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Changes in hot days and heat waves in China during 1961–2007

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ABSTRACT: Based on the daily maximum temperature (DMT) records at 512 stations during 1961–2007, the geographical patterns and temporal variations of hot days (HDs) and heat waves (HWs, including those persisting for 3–5 days and longer) over mainland China were studied. The HD (and hence HW) was defined in two ways, one by an absolute criterion, DMT >35 °C, as applied in the nationwide meteorological agencies and another in a relative sense, DMT > the 90th percentile threshold of a local daily temperature distribution around the day. Two centers of high frequencies (over 5 days per year) of the absolute HDs during June–September were found in the regions of Xinjiang and the mid-lower reaches of the Yangtze River. The highest frequencies of the absolute HWs were about 1.5 times per year in the Xinjiang region and to the south of the mid-lower reaches of the Yangtze River. The frequencies of the relative HWs were about 1–1.5 times per year in most of China. The HDs and HWs increased significantly during the studied period in most of China, especially over the southeastern coast and northern China (by over 4 days per decade for relative HDs and 0.4 times per decade for relative HWs), but decreased significantly at some stations in the lower reaches of the Yellow River. Over most of China except northwestern China, the frequency of HDs was high during the 1960s–1970s, low in the 1980s, and high afterwards, with strong interannual variations. A remarkable increasing trend of HDs occurred after the 1990s in all regions. The changes in HDs and HWs were closely related to those in rain days and atmospheric circulation patterns at the interannual and interdecadal scales. Copyright © 2009 Royal Meteorological Society

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1. Introduction

An increase in global mean surface temperature has been observed and recognised as a result of the effect of enhanced atmospheric greenhouse gases (IPCC, 2007a). However, change in regional temperature extremes, in association with severe weather events such as cold surges and heat waves, is a more considerable aspect of climate change, since it affects the society and ecosystem more directly than does the mean climate change. In a large number of cases, the extreme climate change has been 5–10 times of the mean climate change (Yan and Yang, 2000). Extreme weather and climate events have wide ranging impacts on society as well as on biophysical systems (McGregor *et al.*, 2005). In particular, there is a lot of public concern about possible increase in the frequency and enhancement of extremely hot weather events under global warming, because they may exert a greater impact on human health than any other form of severe weather (Changnon *et al.*, 1996).

In recent years, intense heat waves affect many places over the world. Warm days increased by 2.18 days/decade for the Northern Hemisphere during 1948–2006 (Fang *et al.*, 2008). Exposure to extreme heat is associated with increased morbidity and mortality, and hot temperatures have been associated with increased hospital admissions for cardiovascular disease in many cases in the United States (IPCC, 2007b). A record-breaking heat wave occurred in Europe in the summer of 2003, with temperatures more than 3 °C above the average level of 1961–1990, which resulted in widespread droughts, crop losses, and more than 22 000 heat-related deaths across Europe (Christoph and Gerd, 2004; Levinson and Waple, 2004). In England and Wales, the number of deaths reached 2045 during the episode, which is more than those for the same period between 1998 and 2002; the greatest increase in mortality was found for regions with prolonged anomalous high temperatures (Johnson *et al.*, 2004). In France, the summer was declared the hottest since at least World War II. In Slovenia, temperatures reached the highest level of the past 100 years. In the same year, extremely hot weather lasting for 20–50 days occurred at many sites over South China from July to early September (Chen and Diao, 2004; Wang *et al.*, 2006). The maximum temperatures higher than 38 °C for

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a large area and above 40 °C along the south of the lower reaches of the Yangtze River from 1 July to 10 August 2003 were documented by Xu *et al.* (2003). In 2006, a prolonged heat wave extended across most of China, with daily maximum temperature (DMT) reaching 35 °C at 22 stations in Chongqing, central China (the highest DMT of 43.4 °C was recorded on the 1 September Fuling, (Chen and Fan, 2007).

Regional climate features and changes of hot days and cold days are remarkable in China under global warming (Zhai and Pan, 2003; Qian and Lin, 2004). Climatologically, China can be roughly divided into two parts: the dry environment to the northwest and the humid monsoon regime to the southeast. The inland northwest includes many Gobi deserts and mountains, where intense solar radiation and dry environment are favorable for high temperatures during daytimes in summer. The humid monsoonal southeastern part experiences high temperatures when the northwestern Pacific subtropical high or the continental high circulation controls the region during summer (National Science and Technology Committee, 1990; Gong *et al.*, 2004; Zhang *et al.*, 2004; Shi *et al.*, 2008).

Heat waves are often described by different standards, without a universal definition. The heat wave (HW) is commonly regarded as a prolonged period of hot weather and may be accompanied by high humidity, i.e. an extended time interval of abnormally and uncomfortably hot and unusually humid weather (Peter *et al.*, 2003). In China, it is commonly considered a hot-day (HD) event when the DMT reaches 35 °C. Three classifications of HDs are widely graded, with criteria of 35, 38, and 40 °C, by weather operations and services in China (Zhang *et al.*, 2004). Some investigators used the criteria DMT >35 °C persisting for longer than 3 days as a HW event (Gong *et al.*, 2004; Zhang *et al.*, 2004; Hua *et al.*, 2006; Shi *et al.*, 2008). However, there was little study of the nation-wide distributions and multi-decadal climate changes of extreme summertime hot weather events. The present paper is to provide an overview of the changes in HDs and HWs in China, with updated daily observations. Data and method are described in Section 2. The regional features and variations of hot weather events are illustrated in Section 3 and Section 4, respectively. Section 5 explains the relationships of the variations of hot weather events with rain days and atmospheric circulation anomalies. Conclusions and discussions are given in Section 6.

2. Data and methods

Daily temperature records are chosen from the China Homogenized Historical Temperature Datasets (ver 1.0) for 1951–2004 (Liu *et al.*, 2003; Li *et al.*, 2004a, b), and updated to 2007. The stations are evenly distributed in the plains to the east of 95 °E, but scarce in the western Tibetan Plateau and the Tarim Basin in Xinjiang, Northwest China. Because of numerous missing data before 1961 (Feng *et al.*, 2004), the daily series for 1961–2007 are analyzed in the present paper. Stations with more than 1% missing codes during June-September in every decade are excluded. Finally, 512 stations are used for subsequent analysis (Figure 1(a)). Daily rainfall observations for the same stations are also collected from the National Meteorological Information Center (China Meteorological Administration (CMA), 2003; Li *et al.*, 2004a). The NCEP/NCAR reanalysis data for 1961–2007 (Kistler *et al.*, 2001) are used for analysis of atmospheric circulation anomalies in association with changes in temperature and rainfall.

Both relative and absolute indices of high temperature extremes are considered in the present paper. A HD is defined if the temperature exceeds the 90th percentile of the local daily temperature climatology, as applied in IPCC (2007a) and many previous studies (Jones *et al.*, 1999; Pan and Zhai, 2002; Yan *et al.*, 2002; Hua *et al.*, 2006; Fang *et al.*, 2008). In the absolute sense, the basic criterion for HDs in China is that the DMT is higher than 35 °C, set by CMA (Liu *et al.*, 2008). A HW is defined if the HD condition persists for 3–5 days and a prolonged HW is one with HD condition longer than that. Comparative analyses of the relative and absolute indices of temperature extremes are helpful for understanding details of relevant climate changes in the region.

The least squares method is applied to fit the linear trend and the statistical F-test is used to test the significance of regression equation for simulating time series (Huang, 2004). The moving t-test is used to detect possible rapid transition points in time series (Wei, 1999). The time interval of pentad is used in subsequent analyses. There are six pentads in a month (the 6th pentad is from the 26th to the last day of a month). There are 72 pentads in a year.

3. Spatial patterns of hot weather events

The highest records of DMT for the last 47 years are shown in Figure 1(b). Stations with the DMT maxima lower than 35 °C are mainly located in the Tibetan Plateau and the mountain areas in Southwest China. The DMT maxima beyond the criterion of 38 °C, as well as those beyond 35 °C, are observed in the Xinjiang region and eastern China, mostly to the east of 105 °E. The DMT maxima above 41 °C exist in the desert area in Northwest China, in a zone extending from North China southwestward to the middle reaches of the Yangtze River, and to the south of the lower reaches of the Yangtze River in eastern China. Table I details the 14 stations with the DMT maxima exceeding 43 °C. Seven of these stations are in the northwest dry inland, five in the eastern monsoon area, and two in steppe regions in northern China. The highest record of DMT (47.7 °C) occurred on 23 July 1986 at Turpan, a deep inland desert station in northwestern China.

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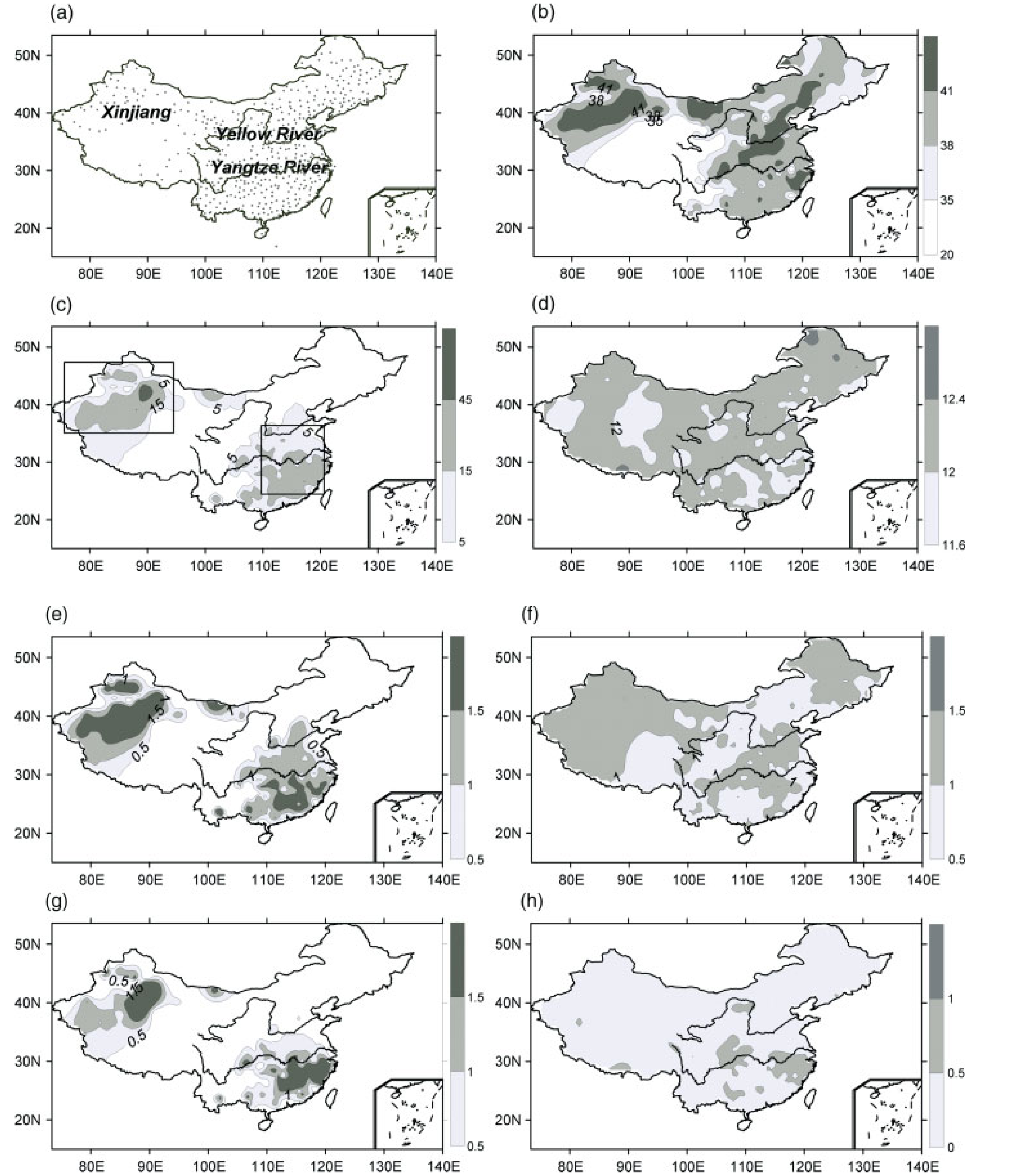

Figure 1. Distributions of HDs and HWs during June-September in China: (a) station location (● for stations qualified), (b) DMT maxima (°C) during 1961–2007, (c) annual number (days/year) of absolute HDs, (d) annual number (days/year) of relative HDs, (e) annual number of absolute HWs lasting for 3–5 days (times/year), (f) annual number of relative HWs lasting for 3–5 days (times/year), (g) annual number of prolonged absolute HWs lasting for longer than 5 days (times/year), and (h) annual number of prolonged relative HWs lasting for longer than 5 days (times/year). In (a), the regions of Xinjiang, the Yellow River and the Yangtze River are highlighted. In (c), two boxes indicate the regions of Xinjiang and East China. This figure is available in colour online at www.interscience.wiley.com/ijoc

Geographical distributions of the annual mean DMT exceeding the absolute and relative thresholds are compared. Figure 1(c) and (d) show the annual mean frequencies of HDs during June-September with the DMT beyond 35 °C and the 90th percentile, respectively. The absolute HDs occurred most frequently (more than 5 days per year) in monsoonal eastern China and northwestern China. Two centers of high frequencies (more than 15 days per year) are located in Xinjiang and the mid-lower reaches of the Yangtze River, respectively. The highest frequency (86.1 days/year) is observed at Turpan, a station in the dry inland in Xinjiang. The mean

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Table I. Highest DMT (°C) recorded at 14 stations associated with different environments.

Station	Lon.(°E)	Lat.(°N)	Elev.(m)	Date(day/month/year)	Temp.	Region	Environ.
Turpan	89.2	42.9	3.5	23/7/2003	47.7	Xinjiang	Desert
Qijiaojing	91.7	43.2	72.1	11/7/2000	44.6	Xinjiang	Desert
Alashankou	82.6	45.2	33.6	12/8/1968	44.2	Xinjiang	Desert
Kelamayi	84.8	45.6	45	14/7/2004	44	Xinjiang	Desert
Caijiahu	87.5	44.2	44	14/7/2004	43.9	Xinjiang	Desert
Zhaluteqi	120.9	44.6	26.5	10/7/2007	43.7	Northeast	Steppe
Baoguotu	120.7	42.3	40	14/7/2000	43.7	Northeast	Steppe
Ruoqiang	88.2	39	88.8	8/7/1968	43.6	Xinjiang	Desert
Mengjin	112.4	34.8	33.3	20/6/1966	43.6	Yellow River	Monsoon
Tieganlike	87.7	40.6	84.6	1/8/2006	43.2	Xinjiang	Desert
Chaoyang	120.4	41.5	17.4	14/7/2000	43.2	Yellow River	Monsoon
Chengde	117.9	41	38.6	14/7/2000	43.2	Yellow River	Monsoon
Lishui	119.9	28.5	6	31/7/2003	43.2	Yangtze River	Monsoon
Baofeng	113.1	33.9	13.6	19/7/1966	43.1	Yellow River	Monsoon

Table II. Numbers (days/year) of absolute HDs at eight stations.

Station	Lon.(°E)	Lat.(°N)	Elev.(m)	Annual days	Region	Environ.
Turpan	89.2	42.9	3.5	86.1	Xinjiang	Desert
Ruoqiang	88.2	39.0	88.8	47.0	Xinjiang	Desert
Lishui	119.9	28.5	6	41.2	Yangtze River	Monsoon
Yuanjiang	102.0	23.6	40.1	40.5	Yangtze River	Monsoon
Guixi	117.2	28.3	5.1	40.0	Yangtze River	Monsoon
Jianou	118.3	27.1	154.9	38.9	Yangtze River	Monsoon
Tieganlike	87.7	40.6	846	36.7	Xinjiang	Desert
Nanping	118.2	26.6	125.6	36.0	Yangtze River	Monsoon

frequencies of the relative HDs during June-September are about 12 days per year everywhere, in accordance with the statistical definition.

Obviously, the use of the absolute criterion (35 °C) for HDs leads to limited occurrences in mountainous southwestern China but over 45 days per year at arid sites in northwestern China. Three sites in Xinjiang and five in the mid-lower reaches of the Yangtze River experienced more than 36 absolute HDs per year (Table II). Because of the intense solar radiation and the dry environments, the DMT at those dry basin terrains such as in the Xinjiang region could easily reach 35 °C or even 38 °C from May to September. At Turpan, the mean frequency is about 86.1 days per year. The absolute HDs usually occur in the mid-lower reaches of the Yangtze River when the northwestern Pacific subtropical high or the continental high circulation controls eastern China during summer (Zhang *et al*., 2004). In both the regions, the absolute definitions are less meaningful than what HDs/HWs should bear with. For these hot regions, the thresholds should be set to ensure the 'extreme' events to be identified stressful for physical, social, and cultural adaptations (Robinson, 2001). Hence the relative definitions in association with a large percentile of the weather observations are useful. The use of the 90th percentile is suitable for a climate change study (Jones *et al*., 1999).

Figure 1(e)–(h) show the geographical distributions of the mean frequencies of the absolute, relative, and prolonged HWs, respectively. High frequencies of the absolute HWs (above 1.5 times per year) are observed mainly in Xinjiang and southeastern China. High frequencies of the prolonged ones are limited within the same regions. For the relative HWs, high frequencies (1–1.5 times per year) occurred in Xinjiang, Northeast China, and a zone from the lower reaches of the Yellow River to the middle reaches of the Yangtze River. For the prolonged ones, frequencies smaller than 0.5 times per year are observed in most of China, except for some sites along the Yangtze River. Table III lists the information about the eight longest relative HWs at eight stations, suggesting that extremely prolonged HWs happened in southern China. The intense HWs in the summer of 2006 occurred with three prolonged periods, from middle July to late July, from early August to middle August, and from late August to early September, as recorded at some sites (within 27–34 °N, 102–110 °E) in the middle reaches of the Yangtze River (Table IV).

In short, HDs and HWs most frequently occur in northwestern China and southeastern China. To quantify the seasonal features in different zones, Figure 2 presents the longitude profiles of pentad-to-pentad frequencies of the absolute HDs for the period of 1961–2007 for northern China (35–50 °N) and the Yangtze River (25–32 °N),

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Table III. Stations and times of the longest relative HWs.

Station	Lon.(°E)	Lat.(°N)	Elev.(m)	Starting date(day/month/year)	Length (days)	Region	Envir.
Nanping	118.2	26.6	15.2	30/6/2003	25	Yangtze River	Monsoon
Yichun	114.4	27.8	13.1	19/8/1963	22	Yangtze River	Monsoon
Ninguo	119	30.6	8.7	9/8/1967	21	Yangtze River	Monsoon
Lishui	119.9	28.5	6	7/8/1998	21	Yangtze River	Monsoon
Xuwen	110.2	20.3	5.6	17/7/1998	21	South China	Monsoon
Lianxian	112.4	24.8	9.8	20/7/2007	20	South China	Monsoon
Haikou	110.3	20	1.4	17/7/1998	20	South China	Monsoon
Qiongzhong	109.8	19	25.1	1/6/1977	20	South China	Monsoon

Table IV. Stations and times of the relative HWs in the middle reaches of the Yangtze River during the summer 2006.

Station	Lon.(°E)	Lat.(°N)	Elev.(m)	Starting date(day/month/year)	Length (days)
Fengjie	109.5	31	30	8/7/2006	15
Hongyuan	102.6	32.8	349.2	10/7/2006	12
Langzhong	106	31.6	38.3	10/7/2006	12
Ruoergai	103	33.6	344	11/7/2006	11
Leshan	103.8	29.6	42.4	2/8/2006	15
Yibin	104.6	28.8	34.1	7/8/2006	13
Nanchong	106.1	30.8	31	7/8/2006	13
Xuyong	105.4	28.2	37.8	8/8/2006	12
Tongzi	106.8	28.1	97.2	10/8/2006	11
Tongzi	106.8	28.1	97.2	26/8/2006	11
Zunyi	106.9	27.7	84.4	26/8/2006	11

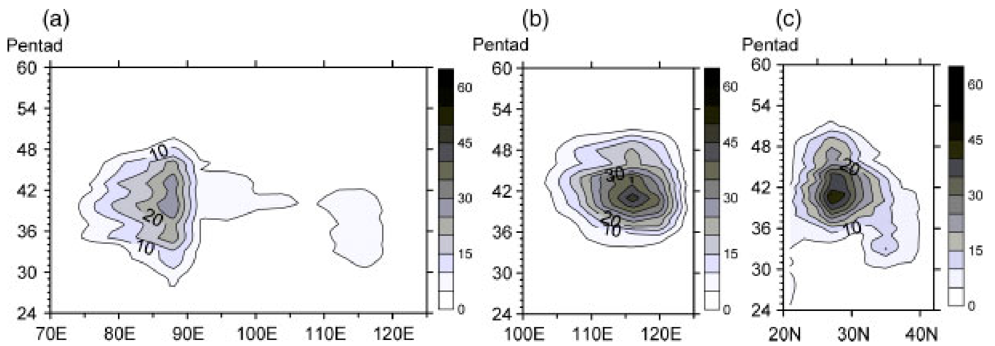

Figure 2. Frequency (%) distributions of absolute HDs to total days in pentad for (a) longitude profile in northern China between 35 and 50 °N, (b) longitude profile along the Yangtze River between 25 and 32 °N, and (c) latitude profile in eastern China between 110 and 125 °E. This figure is available in colour online at www.interscience.wiley.com/ijoc

and the latitude profile for eastern China (110–125 °E), respectively. In Figure 2(a), two high frequency centers of HDs in northern China are separated, one in Xinjiang, to the west of 95 °E, and the other in North China, to the east of 110 °E. Figure 2(b) and (c) indicate the high frequency center of HDs in the mid-lower reaches of the Yangtze River. The highest frequencies are around the 41st pentad (late July) in the regions.

Figure 3 shows the seasonal cycle of frequency of the absolute HD in each of the two regions outlined in Figure 1(c). The highest frequency is observed in East China. The highest frequency occurred around the 40th pentad in Xinjiang, and the 41st pentad in East China. According to the seasonal features of the absolute HD in Figure 3, we define the hot-day summer from pentads 31 to 54, i.e. from June to September, for mainland China. Although HDs/HWs in a relative sense could occur any

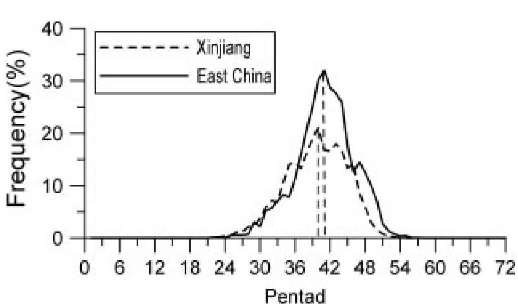

Figure 3. Frequency (%) distributions of absolute HDs in Xinjiang and East China with season for 72 pentads.

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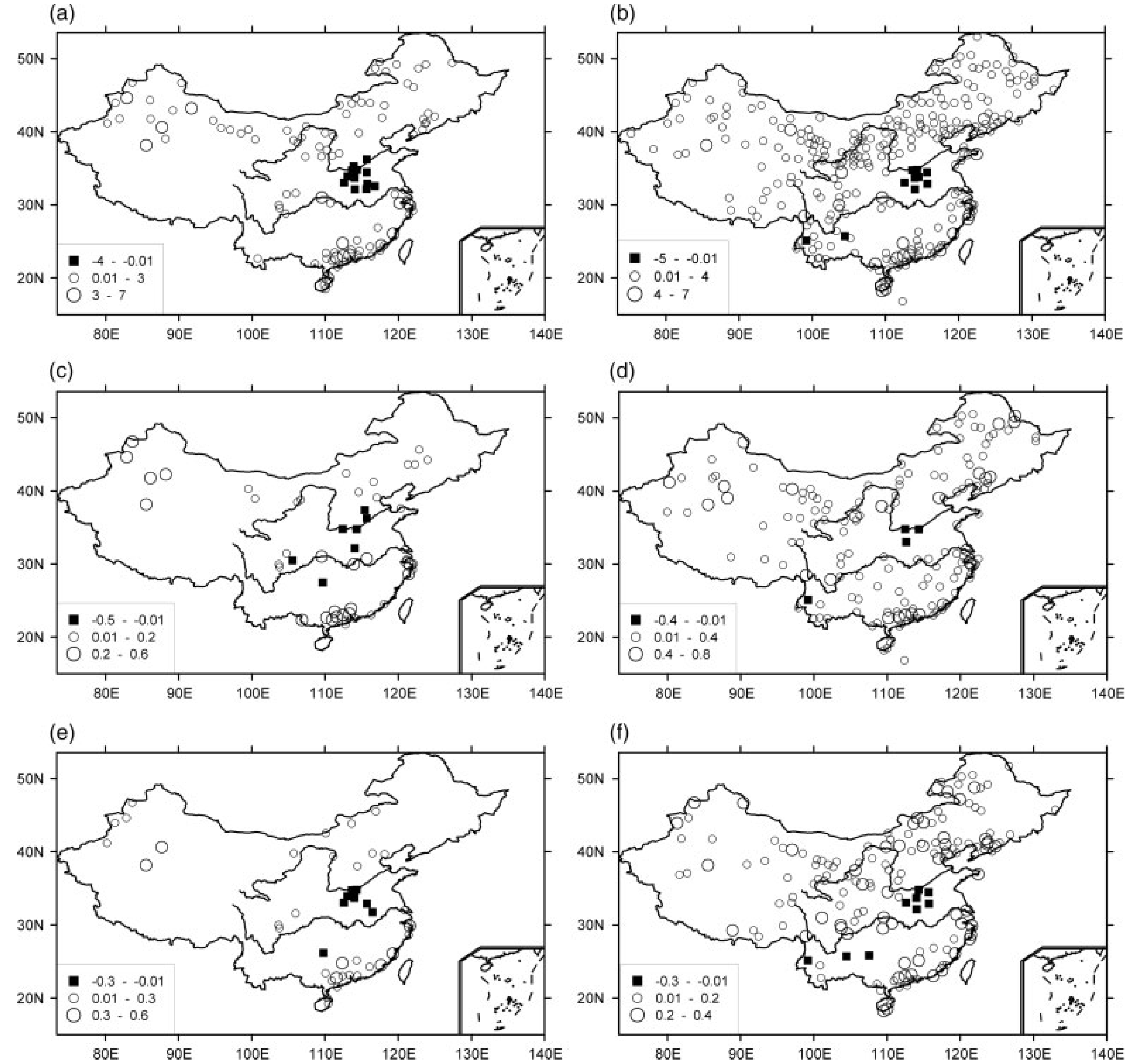

Figure 4. Stations with significant linear trends at the 0.05 level under the F-test to the regression equation for the hot-day summer during 1961–2007, for the series of (a) absolute HDs (days/decade), (b) relative HDs (days/decade), (c) absolute HWs for 3–5 days (times/decade), (d) relative HWs for 3–5 days, (e) prolonged absolute HWs (times/decade), and (f) prolonged relative HWs (times/decade).

time during a year without much seasonal differences, the ones during the summer period are particularly influential indeed.

4. Temporal variations and trends

Figure 4 shows the trends of the frequencies of the absolute and relative HDs, HWs, and prolonged HWs in the hot-day summers during 1961–2007. The stations with a significant trend are shown. For the absolute HDs, significant positive trends were widespread over northern China, the upper and middle reaches of the Yangtze River, and the southeastern coast, while negative trends were at a few sites in the lower reaches of the Yellow River. For the relative HDs, a similar geographical pattern is observed, with significant positive trends over most of China and negative ones at several sites located in the lower reaches of the Yellow River. The present results agree with those of Gong *et al*. (2004) for eastern China.

Stations with a significant negative trend of the absolute HW and prolonged HW are scattered in the lower reaches of the Yellow River, while those with an increasing trend were in northern China and the southeastern coast (Figure 4(c) and (e)). The trends of the relative HWs and prolonged HWs during the hot-day summer exhibited a similar pattern, with positive ones over northern China, the upper and middle reaches of the Yangtze River, and the southeastern coast and negative ones in the lower reaches of the Yellow River.

For the two regions outlined in Figure 1(c), Table V shows the correlation between the frequencies of the absolute and relative HD in the hot-day summer during

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Table V. Correlation between the absolute and relative HDs in the hot-day summer during 1961–2007.

Region	Correlation coefficient	Correlation coefficient (de-trended)
Xinjiang	0.87	0.85
East China	0.90	0.91

All coefficients are significant at the 0.001 level under the t-test.

1961–2007, significant with coefficients between 0.85 and 0.91, indicating similar trends and inter-annual variations between the two types of indices.

Figure 5(a) shows the annual HD and HW series, and their trends in the Xinjiang region. The absolute and relative HDs in Xinjiang show a significant positive trend, with a magnitude of 0.69 and 1.53 days per decade, respectively. The relative HWs are increased significantly by 0.23 times per decade. Inter-decadal variations are evident in three series during 1961–2007. The frequencies of the HDs and HWs remarkably increased during the last decade. A significant transition point at interdecadal timescale is detected around 1995 under the moving t-test. The mean frequency of the relative HD was about 10.4 days per year during 1961–1994 and increased to 16.9 days per year during 1996–2007. The probability distributions of DMT for the two periods are compared

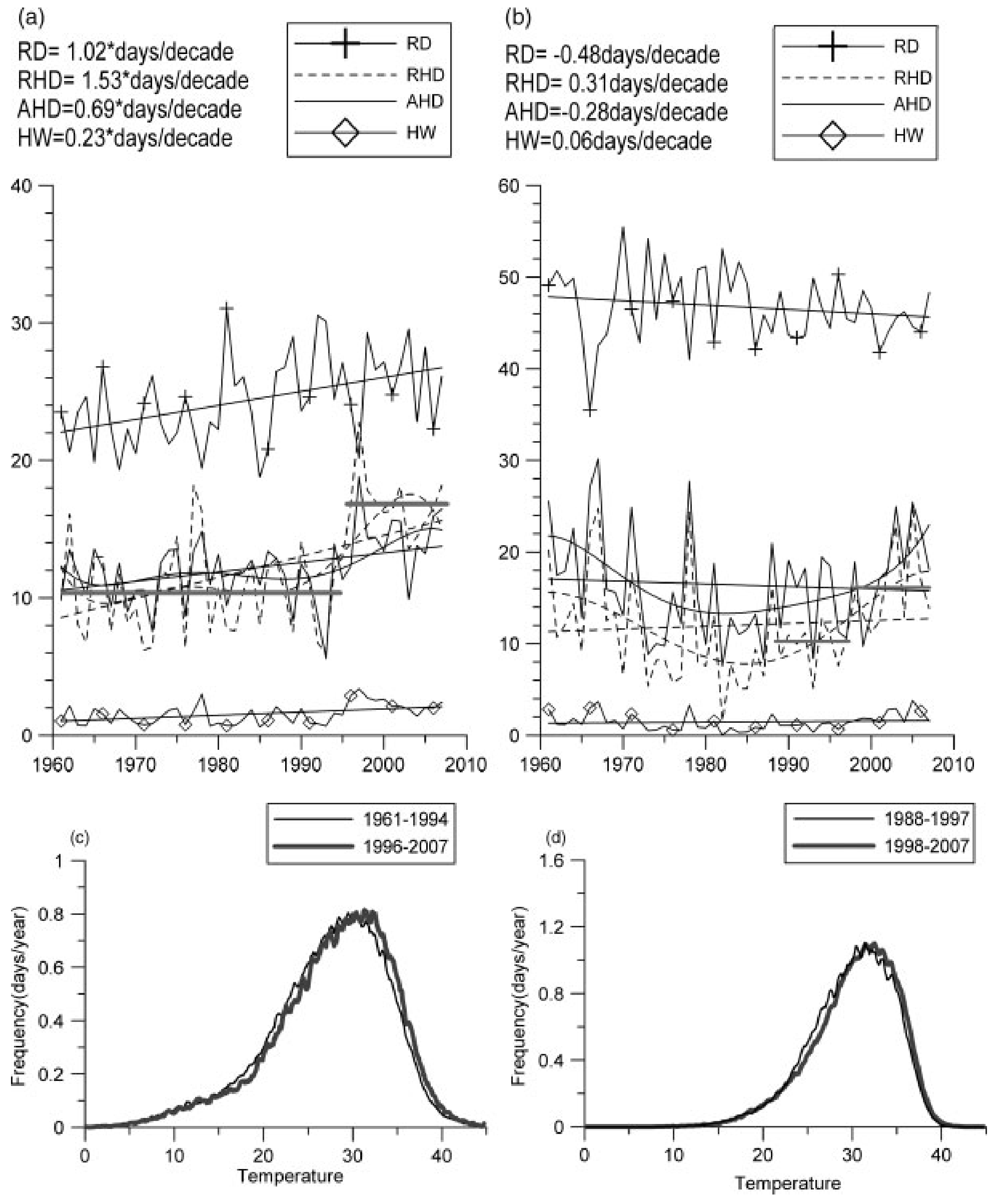

Figure 5. Variations and trends of HDs and HWs during June-September in China: (a) annual numbers of absolute HD, relative HD, RD, and relative HWs (sum of 3–5 days and prolonged) in Xinjiang, (b) annual numbers of absolute HD, relative HD, RD, and relative HWs (sum of 3–5 days and prolonged) in East China, (c) occurrence probability of DMT for 1961–1994 and 1996–2007 in Xinjiang, (d) occurrence probability of DMT for 1988–1997 and 1998–2007 in East China. In (a) and (b), the smoothed curves show the 5-order polynomial fitting trends, and the thick grey line indicates the mean of relative HD in the corresponding periods. Asterisk * denotes the trend significant at the 0.05 level. The curves in (c) and (d) are drawn within the range of DMT between 0 and 45 °C with an interval of 0.1 °C.

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in Figure 5(c). The maximum-frequency DMT was about 30.0 °C during the earlier period and 30.5 °C during the last 12 years, corresponding to a positive shift in HDs from 1961–1994 to 1996–2007. An increase in variance of the DMT distribution is also observed, mainly due to increasing frequencies of DMT by the hot end of the distribution.

For East China, no significant trends in HDs and HWs were noticed in the whole region, except for negative trends at a few sites in the lower reaches of the Yellow River and to the north of the Yangtze River in Figure 4. Inter-decadal variations of the HD and HW frequencies were obvious as shown in Figure 5(b). High frequencies of HDs occurred before 1980 and in the recent decade, with low frequencies in between. No transitional point is detected under a moving t-test; however, changes in the two recent decades are highlighted. The probability distributions of DMT for the two periods 1988–1997 and 1998–2007 are compared in Figure 5(d). The maximum-frequency DMT was about 31.5 °C for the earlier period and 32 °C for the latter. In 1988–1997, the mean frequency of the relative HD was about 10.4 days per year and increased to 16.3 days per year during 1998–2007, corresponding to a positive trend in HDs from 1988–1997 to the last 10 years. For the last 47 years, the highest frequency of the relative HDs and relative HWs are found in 2005 (more than 25 days and more than 3 times respectively). The present results agree with those of Tian *et al.* (2006), who noticed that frequency and strength of extreme hot events in the Yangtze-Huai Valleys had increased remarkably since the 1990s.

5. Relationships with rainfall and atmospheric circulation

Although the long-term trends in HD/HW appeared coherent with a large-scale warming in China, there were still strong inter-decadal variations such as those in East China. One of the most influential factors for extreme DMT is associated with rainfall, as extreme hot events hardly occur on a cloudy or rain day (RD). In fact, the number of days of trace and light rains decreased during recent decades in association with a large-scale warming environment in China (Qian *et al.*, 2007). However, the large-scale atmospheric circulation plays a key role in controlling heavy rain events, which suppress occurrence of HDs. Variations in atmospheric circulation are therefore influential to the occurrence of HD. For example, in central and southern Europe, a HD is often linked to abnormal southerlies and anti-cyclonic circulations (Peter *et al.*, 2003).

As indicated by Rohli and Keim (1994), precipitation and RDs were significantly correlated with extreme temperature events. The frequencies of the relative HDs and RDs are shown in Figure 5 for the two regions outlined in Figure 1(c). Significant positive trends are observed in Xinjiang, with a magnitude of about 1.02 days per decade for RD, about 1.53 days per decade for HD and 0.23 days per decade for HW. However, as Table VI lists, significant opposite correlation exists between the HDs and RDs in Xinjiang, suggesting a typical regional climate relationship during the hot-day period in the dry environment in Northwest China. The situation in East China was different, without any significant long-term trend in RDs, HDs, and HWs during the hot-day summer. However, the negative correlations between the HD and RD remained significant for this region, suggesting that rainfall strongly influenced the interannual-to-inter-decadal variations of HDs.

For the positive trends of HDs and HWs in northern China, an influential fact is the weakening monsoon flow during the last 50 years (Wang, 2001; Hu and Qian, 2007). The weakening of monsoon caused a southward shift of the summer rainfall activities, decreasing number of RDs, increasing solar radiation, and rising numbers of HDs in northern China. Previous studies indicated that the East Asian summer monsoon flow notably weakened during the 1960s and further weakened in the 1990s (Huang and Yan, 1999; Yao *et al.*, 2008). These changes in the East Asian summer monsoon at the decadal scale are somehow reflected in the regional series of RDs in northern China (Figure 4).

During the last 10 years, extreme high temperature events happened in China more frequently than before. In Xinjiang, a significant increasing trend of HDs occurred after the 1990s, with a transitional point around 1995 (Figure 5), coherent with large-scale warming in northwestern China (Yang *et al.*, 2008). The reason for the increase of RDs in Xinjiang is not straightforward. On one hand, surface warming has caused a decreasing trend of the trace and light rain events (Qian and Lin, 2004; Qian *et al.*, 2007). On the other hand, large-scale warming also has changed the local water budget. A significant increase in surface runoff and precipitation in the region was observed and attributed to enhanced glacial melting (Liu *et al.*, 2005).

Table VI. Correlation between the RD and the absolute HD (AHD) and between the RD and the relative HD (RHD) during the hot-day summer.

Correlation coefficient	AHD and RD	AHDand RD (de-trended)	RHD and RD	RHD and RD (de-trended)
Xinjiang	−0.36**	−0.63***	−0.15	−0.48***
East China	−0.56***	−0.58***	−0.60***	−0.60***

Asterisks ‘** ’, and ‘*** ’ indicate correlation coefficients significant at the 0.05, 0.01, and 0.001 levels by the t-test, respectively.

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In East China, no significant trends of HDs and HWs are found for the whole region. However, negative trends are noticed at a few stations in the lower reaches of the Yellow River and the north of the Yangtze River, while increasing trends of HDs and HWs are found in the stations in the west and north parts of the Yellow River basin, and significant upward trend of frequency and intensity of the high temperature events from 1961–2004 was also documented by Zhang *et al.* (2008).

It is clear that the high numbers of HDs correspond to the lower numbers of RDs over the regions at the inter-annual timescale, but not clear at longer timescales. Anomalies in large-scale circulation should play a role in regulating this relationship. We take the Xinjiang case as an example. Composite patterns of the 500 hPa geopotential height anomalies and 850 hPa circulation anomalies for 1961–1994 (a period of low-frequency HDs and HWs in Xinjiang) and 1996–2007 (high-frequency HDs and HWs in Xinjiang), respectively, are given in Figure 6. The anomalies are calculated against the mean climatology for summer 1961–2007. There were negative anomalies of the 500 hPa height centered over the north of China and an anomalous trough of the 850 hPa circulation in northwestern China for the early period, while positive anomalies of the 500 hPa height and an anomalous ridge of the 850 hPa circulation over the north of China existed for the recent period. Because the positive height anomalies of the 500 hPa in northern China were favorable for anomalous descending air motion in the lower troposphere, there should be more clear days and hence more HDs and HWs during the high-solar-radiation summer period.

Interannual variations of the frequencies of HDs and HWs are strong in East China (Figure 5(b)). The mean circulation anomalies for the 10 years with the highest- and lowest-frequencies of HDs are shown in Figure 7. The highest 10 years of HDs were also the highest 10 years of HWs, while the lowest 10 years of HDs were among the lowest 13 years of HWs. Opposite distributions of the 500 hPa geopotential height anomalies and the 850 hPa circulation anomalies are obvious between the two 10-year mean cases (Figure 7). This distribution suggests that positive anomalies of the 500 hPa height centered over eastern China and the Korean Peninsula, as a result of enhancement of the northwestern Pacific subtropical high in summer, are favorable for high frequencies of HDs and HWs in East China. Correspondingly, the anomalous southerlies at the lower troposphere (850 hPa) over eastern China are also indicative of the ridge development of the subtropical high (favorable for a high frequency of HDs and HWs) over the lower reaches of the Yangtze River. The northwestern Pacific subtropical high (NPSH) is the most important circulation system in the lower to middle troposphere over the western Pacific and East Asia (Zhang and Lin, 1992). When the NPSH gets stronger and extends more westwards than usual, positive 500 hPa height anomalies and enhanced descending

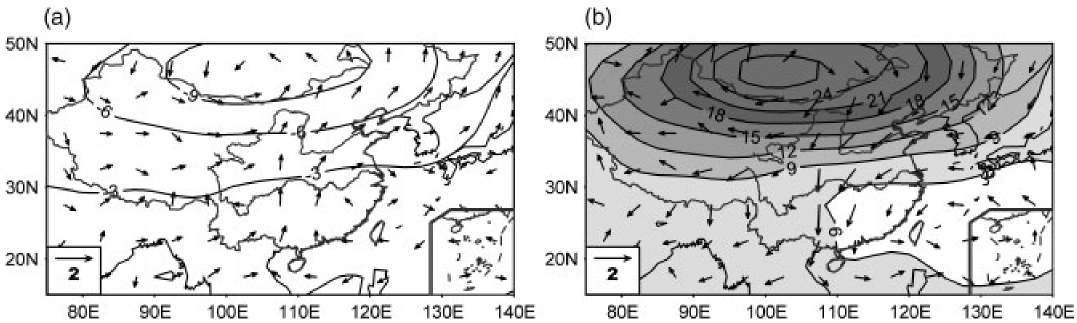

Figure 6. Composite patterns of the 500 hPa geopotential height anomalies (m) and 850 hPa circulation anomalies (m/s) for the years of (a) 1961–1994 and (b) 1996–2007. Anomalies are relative to the mean climatology during summer 1961–2007. Shaded area denotes the positive height anomalies.

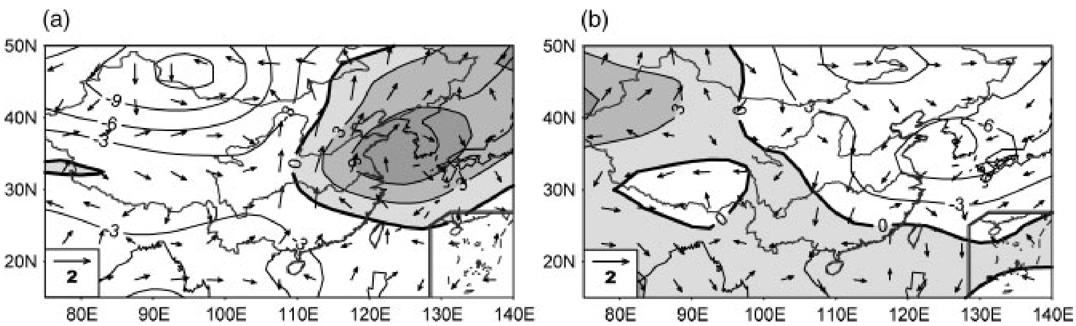

Figure 7. Composite patterns of the 500 hPa geopotential height anomalies (m) and 850 hPa circulation anomalies (m/s) for the years of (a) high-frequencies of the relative HDs, i.e. 1961, 1966, 1967, 1971, 1978, 1988, 2002, 2003, 2005, and 2006; and (b) low-frequency of HDs, i.e. 1970, 1973, 1976, 1977, 1980, 1982, 1984, 1985, 1987, and 1993, in East China. Anomalies are relative to the mean climatology during summer 1961–2007. Shaded area denotes the positive height anomalies.

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air motion should result, causing fewer RDs and higher temperature in the region (Manton *et al*., 2001).

6. Conclusion and discussion

This paper provides an overview of the climatology of the HDs, and HWs (persisting for 3–5 days and longer) in China during 1961–2007. The HDs (and hence HWs) were defined in two ways: one by an absolute criterion, DMT >35 °C; and another in a relative sense, DMT > the 90th percentile of the local DMT distribution. The HDs occurred most frequently (more than 5 days per year) in monsoonal eastern China and northwestern China. Two regions of high frequencies of HDs are located in the Xinjiang region and the mid-lower reaches of the Yangtze River, respectively. High frequencies of the absolute HWs for 3–5 days and the prolonged HWs (above 1.5 times per year) were also observed over the Xinjiang region and to the south of the mid-lower reaches of the Yangtze River. The DMT maxima over 41 °C in the last 47 years occurred mainly in Xinjiang and a zone extending from North China southwestward to the middle reaches of the Yangtze River, and the south of the lower reaches of the Yangtze River in eastern China. Two high-frequency centers of the absolute HDs were located in Xinjiang and the middle and lower reaches of the Yangtze River during the hot-day summer (June-September). High frequencies (1–1.5 times per year) of the relative HWs are concentrated in Xinjiang, Northeast China, and a zone from the lower reaches of the Yellow River to the middle reaches of the Yangtze River.

Zhai and Pan (2003) suggested that the number of HDs displays a slightly negative trend over China as a whole. However, in the analysis above, significant positive trends in the frequencies of the HDs and HWs prevailed in most of China, especially in northern China and the southeastern coast, while significant negative trends existed at a few stations in the lower reaches of the Yellow River and to the north of the Yangtze River. Strong variations at the inter-annual and inter-decadal scales were evident in the frequencies of HD and the HW. There was a clear increase in the frequency of HD after the 1990s in the Xinjiang region and East China, compared to the period from the mid-1970s to mid-1990s.

Two possible reasons for the variations in HDs and HWs were analysed, in association with the number of RDs and large-scale atmospheric circulation patterns in the region. Large-scale warming was considered to be responsible for the decrease of the trace and light precipitation events in summer observed over most of China and partly contributable to the increase of the HDs in recent decades. At the interannual scale, a significant negative correlation between the HDs and RDs existed, implying that the HDs mainly occurred on clear days due to intense solar radiation during the summertime. However, longer-term changes in the HDs, HWs, and RDs should be related with changes in large-scale atmospheric circulation. In the Northern Hemisphere, a significant warming center is located in the region of 70–130 °E and 45–65 °N around Lake Baikal (Zhu *et al*., 2008). The present analysis indicated that positive height anomalies at 500 hPa covering the north of China and easterly anomalies at 850 hPa in northwestern China were corresponding to anomalous high frequencies of HDs and HWs, and low frequencies of RDs in Xinjiang at the decadal scale. In eastern China, interannual variations are strong in the frequencies of HDs and HWs. Our analysis indicated that an enhanced Northwestern Pacific Subtropical High, in terms of positive anomalies of the 500 hPa geopotential height centered over the Yellow Sea and the Korean Peninsula and the circulation anomalies at 850 hPa over eastern China, resulted in anomalously high frequencies of HDs, HWs, and low frequencies of RDs in East China.

During the last 47 years, the annual surface temperature in China increased by 1.1 °C, with a slight increase in summer average temperature (Ding *et al*., 2007). Analysis based on longer data records showed that warm extremes might have increased by more than 10% per century over some regions (Yan *et al*., 2002). The present analysis with updated observations suggested that in the last decade the HD/HW events sharply increased in northwestern China and eastern China. Changes in the HDs and HWs might not be parallel to those of mean climate warming, partly due to strong inter-decadal and interannual variations in regional atmospheric circulations. For instance, the average temperatures of the world and China were relatively low in the 1960s-1970s, followed by a sharp increase since the 1980s. In eastern China, low frequencies of HDs occurred from the 1980s to early 1990s. In some cases, the extreme climate change was opposite to the mean (Yan and Yang, 2000). Further studies of mechanism are needed for explaining these ‘discrepancies’ between mean climate change and changes in climate extremes.

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