Population exposure to large-scale heatwaves in China for 1961-2015

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Abstract. According to the observed daily maximum temperature data from 756 climate stations in China during 1961–2015, the frequency, intensity, impacted area, and population exposure of the large scale heatwaves (HWs) are calculated by the Intensity-Area-Duration method. During 1961–2015, averagely 24.6 HWs happened every year with an average intensity of 34.4°C, impacting 4.71 million km², around 49.1% of the territory of China. In 2000s, the HW frequency and impacted area have increased by 1.5 times and the intensity has increased by 0.3°C. The largest population exposure is in Central China. There are three stable high value centers of population exposure in China: Northwest China, Central China and North China. The northwest high-value-center is almost stable and isolated. As the north and central high-value-centers are becoming larger, they are likely to merge into one. In 2013, the abnormally strong and stable western Pacific subtropical high and the equally stable Qinghai-Tibet high are the main reasons for the severest HWs in the middle and lower reaches of the Yangtze River. Moreover, North China has started to be invaded by HWs. At the same time, the expansion of the central and north HW centers may involve more populated and developed areas with the threat of HWs. These will affect the social stability, the human health and sustainable development of the national economy.

1. Introduction

Over the recent centuries, the global mean surface temperature has been increasing. During 1986–2005, the global mean surface temperature had risen by more than 0.61°C compared with pre-industrial levels (1850–1900) [1]. As the global temperature increases, so do the number of extreme events and its frequency [2,3]. In the second half of the 20th century, a likely-increasing trend of the heatwave (HW) frequency appeared in Europe, Australia and most parts of Asia. However, the research on Africa and South America in this field is insufficient [1,4-6].

Extreme weather and meteorological events have more serious impacts on the global ecology and community than the mean state of climate change. As the earth gets warmer, HWs may have severe impacts on human health and economic growth. In the United States, HWs are the major cause for human mortality related to weather [7,8]. It results in more deaths than earthquakes, hurricanes, floods, tornadoes, and lightning combined every year [9]. In 2003, the HWs in Western Europe, which were record-breaking, displayed the threat imposed by unusually extreme high temperature in public health. Only in France, there were 14800 deaths caused by HWs in 2003. The death toll across Western Europe was estimated to be over 35000, with the number in England and Wales close to 2000 [10-13].

In the mid-1990s, HWs began to increase significantly in China [14]. Since then, there has been progress in the research on extreme high-temperature. Researchers found that the features of extreme
high-temperature have varied in a complicated way. For most parts of China, the increase of air temperature has been accelerating since the 1980s [15]). The characteristics of HWs are very different in different regions. The HW frequency and intensity have shown a significant increase over the southeastern coast and northern areas of China, especially since the 1990s [14]. However, obvious negative trends were observed in the lower reaches of the Yellow River and the north of the Yangtze River [16]. Overall, significant positive trends of HW frequency prevail in most of China. Domestic and foreign studies on HWs mainly focus on potential variations in HW frequency and magnitude, but seldom consider the exposure and vulnerability of society to HWs [17].

Due to the nature of physical hazards, disaster losses can demonstrate the vulnerability of the society to hazards. Vulnerability itself can be regarded as a function of the exposure and society sensitivity to hazards [17,18]. Evaluating the relative importance of different risk factors and quantifying the uncertainty and its different sources are essential to better plan out the research and inform the HW risk management strategies. Currently, most studies focus on the variations of HW characteristics, while the research on population exposure is rare.

The risk of any single HW is determined by many factors, including its duration and intensity [19]. Current researches of extreme events have evolved from value analyses at a single site [20,21] to related investigations of intensity, impact range, and duration [22,23]. By using the intensity–area–duration (IAD) method [22], developed an approach to identify a regional extreme event and analyze its coverage and duration. Based on the daily precipitation data from 771 stations (1960 - 2015), Jing et al (2016) produced the distribution patterns of variation trend of regional extreme precipitation events in China, and they also discussed the population and economy exposure [23].

This study focuses on systematically quantifying, including not only the characteristics variation in larger scale HWs (frequency, intensity, impacted area and location), but also the population exposure to HWs in different regions of China from 1961 to 2015. The assessment of such variations can provide policy makers with some scientific support in formulating climate change mitigation strategies to deal with potential socio-economic risks.

2. Study area, data and method

2.1. Study area

Ranking the third in territory, China has the higher population than any other countries. If the complex topography, population distribution and the common administration division are taken into account, the country can be divided into seven geographic areas: Northeast China, North China, East China, Central China, South China, Southwest China and Northwest China (figure 1). The variations of population exposure in China based on the seven geographic zones are analyzed in this paper.
2.2. Observed data
The observed daily maximum temperature datasets are issued by the National Meteorological Information Center of the China Meteorological Administration. These datasets for 756 meteorological stations throughout China start from Jan. 1, 1961 and end on Dec. 31, 2015 (figure 1). The missing rate of daily maximum temperature data in these datasets is less than 0.25% annually, thus, the observed data can show the spatio-temporal distribution of the daily maximum temperature in China.

2.3. Population data
Based on the 2nd (1964) to the 6th (2010) National Population Census data and yearly population data (1961-2015) from the National Bureau of Statistics of China (http://www.stats.gov.cn/), the 0.5°×0.5° grid population datasets of China are produced. During 1961–2015, the population rose from 658.6 million to 1374.6 million. Compared with the monotonic growth, the natural population growth rate varied differently. The only negative growth rate appeared in 1961 because of the Great Chinese Famine (1959-1961). During 1962 to 1970, China entered the second population growth peak owing to the upturn in the economy and agriculture. During 1971–1980, the growth rate decreased due to the family planning policy. During 1980–1990, the baby boomers (born during 1961–1970) started to get married and have children, thus a small peak appeared. Since 1990, the growth rate has been gradually stabilized, and Chinese population has reached a steady growth stage (figure 2).
2.4. Methods

2.4.1. Heatwaves indicators. Here are different standards for HWs. In China, if the daily maximum temperature exceeds 35°C for consecutive 3 days or more, it is regarded as a HW [24]. However, the daily maximum temperature of 30°C is selected as the threshold in this paper due to the large area of North China and HWs’ impact on human health [25]. If the HW continues for over 3 consecutive days, and the impacted area is larger than 2.0×10^5 km^2, it is regarded as a large scale HW.

2.4.2. Identification of the large scale heatwaves. In many previous studies, the features of HWs were analyzed at station scale or grid scale [26,27] and they failed to consider the spatio-temporal continuity of HWs. In this study, the HWs are identified by using the IAD method [28,29], which takes high temperature intensity, coverage and duration characteristics (≥3–day) into account. The IAD method has already been used successfully in drought and extreme precipitation analyses in China [22,23,29,30].

The IAD method identifies grids that neighbor the high temperature maximum center, and then clusters the grids with high temperature exceeding 30°C into an event. The coverage is the combination of all grids, and the intensity is the average temperature of all grids in one event, as illustrated in figure 3. For example, figure 3 shows three HWs in the area A. Event a is in blue grids, Event b in red grids and Event c in yellow grids. The IAD curve of Event a (dotted blue line) shows that the impacted area of Event a is 1.0×10^4 km^2, and the intensity is 33.5°C (the average of the four grids) with the maximum intensity of 38°C. Event b impacts 0.75×10^4 km^2, and the intensity is 35.3°C (the average of the three grids) with the maximum intensity of 37°C. Event c impacts 0.5×10^4 km^2, and the intensity is 38.0°C (the average of the three grids) with the maximum intensity of 40°C. Overall, in the area A, 2.25×10^4 km^2 area is invaded by HWs with the intensity of 35.1°C. If the three events occur in one year, the frequency would be three. The highest intensity in a contiguous impacted area is shown by the IAD envelope curve (figure 3, solid black line). The IAD curve can be used to compare HWs of different intensities in different areas, and the IAD envelope curve can identify the highest intensity in each contiguous impacted area for the entire study period. More details about IAD method can be found in Zhai et al [22].
2.4.3. **Mann-Kendall (M-K) test.** To detect the trends of the rainstorm time-series and test the variation significance, the widely-used non-parametric Mann-Kendall (MK) test is applied [31,32]. This method has been widely applied in many fields, including hydrology, meteorological ecology and environment [33-34]. MK statistic (MKs) value indicates the tendency and its significance. A MKs > 1.96 means a significant positive trend, and a MKs< −1.96 represents a significant negative trend, both at the 95% confidence level. In this study, time series with MKs below the 95% confidence level are only considered as tendencies.

3. **Results**

3.1. **Characteristics changes of heatwaves**

Figure 4 illustrates the characteristics (frequency, intensity and impacted area) and abrupt changes of HWs in China. During 1961–2015, averagely 24.6 HWs happened every year, with an average intensity of 34.4°C, impacting 4.71 million km² (around 49.1% of the territory of China). The frequency, intensity and impacted area all had increasing trends and reached its peak at the 2000s (2001-2015, 29.2times/yr, 34.6°C and 5.62 million km²). Both the frequency and impacted area abruptly increased in the middle and late of 1990s (1991-2000), while the intensity increased abruptly in the late 2000s.

Due to the strong El Nino in 1997 (China Meteorological Administration, 1997; Wang et al., 2016), the impacted area was the largest, around 90% of the territory of China (8.64 million km²), while the Tibetan Plateau was not affected. The HW frequency was also the highest (around 41 times). According to the current research and record, the summer of 2013 was the hottest in China because of the abnormal Tibetan high and the western Pacific subtropical high (WPSH) [35,36]. These results are consistent with our findings. The HW intensity reached the peak of 35.6°C this year.
3.2. Changes of spatial distribution of heatwaves

Figure 5 illustrates the spatial distribution of HWs’ decadal frequencies in China from 1961 to 2015. From figure 5, the following results can be observed. First, there are three stable high-value centers in China: Northwest China (Xinjiang Province), Central China (Jiangxi-Hunan-Hubei Province) and North China (Beijing-Hebei-Tianjin). Second, the impacted area in North China has had a marked increase since 1990s, which can support the conclusion of 3.1.

From figure 5, it can be seen that the high-value center of Northwest China is almost stable, both in frequency and impacted area. From the 1960s to the 2000s, the color in the high-value center of Central China deepened, indicating that HWs have become more frequent in this area. The HW frequency in North China was stable from the 1960s to the 2000s, but the center area has become larger. The two centers have tended to merge into one piece since the 1990s. If this tendency continues, there will be a super HW center over Central China and North China where the high density of population and social economy can be found. In the future, HWs may lead to more severe problems.

From figure 5, the impacted area in North China has become larger and has merged into one piece since 1990s. With the increasing temperature, more areas in North China are invaded by the large scale HWs, and the frequency has a slight increase. Until now, there are only two provinces which are not invaded by the large scale HWs: Qinghai Province and Xizang Province, both in the Tibet Plateau.
3.3. Changes of Population exposure to heatwaves

From 1961 to 2015, 4.65 million people had been exposed to HWs every day. The overall trend in the number of people exposed to HWs was increasing in China, reaching the largest in the 2000s (6.57 million/d), which doubled the exposed population in the 1960s (3.10 million/d) (figure 6). From figure 7, the number of people exposed to HWs had a significant increase in the middle of the 1980s and an abrupt change in the 1990s. The population exposure significantly increased in the 1980s for the rapid population growth in that period, as mentioned in Section 2.1.

![Figure 5](image_url)  
**Figure 5.** The spatial distribution of HWs in China, from 1961 to 2015.

![Figure 6](image_url)  
**Figure 6.** The change number of people exposed to HWs from 1961-2015, China.
The number of people exposed to HWs in most parts of China reached the peak in the 2000s, except for the northern parts of China (Northeast, North and Northwest China) which reached the peak in the 1990s. The number of people exposed to HWs every day in Central China is 1.89 million, the largest in all regions. It is followed by East China (around 1.39 million/d) and North China (around 0.66 million/d). Because of the high latitude and low population density, the number of people exposed to HWs in Northeast China is the smallest.

Figure 8 illustrates the contribution rate of each administration zone in China every decade. It can been found that the contribution rate of Central China is the highest (41.3%). The rate of East China (31.0%) ranks the second, and that of North China (14.4%) ranks the third, followed by that of Northeast China (0.8%). There are two main reasons. First, the high-value centers are located in Central China and North China. Second, the three regions are all developed areas of China with high population and economic density. Although there is a high-value center in Northwest China, the low population density in this region leads to the low contribution. For the contribution rate, the northern parts of China (North China, Northeast China and Northwest China) had a greater contribution in the 1990s than in other decades, indicating that even the high-latitude area of China may suffer severe HWs as well.

3.4. Atmospheric circulation pattern in typical year
China suffered the severest HWs in 2013 [23,35,36]. Those extreme conditions might be somehow
related to the variations or shifts in the atmospheric circulation patterns in China. Based on NCEP re-Analysis data, the geopotential height of 500 hPa for the 55-year summer average (1961-2015, June, July and August) and the circulation pattern in summer of 2013 are compared.

Figure 9. The circulation for 1 July to 31 August in 500 hpa. (a): 2013; (b): the average from 1981 to 2010; (c): the 2013 minus the average from 1981 to 2010.

In July and August of 2013, the average surface temperature was more than 2°C to 4°C than the meteorology mean in most areas of the Yangtze River. In most regions east of 105°E and between 25°N to 35°N, the days with maximum temperatures of 35°C or above were 20 days more than the meteorology mean [36,37]. HWs in China are mainly caused by the anomaly of the WPSH. From figure 9(a), it can be seen that the most-western part of the 5880-gpm, almost covering the Zhejiang Province, reached 120°E. And the center of the WPSH was located between 25°N to 35°N. Figure 9(b) shows that the meteorology mean (from 1981 to 2010) of the most-western part of the 5880-gpm reached around 135°E, which means that the WPSH extended almost 15° westward. The abnormally strong subtropical high in East China can be seen in figure 9(c). Unlike other years, there was an obvious Qinghai-Tibet high (QH) in West China. From Figures 9(b) and 9(c), the QH had an obvious eastward extension compared with the meteorology mean (1981-2010). The “face to face” or “back to back” relationship between WPSH and QH means that a westward WPSH tends to be accompanied by an eastward QH, and vice versa [38,39]. It strengthened QH, causing it to expand eastward at 500 hPa. And it strengthened WPSH as well, causing it to expand westward. At 500 hPa, the middle and lower reaches of the Yangtze River was controlled by a strong anomalous anticyclone (figure 10(a)), indicating that the WPSH maintenance was only a part of the anomaly of the high pressure system. The deep anomaly system throughout the troposphere led to the system stable [40]. At the same time, Wei et al. (2016) pointed out that the system configuration of westerlies, mid-high latitude condition and the weaker cold activity from the polar region contributed to the persistent extreme summer
conditions in the middle and lower reaches of the Yangtze River [36].

4. Conclusions and discussions
HWs in China have already changed during the 20th century, and they may make further severe impacts as global warming continues [41-43]. In this study, not only the variations of HWs are evaluated, including the frequency, intensity and impacted area, but also the exposed population in China and its administration zones are calculated. At the same time, 2013 is chosen as a typical year to study how the atmospheric circulation patterns influence HWs in China. The main conclusions are as follows.

First, on the whole, the frequency, intensity and impacted area are gradually growing. And in the perspectives of frequency, intensity and impacted area, China suffered the severest HWs in the 2000s. Specifically, both the frequency and impacted area suddenly increased around the middle and late 1990s. One explanation is that China, except Qinghai-Tibet Plateau, suffered severe HWs, especially in North China because of the super El Nino event in 1997 [44,45]. Unlike the frequency and impacted area, the intensity did not show a significant increase until the late 2000s. Another year with abrupt change is 2013. It is shown that 2013 has been the year with the strongest HW since 1961, and the 2010s may be the decade with the strongest HWs. The findings are consistent with other studies and government statistics [35,36].

Second, the spatial distribution of HWs is analyzed in this study. The stable high-value centers in China are found: Northwest China (Xinjiang Province), Central China (Jiangxi-Hunan-Hubei Province) and North China (Beijing-Hebei-Tianjin). The northwest center is stable and isolated from the 1960s to the 2000s. The HWs in the central center have become more frequent. The areas of the central center and north center have become larger. The trend indicates that the two centers will merge into one super center, which will cover both Central China and North China—the important area with developed economy, dense population and political center [46,47].

Third, since 1961 to 2015, the number of people exposed to HWs in China has been doubled from 3.10 million/d (1960s) to 6.57 million/d (2000s). Central China has the largest exposed population, followed by East China and North China. Northeast China has the smallest number. Most parts of China reached the peak in the 2000s, except in the northern parts of China (Northeast, North and Northwest China) which reached the peak in the 1990s.

Because of the “face to face” or "back to back" effect of the WPSH and QH, the WPSH expanded westward and became more stable in the middle and lower reaches of the Yangtze River in 2013. At the same time, the two formed blocking systems which resisted the cold air moving south. Therefore, the persistent extreme HWs stayed in the middle and lower reaches of the Yangtze River.

Since 1961 to 2015, China has suffered more severe HWs as the HW frequency and intensity are increasing. Moreover, with the temperature increasing, some regions in North China, which had never been invaded by HWs, confronted the invasion. The people and ecological system in these regions may be more fragile and HWs could cause more serious problems. At the same time, the expansion of the Central and North high-value centers may affect more population and cause the developed areas to face the threat of HWs. These consequences will affect social stability, human health and sustainable development of the national economy. Moreover, with the global warming, HWs may become more severe. The study suggests that the government take effective measures to prevent and mitigate the bad effects of HWs. And two important areas deserve more attention: the northern region, which rarely suffered HWs and may be more fragile, and the Central and North high-value centers with a large population density and prosperous economy, which suffered the highest-frequency HWs.

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