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An Abrupt Increase in the Summer High Temperature Extreme Days across China in the mid-1990s

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ABSTRACT

Based on the daily maximum surface air temperature records from an updated homogenized temperature dataset for 549 Chinese stations during 1960–2008, we reveal that there is an abrupt increase in the number of days with high temperature extremes (HTEs, an HTE day is defined when the maximum temperature exceeds the 95th percentile of the daily maximum temperature distributions) across China in the mid-1990s. Before this regime shift, the average number of HTE days is about 2.9 d yr^{-1} during the period from the 1970s to the early 1990s, while it rocketed to about 7.2 d yr^{-1} after the mid-1990s. We show that the significant HTE day increase occurs uniformly across the whole of China after the regime shift. The observational evidence raises the possibility that this change in HTE days is associated with global-scale warming as well as circulation adjustment. Possible causes for the abrupt change in the HTE days are discussed, and the circulation adjustment is suggested to play a crucial role in the increase in HTE days in this region.

Key words: high temperature extremes, hot days, long-term trend, regime shift

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1. Introduction

Under the background of global warming, the high temperature extremes (HTE) have captured the concerns and worries of both officials and the public on a global scale as the record-breaking heat waves scorch almost every continent in the first decade of this century. An increasing trend in the HTE was documented in many regions around the globe in the past half century (Bonsal et al., 2001; DeGaetano and Allen, 2002; Fink et al., 2004; Bartolini et al., 2008). For densely populated East China, however, a slightly decreasing trend in the number of hot days (Tmax over 35°C) was detected by Zhai and Pan (2003b) during the period of 1951–1999. This was confirmed by Su et al. (2006) in the Yangtze River basin despite its minor value. There are also studies claiming an upward trend of frequency and intensity of the high temperature events in the Yellow River basin (Zhang et al., 2008). Meanwhile, some studies (Ma et al., 2003; Zhai and Pan, 2003a; Wei and Chen, 2009) noticed a remarkable increasing trend in the maximum temperature days after 1990 over arid and semi-arid northern China. Studies also revealed that the linear trends of the frequency of high temperature extremes change from one region to the other in China (Gong et al., 2004; Tang et al., 2005; Qian and Qin, 2006). Therefore, the trend variation of HTE in China is still not very clear. In addition, there are some studies on a specific region in China, such as North China (Zhang et al., 2006; Wei and Sun, 2007), East China (Lin and Guan, 2008; Shi et al., 2008), the Tibetan Plateau (You et al., 2008), and Northwest China (Wang and Yang, 2007). The evaluation of the HTE change over the whole of China is lacking and needs to be performed.

On the other hand, some studies found distinctive summer cooling trends in China during the last two decades of the 20th century despite the global warming trend (Hu et al., 2003; Li et al., 2007), which was suggested to be associated with lower stratospheric cooling (Yu et al., 2004) or due to sulfate aerosol forcing (Li et al., 2007). Accordingly, the study of the summer

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high temperature extremes is complicated by the counteraction between global-scale warming and regional-scale cooling. The main motivation for this study is to characterize the HTE variations across China and discuss their associated circulation changes.

2. Data and methodology

Previous homogeneity assessment of Chinese station records (Li et al., 2004b) revealed that station relocation was found at more than 70% of the Chinese stations. Although we can omit the stations with certain and serious relocation problems, the inhomogeneity caused by relocation cannot be avoided due to the lack of complete station metadata, let alone all kinds of undocumented records of station and surrounding environment changes. There are also inevitable homogeneity problems caused by changes to the instrumentation and observing practices. Therefore, adjustments of temperature should be made for the daily temperature observations beforehand. Though it is impossible to completely remove inhomogeneities from climate data, the reliability can be undoubtedly improved through data homogenization for climate change analyses. In this study, the primary dataset employed is an updated homogenized temperature dataset (Li and Yan, 2009) for 549 Chinese stations during 1960–2008. This dataset was developed using the Multiple Analysis of Series for Homogenization (MASH) software package, which can be used to detect all the major breakpoints caused by non-natural changes in the long-time series and, meanwhile, make adjustments to homogenize the whole dataset. It has been suggested that MASH usually performs better than other methods (Lizuma et al., 2008). By comparing the homogenized temperature series with different reference stations, Li and Yan (2009, 2010) showed that the MASH results are robust and can be applied to the whole set of Chinese stations (including the stations on the Tibetan Plateau). As the extreme temperature events that can cause large-scale turmoil occur mainly in the summer season of June, July, and August, we conducted our studies only in the June-August period. In addition, our study uses the gridded monthly mean reanalysis dataset (Kalnay et al., 1996; Kistler et al., 2001) which is obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) for the same time period as the station dataset.

Temperature percentiles are usually used to assess the extreme temperature events. We used the empirical plotting position formula by Bonsal et al. (2001) and adopted the criterion of 95th percentile to define the extremely warm events in this study (the use of 99th and 90th percentile criteria derives similar results, therefore not shown in this paper). For a single station, an HTE day is defined when the maximum temperature (Tmax) in this day is above the 95th percentile, T_{95}. To get this value, the Tmax are firstly ranked into ascending order $T_1, T_2, \ldots, T_N$ for each calendar day during a climatology domain (i.e., from 1971 to 2000 in this study). The probability, P, that a random value is less than or equal to the rank of that value T_m $(m = 1, 2, \ldots, N)$ is estimated by

$$P = (m - 0.31)/(N + 0.38),$$

where $N = 30$.

Therefore, for 30 years of data, the temperature representing the 95th percentile, T_{95}, is linearly interpolated between the 30th-ranked value (corresponding to P=97.7%) and 29th-ranked value (P=94.4%). We calculate the number of HTE days at each station as the cumulative number of HTE days for that station during June–August of each year. The area-averaged number of HTE days over China was also calculated for the period from 1960 to 2008. To get this series, the yearly HTE days data at the 549 stations are firstly interpolated to a $1° \times 1°$ mesh grid using a Cressman objective analysis. Then, the gridded HTE days are averaged over China for every year. Considering the large size of the region analyzed, the interpolated gridded data are weighted by the cosine of latitude to ensure that equal areas are afforded equal weight in the average analysis. The Mann-Kendall technique (Sneyers, 1990) is used to detect any abrupt change in the HTE days across China.

3. An abrupt increase in HTE days

Figure 1a shows the area-averaged number of HTE days in China from 1960 to 2008. Two obvious abrupt changes can be observed, with one in the early 1970s and the other in the mid-1990s. The Mann-Kendall technique is used to check these abrupt changes and confirms the first change point at 1973 and the second one at 1996. During the first period from 1960 to 1972, the average number of HTE days is about 4.9 days, while it is only about 2.9 days from 1973 to 1996. In the most recent regime, from 1997 to 2008, the average number of HTE days is at a much higher level of about 7.2 days, an abrupt increase leading to about 2.5 times of the average HTE days as the previous period across China. Since the mean maximum temperature is an important indicator reflecting the extreme events and the high temperature variability, we also checked the interannual variability of mean maximum temperature in Fig. 1b. An abrupt maximum temperature change

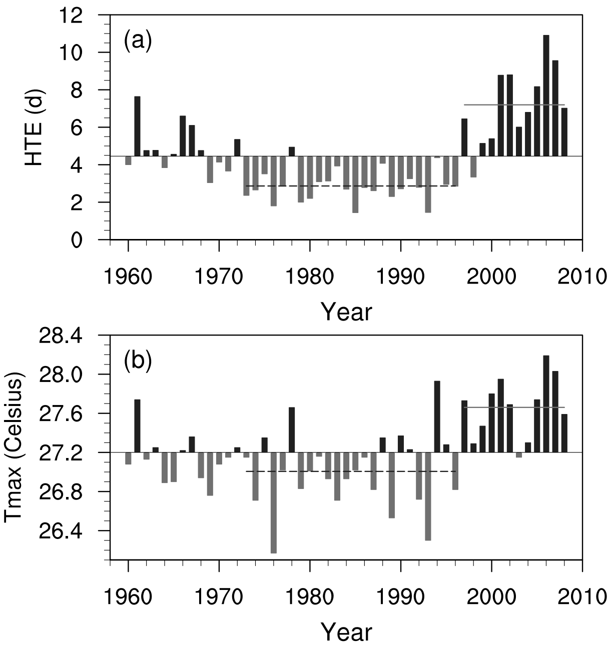

Fig. 1. (a) The number of days with summer high temperature extremes (exceeding the 95th percentile) and (b) the summer (JJA) mean maximum temperature averaged across China. The dashed line indicates the average from 1973 to 1996, and the solid line indicates the average from 1998 to 2008.

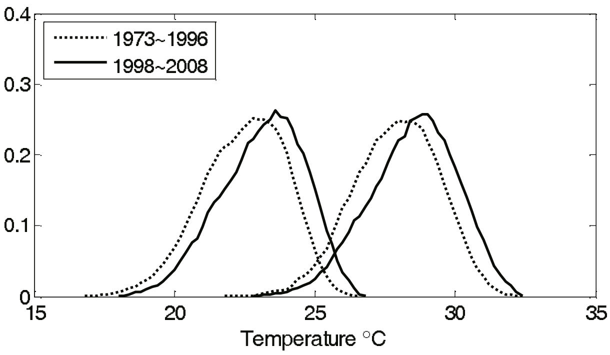

Fig. 2. Probability density distribution of the summertime (JJA) daily mean (left group) and daily maximum (right group) temperature during the period 1973–1996 (dashed line) and 1998–2008 (solid line).

can also be observed around the mid-1990s. Before the mid-1990s, the maximum temperature was seldom observed above the climatology value, while 11 of the 12 years from 1997 to 2008 had a higher maximum temperature than the climatology value.

The change in the HTE days is highly associated with the change in mean temperature. We show in Fig. 2 the probability density distribution of the summertime daily mean and daily maximum temperature before and after the abrupt change of HTE days around 1996. The distributions are close to a Gaussian function while the median value is tilted toward the higher end with a relatively longer tail at the lower end, actually similar to the Gamma function. Before the mid-1990s shift, the average value of daily mean temperature rests at about 22.5°C. It shifts to about 23.3°C after that. The average value of daily maximum temperature is about 27.0°C before the mid-1990s while it increases to about 27.7°C after the mid-1990s. This change will inevitably produce an increase in the number of extremely hot days and a decrease in the number of extremely cold days. The nonlinearity effect of extreme events indicates that a small increase in the mean can result in a large change in the frequency of high extremes (Mearns et al., 1984; Meehl et al., 2000)

The changes in the HTE days are further demonstrated in Fig. 3, which is the composite difference of the number of HTE days between the period of 1997 to 2008 and 1973 to 1996 across China. A large and significant increase in HTE days can be observed across the whole of China. Among the 549 stations used in this period, 546 stations have an increasing tendency and 484 stations pass the 95% confidential level, accounting for 88% of the total stations. If scaled with the 90% confidential level, 91% of the total stations, or 499 stations, pass the significance test. For the 3 stations with decreasing HTE days, no station can pass the 95% or 90% confidential levels. This indicates that the abrupt change in HTE shows large-scale features with most observational stations affected. There are some regions with larger changes, for example, the Loess Plateau, Inner Mongolia, the Sichuan Basin, the Yunnan-Guizhou Plateau, and the southeast coastal regions. This nationally uniform increase differs from some of the previous studies claiming a deceasing long-term trend in northern China (Zhai and Pan, 2003b) or the mid-low valley of the Yangtze River and Yellow River (Qian and Qin, 2006). Wei and Chen (2009) illustrate that the long-term trend studies are sensitive to the chosen time period, and that this nationally uniform increase becomes significant after the mid-1990s.

As a country with complex topography, western China is mainly mountainous Tibetan Plateau with an average elevation of more than 4000 m. The temperature there can rarely reach as extremely high as 35°C in summer. However, we can still witness a significant increase in HTE days. For example, the number of HTE days in Lhasa has doubled from 3.17 days to 6.3 days after 1998. Another region worthy of notice is Northeast China. Due to high latitudes summer is always mild with a maximum temperature that seldom exceeds 35°C. However, the extremely hot days with temperatures higher than 35°C are more frequent

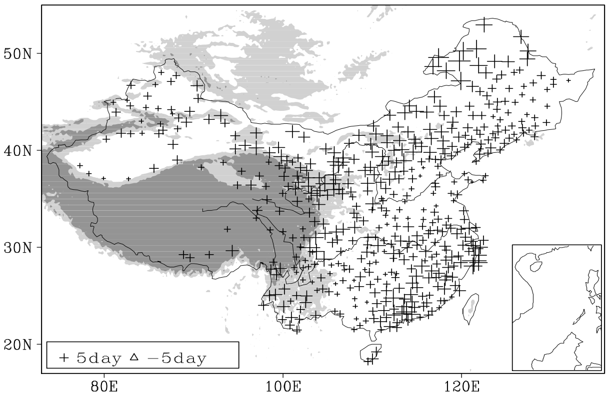

Fig. 3. Change of (1998 to 2008 minus 1973 to 1996) the number of HTE days. The marks are proportional to the number change of HTE days with plus signs for positive and dots for negative values. Only the stations with trend level above 95% confidential level are displayed. Light and dark shadings outline the regions with elevations of more than 1000 and 3000 m, respectively.

in the recent decade. For example, the Chifeng station (42°16′N, 118°58′E, Inner Mongolia) has 16, 11, and 9 hot days with temperature higher than 35°C in 2000, 2007, and 2008, while the average number is only about 2.2 days from 1973 to 1996.

4. Discussion

We have shown that the number of summer HTE days has increased across China, with a strikingly abrupt increase in the middle 1990s. This abrupt jump lagged behind the global warming trend. The global land surface temperature increased about 0.3°C from the 1970s to the early 1990s (IPCC, 2007). The number of HTE days across China, however, remains stably low throughout the 1980s and the early 1990s, with even extremely low values recorded in 1985 and 1993 (Fig. 1). The change in summer extremely high temperature events in other regions, however, has different characteristics. For example, the frequency of summer extremely high temperature events has increased in south-central Europe since the mid-1970s, with the 1980s witnessing continuous increase (Domonkos et al., 2003). The high temperature extremes are also shown to increase from the 1960s to the 1990s in the United States (DeGaetano and Allen, 2002), Australian region, and New Zealand (Plummer et al., 1999).

The causes of such an abrupt change in HTE days across China can be complicated. Two questions should be answered before a reasonable mechanism is obtained. First, why was there a prolonged period with low HTE activities from the early 1970s to the middle 1990s regardless of the global warming trend during this period? Second, what caused the abrupt increase in the mid-1990s?

The summer cooling across central China, as mentioned in the first section, is estimated at above 0.6°C at the surface between 1958–1979 and 1980–2001 [Fig. 1b of Yu et al. (2004)]. Although a warming trend can be detected for the whole of China using long-term data which is updated to the present, the summer warming is weakest if compared with other seasons. For example, Ren et al. (2005) pointed out that the warming is only 0.15°C (10 yr)$^{-1}$ in summer, while it's 0.39°C (10 yr)$^{-1}$ in winter, 0.28°C (10 yr)$^{-1}$ in spring and 0.20°C (10 yr)$^{-1}$ in autumn. This can be confirmed from early studies using data before the mid-1990s. Lin et al. (1995) analyzed the time series of averaged air temperature over China for the last 100-yr period using the data before 1990. They detected a summer cooling after the 1950s. Therefore, the cooling before the mid-1990s is an essential factor that helps to maintain the high temperature events at low frequency in spite of the global warming trend and leads to the abrupt HTE change in the mid-1990s. The cooling rate is large from mid-1960s to early 1990s, while it stabilizes and shows warming since the 1990s, especially at the surface level. Figure 4 demonstrates the circulation change in East Asia after the mid-1990s regime shift. Positive geopotential height change can be observed above northern China and Mongolia, which weakens the Asian low in summer, favors downward velocity anomaly, and helps to restrain large-scale convection in this region. Negative geopotential height can be observed over the northwest Pacific and west Pacific. This anomaly pattern reduces the west-east pressure gradient between the continent and the ocean, which leads to weaker East Asian summer monsoons (Guo, 1983; Shi and Zhu, 1996; Zhao and Zhou, 2005). Northerly anomalies can be observed in eastern China, especially North China and Northeast China, which is another indicator of weaker monsoons in this region (e.g. Wang, 2001; Wang et al., 2008). Therefore, the northward transfer of water vapor is reduced in this region, leading to drier conditions and favoring the occurrence of extremely hot weather. This is further validated by the temperature anomaly across China, which shows a striking warming change (shading of Fig. 4). The maximum temperature anomaly in northern China exceeds 1.5°C. This circulation-related regional warming, superimposed on the global warming, inevitably increased the frequency of extreme hot days and resulted in a large change in the HTE frequency via the nonlinearity effect of extreme events (Mearns et al., 1984; Meehl et al., 2000). As there is concern about the unrealistic changes in the low-level circulation field over Asia before the late

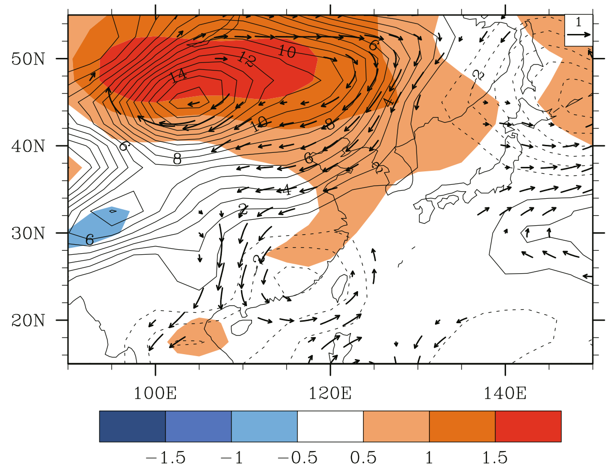

Fig. 4. Change of summer (JJA, 1997–2008 minus 1973–1996) low level temperature (shaded), geopotential height (contour) and 850 hPa wind, the temperature and geopotential height are averaged from 1000 hPa to 700 hPa. The shading interval is 0.5°C and the contour interval is 1 gpm with the zero lines omitted. The small wind change of less than 0.5 m s^{-1} has been masked. All of the used data come from the NCEP/NCAR reanalysis.

1970s caused by the NCEP-NCAR reanalysis dataset (Inoue and Matsumoto, 2004; Wu et al., 2005), we also analyzed the results using data after 1979, and similar results were obtained (not shown), which indicates the robustness of the results in this study.

The regional warming may be contributed to by other factors besides the greenhouse gas-related global warming and circulation adjustment. For example, there are concerns about the warming caused by quick urbanization. Ren et al. (2008) estimated a trend of urban warming of about 0.11°C (10 $yr)^{-1}$ in North China and that the urban warming contributes to about 37.9% of the annual mean surface air temperature trends. Other studies indicated larger urban heating effects in megacities such as Beijing and Shanghai (Deng et al., 2001; Ji et al., 2006; Wang and Hu, 2006). Warming of such magnitude will inevitably add fuel to the extremely hot weather in this region. However, several studies (Li et al., 2004a; Jones et al., 2008; Li et al., 2010b) pointed out that the urban heat island effect on the large-scale surface air temperature trends can be neglected. For example, it is only about 0.1°C (10 $yr)^{-1}$ over the period 1951–2004 according to Jones et al. (2008) and less than 5% for the total warming trend for 1951–2001 (Li et al., 2010a). These estimated values are small, however, in accordance with the estimation in the 2007 IPCC report (IPCC, 2007). Therefore, further diagnosis and numerical simulation studies are still needed to give a quantitative evaluation of the effect of urbanization. It is likely that the rainfall change in recent decades helps to characterize the HTE distribution pattern across China. For example, central China between the lower reaches of the Yellow River and the Yangtze River shows low significance levels (see Fig. 3), which may result from the increased rainfall in this region. A deficit of mei-yu (precipitation along the persistent stationary front known as the mei-yu front during the early summer between eastern China, Taiwan, South Korea, and Japan.) was shown to occur over the middle and lower reaches of Yangtze River (Bao, 2009), which helps to maintain the HTE at a higher level over this region. The past decade also witnessed severe drought in North China and Northeast China, which can lead to a decrease in soil moisture and help to increase the surface temperature through land-air interaction, mainly via sensible heating (Su and Wang, 2007).

5. Concluding remarks

Using a homogenized Chinese station temperature dataset with enough time coverage, we conclude that in contrast to the global warming and HTE days increase around the globe, the HTE average is very low for the long period from the 1970s to the early 1990s in China (2.9 d yr^{-1}). However, it increases sharply to about 7.2 days after the mid-1990s, bringing record-breaking heat waves across China, especially after 2000. Moreover, we find a statistically significant increase in HTE days around the mid-1990s at all the Chinese stations. It is likely that these features are dynamically, not just statistically, linked to the large-scale circulation adjustment. The regional cooling in central China in the past half century has now weakened and turned to warming, which overlaps the global warming in this region and can lead to the abrupt increase through the nonlinearity effect of extreme events.

The climate change projection into the 21st century indicates a more serious situation in China by way of the possibility that the warming is likely to be above the global mean level in the regions of central Asia, the Tibetan Plateau, northern Asia, and East Asia (IPCC, 2007). Therefore, the whole of China will be under the influence of stronger warming, which will inevitably lead to more summer HTE days, as well as the increase of their intensity and duration. This study leaves more questions unsolved. Determining the cause of the abrupt HTE days increase and its consequences will require a combination of further analysis and modeling. Also, further study on the methodology of homogenization of station data is needed to fully account for instrumentation changes in the last decade.

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