.3% of the variability of high temperature days, and climate warming and urbanization are the two main contribution sources. However, there is 48.7–50.9% of the variability of high temperature days contributed by those influencing factors not included in the Equation (1).

Aerosol can influence climate and also has an impact on heat wave events (Ma et al., 2018; Persad and Caldeira, 2018; Luo et al., 2019). Due to the short history of aerosol observation in China, aerosol is not considered as a factor in Equation (1), but it does not mean that aerosol is not important. Figure 7 shows the observation data of a heat wave in Beijing on June 11–20, 2017. During this period, the urban heat island intensity (UHI) on the average temperature remains positive and increases with the increase of PM2.5 concentration, but the UHI on the maximum temperature clearly weakens and even shows negative values. This phenomenon is related to the effects of aerosol absorption and scattering radiation (Yang et al., 2020). Obviously, the PM2.5 concentration and UHI on the maximum temperature show a quasi-opposite trend, implying that the high PM2.5 concentration may restrain the development of the daily maximum temperature. As a result, some weather processes that may develop into high temperature days fail to meet the high temperature threshold because of aerosol pollution. According to Zheng et al. (2019), the number of haze days in summer in Beijing presents an increasing trend in recent decades. This means that some high temperature days may be restrained by atmospheric pollution. If the repression effect of atmospheric pollution is not existed, heat wave events may be more frequent and stronger.

5 | CONCLUSIONS

This paper analyzes the distribution characteristics and change trend of heat wave events in three major cities of Beijing, Tianjin and Shijiazhuang in northern China during 1970–2019, and quantifies the contributions of some
influencing factors to the variability of high temperature days. The conclusions are drawn as follows.

High temperature events in Beijing–Tianjin–Shijiazhuang cities mainly occur from June to July, accounting for 60–65% of the annual total. The number of high temperature days increases significantly with a mutation in 1995. Moreover, there is a trend of high temperature events starting early and ending late in recent 50 years, and urbanization effect reinforces this trend.

Due to geographical location and city scale, the number of average annual high temperature days in recent 50 years is ranked as Shijiazhuang > Tianjin > Beijing, and the growth rate is ranked as Beijing > Tianjin > Shijiazhuang. The average annual heat wave frequency and HWMI are ranked as Shijiazhuang > Beijing > Tianjin, while the growth rate is ranked as Beijing > Shijiazhuang > Tianjin.

The normalized variance analysis shows that climate warming contributes the most to the variability of high temperature days in Beijing–Tianjin–Shijiazhuang cities (20.2–25.5%), followed by urban heat island effect (14.7–24.2%), which is approximately the sum of the contributions of atmospheric circulation (8.5–13.2%) and solar activity (3.5–8.7%).

ACKNOWLEDGEMENTS
This study is supported by Beijing Natural Science Foundation (8202022, 8171002), the National Natural Science Foundation of China (41575010).

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