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Characteristics and changes of regional wet and dry heat wave events in China during 1960–2013

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Abstract Using observed surface maximum/minimum temperature and relative humidity (RH) data from 534 meteorological stations in China, the geographical patterns and temporal variations of heat wave (HW) events over the 54 years (1960–2013) were investigated. The HW events were classified into two groups by mean RH: dry HW and wet HW. In total, 211 wet HW events and 64 dry HW events were identified. Wet HW events were commonly located in the southeastern China in the monsoon area, while dry HW events occurred mostly in the northwestern China and North China. Wet HW events occurred from April to September and mostly in July and August, while dry HW events occurred from May to August and mostly in June. The average duration of wet HWs was longer than those of dry HWs, while the average intensity of the wet HWs was lower than those of dry HWs. The annual occurrences of wet HW events and dry HW events increased significantly during 1960–2013, with magnitudes of 0.54 and 0.34 times per decade, respectively. The comprehensive index (C_i) of wet HWs showed a significant positive trend, indicating an increasing severity of wet HWs. The strong wet HW events and dry HW events became more frequent and stronger significantly in the 54 years. The decadal changes in HWs are remarkable, with significant transition points for the frequencies of the wet HWs and dry HWs at 2002 and 1996, respectively. A remarkable increasing trend of frequencies of HWs occurred after the 1990s. Stations with significant positive trends for the annual number of days of the wet HWs were widespread over southern China. The wet HWs in 2003 and 2013 summer were among the top three events in China in the study period, and a large number of sites in East China were affected. The HW event in 2013 lasted shorter and affected less area than that in 2003 but was more intense with higher temperature anomaly during the duration. The more frequent and stronger HW events in the recent years may be partly due to global warming. However, different variations in the dry and wet HW events existed, and possible reasons might be the strong interdecadal and interannual variations in different regional atmospheric circulations.

1 Introduction

Global mean surface temperature has increased since the late nineteenth century, and warming has led to changes in temperature extremes, including heat wave (HW), since the mid-twentieth century (IPCC 2013; Unal et al. 2013). Changes in extremes of climate are highlighted because of their disproportionate impact on society and ecosystems compared with changes in mean climate. HWs are harmful to the biophysical systems and can create danger on human health, especially on children, elderly people, and people who have serious health problems (World Health Organization 2003). Several high-impact HW events have occurred in recent years, e.g., in Europe in 2003 (Beniston 2004; Levinson and Waple 2004; Christoph and Gerd 2004) and Russia in 2010 (Barriopedro et al. 2011; Dole et al. 2011; Trenberth and Fasullo 2012; Twardosz and Kossowska-Cezak 2013). It was very likely that a large majority of global land areas had experienced increases in indices of warm extremes since the middle of the twentieth century, and globally averaged multi-day heat events had likely exhibited increases over a similar period (IPCC 2007). Further evidence indicates that the level of confidence that the majority of warm extremes show warming remains high, and it is likely that HW frequency has increased since the middle of the twentieth century in large parts of Europe, Asia, and Australia (IPCC 2013). Song et al. (2014) showed that the

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frequencies of HWs have increased 2.7 times since the 1980s at the global scale.

Of the various types of disasters caused by extreme climate, HWs have led to a heightened awareness due to their increasing frequency, intensity, widespread distribution, and severe health impacts. In China, extreme high-temperature days (hot days) can be defined in two ways: first, by an absolute criterion, daily maximum temperature (DMT) >35 °C, as applied in the nationwide meteorological agencies (Liu et al. 2008), and second, in a relative sense, DMT>the 90th percentile threshold of a local daily temperature distribution around the day (Yan et al. 2002; Zhai and Pan 2003; Hua et al. 2006; Fang et al. 2008; Ding et al. 2009). The criterion DMT>35 °C persisting for longer than 3 days was used as an indicator of a HW event (Gong et al. 2004; Zhang et al. 2004; Hua et al. 2006). Significant increasing trends in high temperature extremes have been uncovered for North China, East China, South China, and Northwest China, both by the absolute criterion and the relative criterion (Zhai and Pan 2003; Zhang et al. 2008; Shi et al. 2009; Yan et al. 2002; Gong et al. 2004; Qian and Lin 2004; Hua et al. 2006; Ding et al. 2009; Zhou and Ren 2011; Wang et al. 2012). Almost all of these studies concentrate on high temperature extremes at individual sites (observing sites) in China.

HWs are extreme high-temperature events affecting a large area rather than an individual site. Recently, there has been some attention to such regional high temperature events. Geographical patterns and temporal variations of regional dry and wet HW events in China during 1960–2008 were investigated by Ding and Qian (2011). An objective identification technique was applied to identify regional high-temperature events in China using daily maximum temperature data at 642 stations from 1961 to 2010, and spatial and temporal variations were examined (Wang et al. 2013). They found that the regional high-temperature events were becoming more severe in both space and time and impacting more areas, and the frequency and severity of regional wet HW events were relatively low in the 1980s, increasing remarkably since the 1990s.

Temperature alone is not enough for a robust meteorological measure of heat stress. The HW is commonly regarded as a prolonged period of hot weather and may be accompanied by high humidity (Peter et al. 2003). Shi et al. (2011) analyzed the changes of high temperature weather, high humidity weather, and sultry weather in China over the period 1961–2004. The study by Shi et al. (2011) focused on the annual number of days of extreme events at individual sites, and eight rectangle regions were divided subjectively for the analysis. However, the HW event usually occurred in a large area for several days, neither at a single site nor in a rectangle region for a single day. The implications of HWs for humans are not only described through the intensity of the HWs, but also through their duration over consecutive days (Matzarakis

and Nastos 2011). Besides, different characteristics and changes may exist for the HWs in different regions in China. The high frequencies of hot days are located in northwestern China and southeastern China (Ding et al. 2009; Shi et al. 2011). The inland Northwest China includes many Gobi deserts, where intense solar radiation and dry environment are favorable for high temperature and low humidity during daytime in summer. The monsoonal southeastern part of China experiences high temperature and high humidity when the western North Pacific Subtropical High or the continental high circulation controls the region, and the southerly flow brings water vapor during summer (Gong et al. 2004; Zhang et al. 2004; Ding et al. 2009). Dry HWs and wet HWs by Ding and Qian (2011) and Shi et al. (2011) overlapped, as dry HWs were defined by temperature, while wet HWs by heat index (consisting of temperature and humidity) in the previous studies. Without complete division of these two groups of events, similar and different features of dry HWs and wet HWs were not investigated and compared thoroughly. There have been very few studies of the nationwide distributions and multidecadal climate changes of long-lasting and strong regional wet HWs and dry HWs. The aim of the present paper, therefore, is to investigate changes in dry HW and wet HW events in China and compare them using the latest updated daily observations. Section 2 describes the data and methods used. Definitions of regional wet HW events and dry HW events are discussed and HW time series are given in Section 3. The characteristics and variations of HW events are illustrated in Sections 4 and 5, respectively. The HWs in 2003 and 2013 were compared in Section 6. Finally, a discussion and conclusions are presented in Section 7.

2 Data

The daily maximum/minimum temperature and relative humidity (RH) records were chosen from the daily observations of 752 stations during the period 1951–2013 from the National Meteorological Information Center of the China Meteorological Administration (China Meteorological Administration 2003; Li et al. 2004a, b). The datasets have been quality-controlled and homogenized, and used in numerous previous studies for extreme high-temperature events in China (Gong et al. 2004; Ding et al. 2009; Ding and Qian 2012; Qian and Ding 2012; Wang et al. 2013). The number of observation stations in China ranged from about 160 to 400 in early 1950s and remained more stable since 1960. Because of numerous missing data before 1960, the daily series for 1960–2013 are used in the present paper. In this study, stations with more than 0.1 % missing codes in every decade were excluded. Finally, 534 stations are used for subsequent analysis. The geographical distribution of the 534

stations in China is shown in Fig. 2a. Dry HW refers to the HW with high temperature and low RH, while wet HW with high temperature and high RH.

The least-squares method is applied to fit the linear trend, and the statistical *t*test is used to test the significance of regression equation for simulating time series (Huang 2004; Ding et al. 2009; Ding and Ke 2013). The moving *t*test is used to detect possible rapid transition points in time series (Wei 1999).

3 Definitions and time series of wet HWs and dry HWs

For the analysis of HW events, the first requirement was to consider how a HW event could be identified. The event should be measured from the observation records. In climatology, air temperature is considered to be the most important climate element (Radinović and Ćurić 2012). On the basis of daily maximum/minimum temperature data, a basic definition was created for HW events for a site and a region, respectively. The definition for a site HW event was similar to that by Ding and Qian (2011) but was modified. For the site event, daily maximum temperature exceeded both 35 °C and the 80th percentile of the local climatology (running 11-day mean) and daily minimum temperature exceeded the 80th percentile of the local climatology for more than five consecutive days. Regional HW events were defined by at least five adjacent stations in the same period meeting the criteria for a site event, and the central geographical position was identified as the average latitude and longitude of all the stations affected by a HW, as proposed by Ding and Qian (2011). If the 80th/90th percentile was chosen, we could get 275/147 regional HW events. For the statistical study with more cases, lower threshold (e.g., the 80th percentile), instead of the 90th percentile, could be used (Della-Marta et al. 2007; Ding and Qian 2011). The heat wave series are sensitive to the threshold of heat wave definitions. Based on the definition, 275 regional HW events were identified.

Then the 275 events were classified into two types of events (i.e., dry and wet) by the mean RH. The mean RH for a regional HW event is calculated as the mean RH for all the stations satisfying the site HW definition for the duration of a HW event. RH under 60 % was to be considered as optimal to minimize risks to human health at normal room temperatures (Sterling et al. 1985). On the conditions of temperature 35 °C, physical equivalent temperature (PET) increases rapidly as RH increases when RH reaches 60 % (Zheng et al. 2007). If air temperature and wind speed are 38 °C and 1 m/s, respectively, PET increases slowly as RH increases when RH is between 10 and 60 %, and increases rapidly as RH increases while RH exceeding 60 % (Yu 2008). The RH60 ratio was calculated by the number of stations with mean RH exceeding 60 % divided by the total station numbers affected by a HW

event. The distributions of the mean RH and the RH60 ratio for the 275 events were given in Fig. 1. It was obvious that the dots could be classified into two groups: dots with the RH60 ratio above 40 % and below 40 %, as the dividing line shown in Fig. 1. Wet HW events were defined as those with RH60 ratio above 40 %, while dry HW events with RH60 ratio below 40 %. Finally, 211 wet HW events and 64 dry HW events were identified.

Compared with the HW definition given by Ding and Qian (2011), the new definition was greatly improved in two aspects. (1) The definition by Ding and Qian (2011) used the absolute criteria of daily maximum/minimum heat index exceeding their daily climatology and daily maximum heat index exceeding 35 °C. Then high-temperature courses were ranked depending on the anomaly during the duration. Finally, high temperature courses with intensity exceeding the 90th/80th percentile were defined as HW events. The temperature climatology in July was higher than that in May–June and September. It was easier to get higher temperature anomaly in May–June and September than in July. HW events in southeastern China occurred with two peaks in May–June and September, while relatively low in July. The new definition for a site HW event considered both absolute criteria of above 35 °C for hot days in China and the relative criteria of the 80th percentile. The highest frequency of hot days occurred in July for East China (Ding et al. 2009). The events defined by the new definition occurred mostly in June–August with one peak in July, and this is more reasonable than the definition by Ding and Qian (2011). (2) On the definition by Ding and Qian (2011), wet HW events were calculated by heat index, while dry HW events by daily maximum temperature only. There was great similarity between wet and dry events, and the two types of extreme HW events were not completely distinguished. Dry HWs and wet HWs were commonly located in southeastern China in the monsoon area on the definition by Ding and Qian (2011). However, the southerly flow brings water vapor and forms more hot and wet HW events but fewer hot and dry HW events in southeastern China in the summer monsoon season. On the new definition, extreme hot and dry events and extreme hot and wet events were classified into two groups by RH without overlap: dry HWs and wet HWs. Wet HW events but few dry HW events were observed in southeastern China, while dry HW events only in the northwestern part of China and North China by the new definition. The new definition for the dry HWs and the wet HWs distinguished by RH could describe rationally the geographical characteristics of HW events.

Severe HW events cause heat-related deaths and economic losses. However, it is difficult to measure the disasters directly from the data of deaths or economic losses. The population distribution is uneven, and the eastern part of China is more developed than the western part of China. Quantitative HW criteria for duration, extent and intensity were developed to
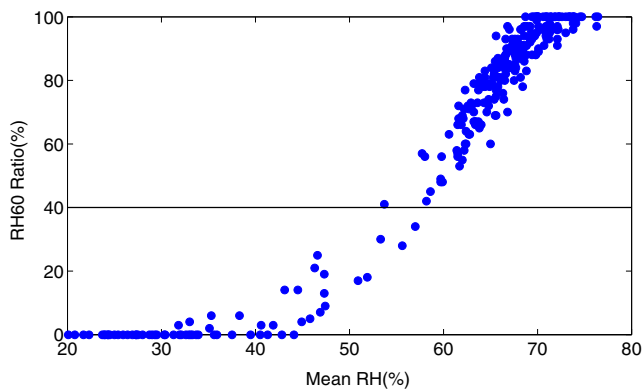
Fig. 1 The mean RH (%) for regional HW events and the RH60 ratio (%). The *black line* indicates the RH60 ratio of 40 %

examine the severity of the wet and dry HW events. The duration of a HW event expressed the persistent length of the event and was calculated as the number of lasting days. For a given HW, if a station was affected by a HW during the HW duration, the station was marked. The maximum number of stations affected by a HW was used as the extent. The average daily temperature anomaly of all the stations affected by a HW for the duration of a HW event was used as the intensity criteria. Similar intensity index was defined by Wang et al. (2013) as the accumulated values of differences between the daily maximum temperature and the 90th percentile threshold for all the impacted stations. If we focus on the persistent length/coverage/intensity, series ranked by the corresponding criteria can be used, as applied by Ding and Qian (2011). An extreme climate event does not only mean that an extreme occurs at an individual point (station), but, more generally, it has a certain impacted area and duration with high temperature anomaly. The longest event might occur in a small coverage, and events with large coverage might occur below the intensity criterion. The duration, extent, and intensity are different aspects of severity. In order to measure heat wave severity from different aspects, the comprehensive index (C_i) was constructed as follows:

$$C_i = a_1 \times F_1 + a_2 \times F_2 + a_3 \times F_3 \tag{1}$$

where F_1, F_2 and F_3 were the standardized duration index, extent index, and intensity index, respectively, and a_1, a_2 and a_3 were their coefficients. The equal weight coefficients can

be used to the three indexes, as applied by Ding and Qian (2011). But the importance and the degree of abnormality of each index may be different. Here the method recommended by Ren et al. (2012) was applied to calculate the weight coefficients for duration index, extent index, and intensity index. The proposed method by Ren et al. (2012) was first applied to examine four types of regional extreme events (REEs) in China: heavy precipitation, drought, high temperature, and low temperature. Results show that the technique was skillful in identifying REEs, demonstrating the usefulness of the proposed method in detecting and studying of REEs and operational application. (1) The series of each index was normalized by the mean and standard deviation of 1981–2010. (2) The standardized series of each index ranked in descending order, and the ratio of the sum of the top 10th percentile values divided by the sum of all values for each index was calculated. (3) The three coefficients were obtained by that ratio for each index divided by the sum of the three ratios, and the three coefficients were 0.345, 0.417, and 0.238, respectively.

Wet HWs and dry HWs for C_i were ranked from 1 to 211 and from 1 to 64, respectively, with no. 1 corresponding to the most severe condition. Tables 1 and 2 list the top three most severe wet HW events and dry HW events, respectively. The most severe wet HW event occurred on 11 July 2003, lasted for 33 days (rank 2), and affected 147 stations (rank 2), with the average temperature anomaly 1.6 °C (rank 85) and a C_i value of 3.37. The event occurred in southeastern China with its central position at 28.1°N, 114.4°E. However, the 2003 event by Ding and Qian (2011) was identified as the top one dry HW. Mean RH of 67 % indicates that this event defined as a wet HW should be more reasonable. The most severe dry HW event occurred on 23 July 1999, lasted for 12 days (rank 1), and affected 62 stations (rank 1), with the average temperature anomaly 3.3 °C (rank 1) and a C_i value of 1.17.

4 Characteristics of wet HWs and dry HWs

Geographical distributions of the annual mean wet and dry HW frequencies and number of days were compared in Fig. 2. High-frequency areas of wet HW events (more than 0.3 times

Table 1 The top three most severe wet HW events

Rank	Start date	Duration		Extent		Intensity		Mean RH (%)	Center		C_i
		Days	Rank	Stations	Rank	°C	Rank		Lat (°N)	Lon (°E)	
1	11 July 2003	33	2	147	2	1.6	85	67.0	28.1	114.4	3.37
2	3 July 2007	40	1	88	14	1.3	131	63.2	26.8	115.3	2.90
3	23 July 2013	28	3	122	3	2.3	33	59.7	30.9	115.5	2.85

Table 2 The top three most severe dry HW events

Rank	Start date	Duration		Extent		Intensity		Mean RH (%)	Center		C_i
		Days	Rank	Stations	Rank	°C	Rank		Lat (°N)	Lon (°E)	
1	23 July 1999	12	1	62	1	3.3	1	46.6	39.9	105.8	1.17
2	24 June 2010	5	17	31	17	5.3	17	40.6	47.9	123.9	0.76
3	8 July 2000	8	3	41	3	3.9	3	47.3	43.0	119.6	0.75

per year) occurred mostly in East China, including the lower reaches of the Yellow River, the mid-lower reaches of the Yangtze River and South China, while there were few events in the non-monsoon regions in the northwest part of China (Fig. 2a). The highest frequency spot of wet HW events (1.5 times per year) occurred at Hengyang (26.9°N, 112.6°E), a station in the monsoon region in Hunan province in southern China. The distribution of annual number of days of wet HW events was similar to that of the frequency distribution, with more than 3 days per year in eastern China mostly to the east of 105°E except for Northeast China and North China (Fig. 2c). Wet HW events occurred when the western North Pacific Subtropical High or the continental high circulation controlled eastern China during summer (Ding and Qian 2011).

Stations with dry HW frequencies over 0.1 times per year were located in the northwestern part of China and North China, while frequencies over 0.3 times per year existed in the Gebi desert in Xinjiang Province (Fig. 2b). The highest frequency (0.7 times per year) of dry HW events could be found at Karamay (45.6°N, 84.9°E), a station in the dry inland in Xinjiang Province. Stations with dry HW events more than 1 day per year were also observed in Northwest China (Fig. 2d). Intense solar radiation and dry desert environment

are favorable for high temperature events in Northwest China (Ding and Qian 2011). It can be noted that dry HW events mostly occurred in Northwest China and North China. Wet HW events were commonly located in southeastern China in the monsoon area. Few HW events occurred in Northeast China. Neither dry nor wet HW events occurred in Southwest China. Based on the distribution of dry and wet HW events, typical dry HW regions (A) and typical wet HW regions (C) can be distinguished while, in region B, both dry and wet HW events occurred, as shown in Fig. 2a and b. For region B, the large-scale circulation characteristics associated with wet HW differed from those with dry HW. For instance, there was a significant northerly anomaly and a descending anomaly over Beijing (a station in North China in region B) during dry HWs, while an upper-tropospheric anticyclonic anomaly and a very weak vertical velocity anomaly over Beijing during wet HWs (Chen and Lu 2014a, b).

Figure 3 shows the seasonal frequency cycle of dry HW and wet HW events, and the frequency distributions of single indices of duration, extent, and intensity during 1960–2013. As shown in Fig. 3a, a high frequency of dry HW events mainly occurred from May to August, with one peak in June, while wet HW events occurred from April to September and mostly in July and August. Hot-day summer was defined from

Fig. 2 Geographical distributions of annual mean frequency (times per year) in China for **a** wet HW events, **b** dry HW events and annual number of days for **c** wet HW events and **d** dry HW events. In **a** and **b**, A, B, and C indicate the three regions of the northern Northwest China, North China, and southeastern China, respectively
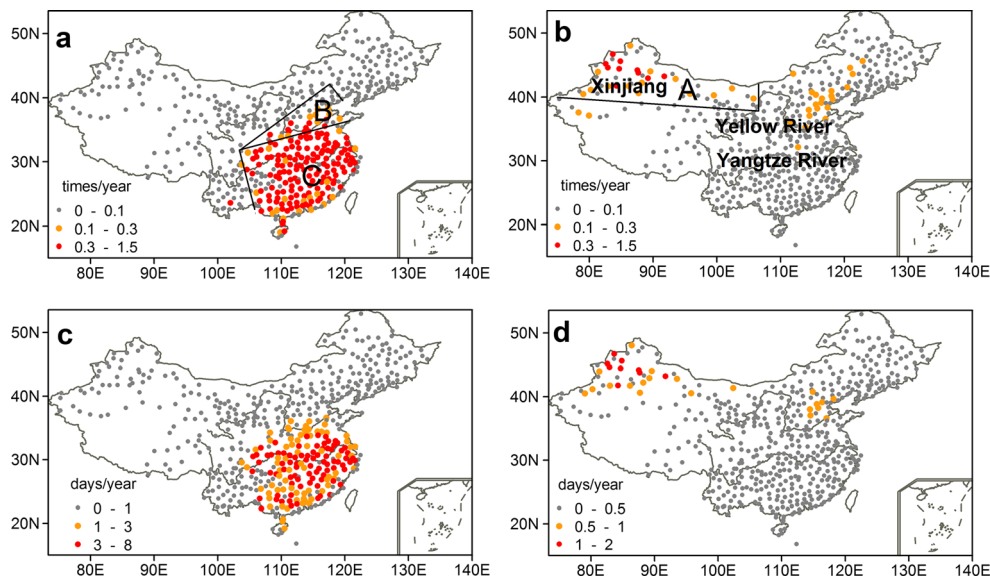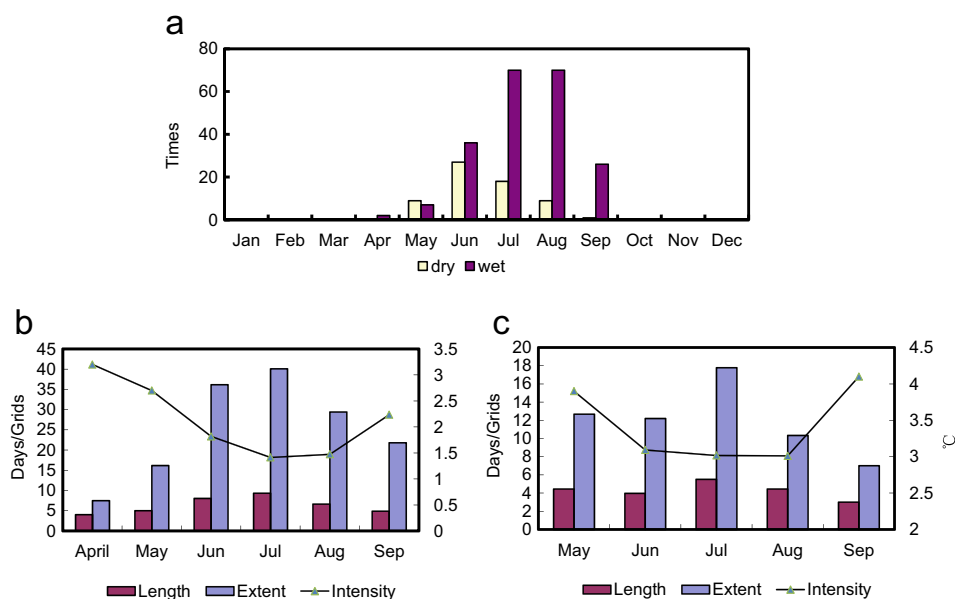
Fig. 3 a The seasonal frequency cycle of dry HW and wet HW events (times per month) during 1960–2013 for 12 months, and the frequency distributions of single indices of duration, extent, and intensity for **b** wet HW and **c** dry HW. The frequency is shown as the total times for 54 years in each month

June to September for Northwest China and East China (Ding et al. 2009). In Fig. 3b and c, the high frequency of duration and extent of wet and dry HW events were from June to August, while low values of intensity were in the 3 months. The temperature climatology was high from June to August, and it was more difficult to get higher temperature anomaly in these months.

Events with C_i values below -0.5σ (standard deviation) and exceeding $+0.5\sigma$ were grouped as weak and strong HW events, respectively, while those with C_i values between -0.5σ and $+0.5$ were classified as moderate. Seasonal frequency variations of strong, moderate, and weak events of wet HW and dry HW were given in Fig. 4. In Fig. 4a, strong wet HW events occurred mainly in June, July, and August, with the highest frequency in July. Moderate and weak wet HW events were mostly in July and August. The peak C_i values appeared in July and secondly in June, which indicated that the events in these two months were strong. Strong dry events occurred mostly in July (Fig 4b). The highest frequency of moderate and weak dry HW events was observed in

June. The C_i values were relatively high in May and July, while low in June and August. The majority of wet and dry HW events were observed from June to August. This is more rational than the previous results of least strong events and lowest C_i values in July by Ding and Qian (2011).

Based on the 211 wet HW events and 64 dry HW events, the frequency distributions by major attributes of duration, extent, intensity and C_i values were plotted in Fig. 5. The duration of wet HW events varied from 3 to 40 days, with a peak number of 51 events lasting 3 days (Fig. 5a). For the dry HW events, the duration ranged from 3 to 12 days, with a peak number of 24 events lasting 3 days (Fig. 5b). The extents affected by wet HW events ranged from 5 to 158 stations, with the majority less than 60 stations and a peak number of 29 events covering seven stations (Fig. 5c). The extents affected by dry HW events were from 6 to 62 stations (Fig. 5d). The intensity of wet HW events ranged from 0.5 to 4.0 °C, with a peak number of 22 events at 1.3 °C (Fig. 5e). For the dry HW events, the intensity varied from 1.6 to 5.3 °C, with a peak number of eight events at 3.2 °C, which was higher than that
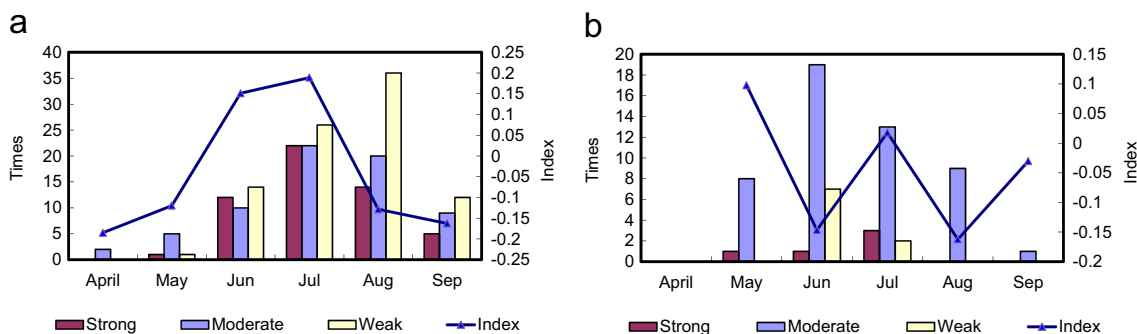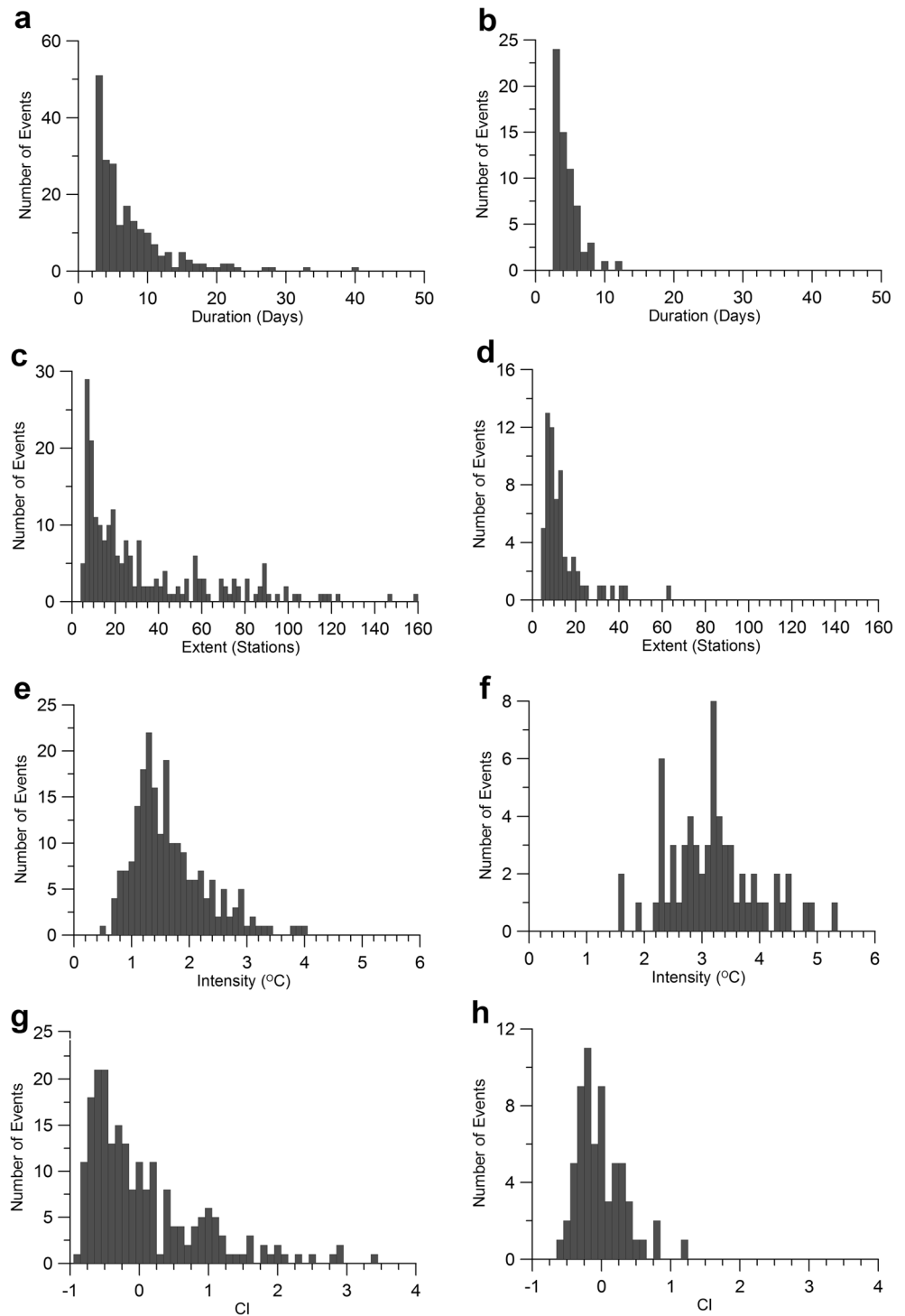

Fig. 4 Seasonal frequency variations with the three groups (strong, moderate, and weak) (times per month) and C_i index of **a** wet HW, **b** dry HW

Fig. 5 Frequency distributions of wet HW events and dry HW events by major attributes of **a**, **b** duration (days), **c**, **d** extent (stations), **e**, **f** intensity (degrees Celsius), and **g**, **h** C_i value, respectively

of wet HW events (Fig. 5f). The C_i value of wet HW events varied from −0.97 to 3.37, with a peak number of 21 events at around −0.5 (Fig. 5g). The C_i values of dry HW events were from −0.6 to 1.17 (Fig. 5h).

In order to get more comparisons between wet and dry HW events, C_i values, occurrences, and averaged major attributes of wet and dry HW events for the three groups (strong, moderate, and weak) are listed in Tables 3 and 4, respectively.

There were 54 strong wet HW events with the average duration 14.5 days, average extent 77 stations, and average intensity 1.9 °C. There were 68 moderate wet HW events and 89 weak wet HW events. For the dry HW events, there were five strong HW events in the last 54 years, 50 moderate events, and nine weak events. The average duration of the strong, moderate, and weak dry HW events were 7.0, 4.3, and 3.3 days, which were shorter than those of wet HW events. The average

Table 3 C_i values, occurrences, and averaged major attributes of wet HW events for the three groups (strong, moderate, and weak)

Groups	C_i values	Occurrence (times)	Average duration (days)	Average extent (stations)	Average intensity (°C)
Strong (>+0.5σ)	0.39–3.37	54	14.5	77	1.9
Moderate	−0.37–0.32	68	6.6	26	1.9
Weak (<−0.5σ)	−0.97 to −0.37	89	3.8	11	1.3

intensity of the strong, moderate, and weak dry HW events was 3.1, 3.3, and 2.2 °C. The average intensity of dry HW events were higher than those of wet HW events, and this indicated the average temperature anomaly of the dry events were higher than those of the wet events.

5 Variation in regional wet HWs and dry HWs

Linear trends and temporal variations of wet HW events for the period 1960–2013 are shown in Fig. 6. The annual occurrences of wet HW events showed a significant positive trend, with a magnitude of 0.54 times per decade (Fig. 6a). The occurrences of wet HW events remarkably increased during the last decade. Significant transition at interdecadal timescale was detected around the year 2002 at 2–10 years under the moving $t$test. The two periods of wet HWs in 1960–2001 and 2002–2013 were highlighted in Fig. 6a. The mean frequency of wet HWs was 3.3 times per year during 1960–2001 and increased to 5.9 times per year during 2002–2013. For the C_i value, a significant positive trend was observed with a magnitude of 0.08 per decade (Fig. 6b). This indicated that wet HW events became more severe in the last 54 years. Significant transition was detected around the year 1994. The mean C_i values for 1960–1993 and 1994–2013 were −0.17 and 0.31, respectively, suggesting an abrupt increasing severity of wet HW events in the last two decades. The mean duration of wet HW events increased significantly with a magnitude of 0.47 days per decade, while no significant trends were noticed for extent and intensity of wet HW events (Fig. 6c–e).

Figure 7 shows the linear trends and temporal variations of dry HW events for 1960–2013. A significant positive trend of the frequency of dry HW events was observed with a magnitude of 0.34 times per decade (Fig. 7a). A significant transition point at interdecadal timescale was detected around 1996 under the moving $t$test. The mean frequency of the dry HW events was about 0.6 times per year during 1960–1996 and increased to 2.5 times per year during 1997–2013. In the 54 years, the mean duration showed a significant positive trend with a magnitude of 0.63 days per decade (Fig. 7c). A significant transition point of the mean duration was detected around 1996 under the moving $t$test, which was the same as the frequency series. In 1960–1996, the mean duration of the dry HW events was about 1.5 days per year and increased to 4.6 days per year during 1997–2013. The C_i value, extent, and intensity for the dry HW events increased slightly but not significantly (Fig. 7b, d, and e). An abrupt increase of the frequency and the duration after 1997 was remarkable, which was consistent with the positive trend of hot days in Xinjiang by Ding et al. (2009).

To study more objectively the variations of the wet HW and the dry HW events in China, further analysis for the trend of each group was carried out, as shown in Table 5. The frequency and C_i value for strong wet HW events can be seen to increase significantly, with magnitudes of 0.28 times per decade and 0.18 per decade, respectively. The frequency and C_i value for moderate and weak wet HW events increased slightly. The frequency of dry HW events increased significantly for strong and moderate groups. The C_i value for strong dry HW events also showed a significant positive trend. Strong wet and dry HW events tended to become more frequent and more severe in the last 54 years.

Linear trends and temporal variations of annual maximum values of single indices for wet HW events for 1960–2013 are displayed in Fig. 8. Interdecadal variations were evident in these series during the 54 years. It could be seen that all annual maximum of single indices showed increasing trends. The trends of maximum duration, extent, and C_i value were significant, with magnitudes of 1.6 days/decade, 10.1 stations/decade, and 0.26/decade. Interdecadal variations of maximum intensity were evident, with a decreasing trend before 1980s

Table 4 C_i values, occurrences, and averaged major attributes of dry HW events for the three groups (strong, moderate, and weak)

Groups	C_i values	Occurrence (times)	Average duration (days)	Average extent (stations)	Average intensity (°C)
Strong (>+0.5σ)	0.42–1.17	5	7.0	37	3.1
Moderate	−0.36–0.37	50	4.3	12	3.3
Weak (<−0.5σ)	−0.60 to −0.40	9	3.3	8	2.2

Fig. 6 Linear trends and temporal variations of wet HW events in China for 1960–2013, separated by **a** annual number, **b** annual C_i value, **c** annual duration, **d** annual extent, and **e** annual intensity. The *thick grey line* indicates the mean value in the corresponding periods. *Asterisks* denote the trend significant at the 0.05 level
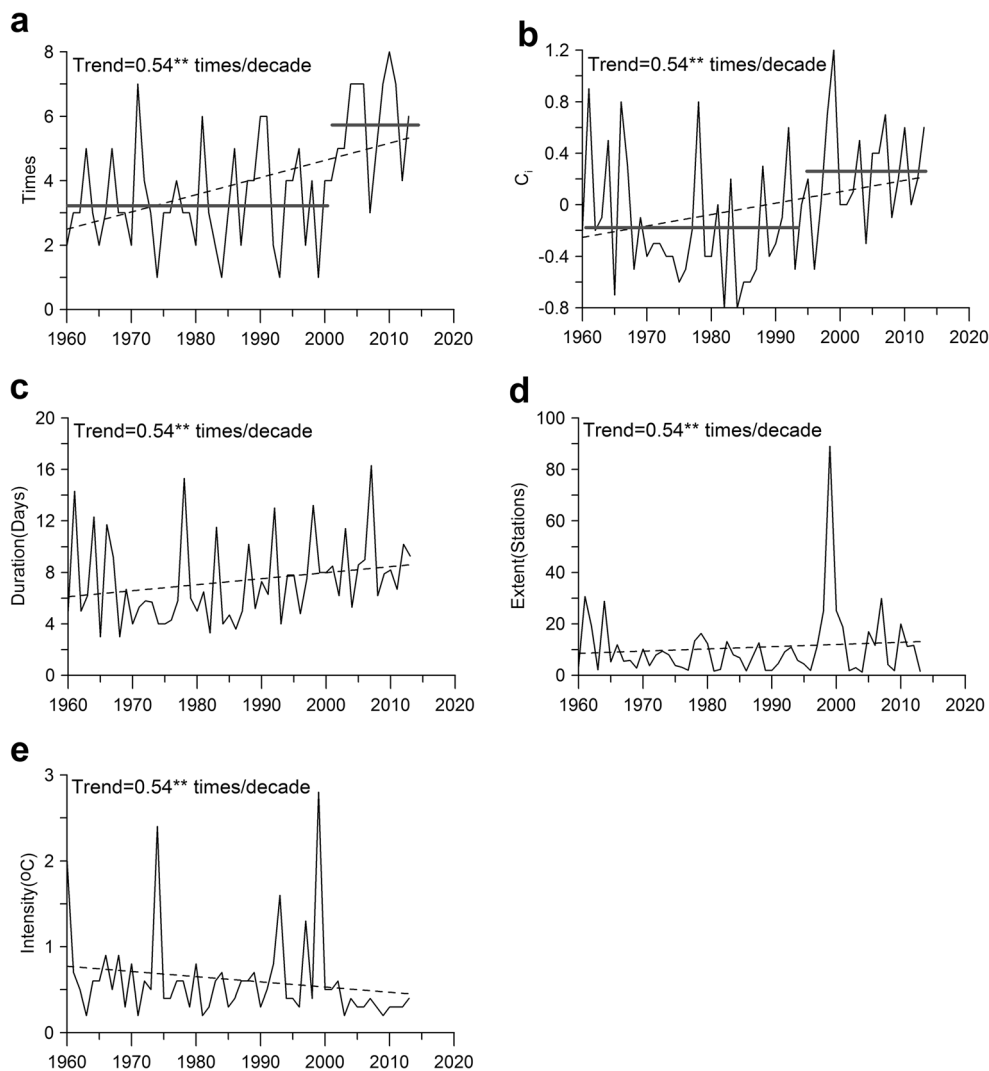
and an increasing trend after 1980s. Figure 9 shows linear trends and temporal variations of annual maximum values of single indices for dry HW events. Significant positive trends of the annual maximum indices for duration, extent, and intensity were noticed, with magnitudes of 0.9 days/decade, 3.0 stations/decade, and 0.42 °C /decade, respectively. Figures 8 and 9 suggested the evidence for an increasing severity of the extreme HW events in China.

Figure 10 shows the trends of the frequency and the number of days of the wet HWs and dry HWs during 1960–2013. The stations with a significant trend were shown. For the frequencies of the wet HW, significant positive trends were at four sites in the mid-lower reaches of the Yangtze River (Fig. 10a). Stations with a significant positive trend of the frequencies of the dry HW were scattered in the Northwest China and North China (Fig. 10b). Wang et al. (2013) found that the significant increasing trends of regional high-temperature events frequency existed in northern China, while significant decreasing trends scattered in eastern regions

between the Yangtze River and the Yellow River during 1961–2010. The trend distributions in Fig. 10a and b were similar with the previous study by Wang et al. (2013). For the annual number of days of the wet HWs, significant positive trends were widespread over southern China, while negative trends were at a few sites in the south of the lower reaches of the Yellow River (Fig. 10c). The trends of the annual number of days of the dry HW were positive over most sites of Northwest China and a few sites in North China, while negative trend was at one site in the lower reaches of the Yellow River (Fig. 10d).

6 Wet HWs in 2003 and 2013

The HWs in July–August in 2003, 2007, and 2013 were the top three wet HWs in China in the last 54 years. The HW in 2007 lasted longest, but the extent and intensity were not as exceptional as that in 2003 and 2013. The characteristics of

Fig. 7 As with Fig. 6, but for dry events
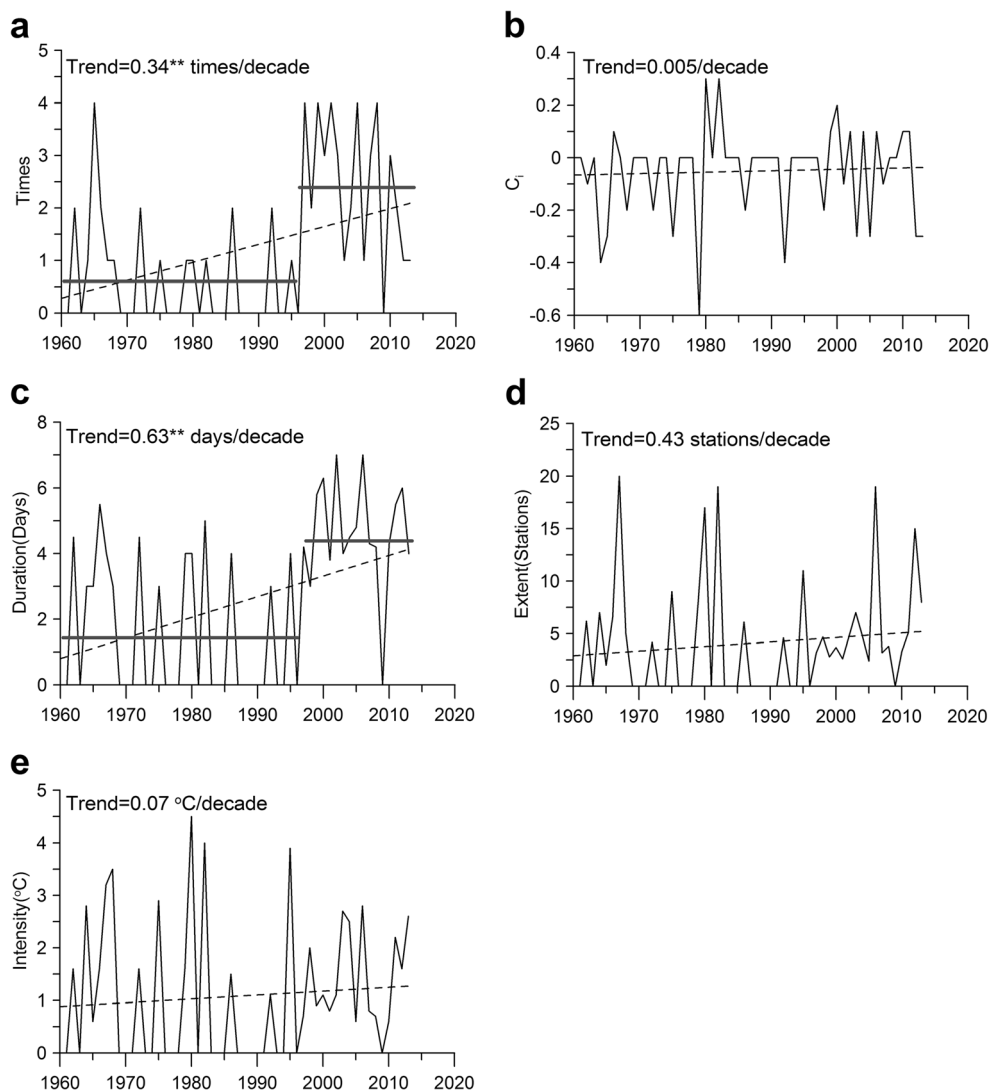
wet HWs in the summer 2013 and 2003 were compared. In the summer 2013, an intense wet HW affected most East China. As shown in Table 1, the event occurred from 23rd of July to 19th of August. Figure 11 shows the result for the event in detail. Distribution of the maximum impacted stations from 23rd of July to 19th of August was given in Fig. 11a. A large number of sites in East China were affected, in a zone extending from North China southward to the mid-lower reaches of the Yangtze River, and to

the south of the lower reaches of the Yangtze River. Figure 11b presents the evolution of the average daily mean temperature anomalies of stations affected by the HW and the station numbers during the duration. The average daily temperature anomalies of each day during the duration was above 1.1 °C, with the maximum temperature anomaly 3.2 °C on the 17th August. The daily maximum number of stations affected by the HW was observed on 6th of August.

Table 5 Trends of the occurrences and C_i values of the wet and dry HW events for the three groups (strong, moderate, and weak)

	Wet HW			Dry HW		
	Strong	Moderate	Weak	Strong	Moderate	Weak
Occurrence (times/decade)	0.28*	0.14	0.11	0.06*	0.23*	0.06
C_i value (/decade)	0.18*	0.01	0.01	0.04*	−0.0005	−0.02

*0.05 level of significance

Fig. 8 Linear trends and temporal variations of annual maximum values of single indices for wet HW events in China for 1960–2013, separated by **a** duration, **b** extent, **c** intensity, and **d** C_i value. *Asterisks* denote the trend significant at the 0.05 level
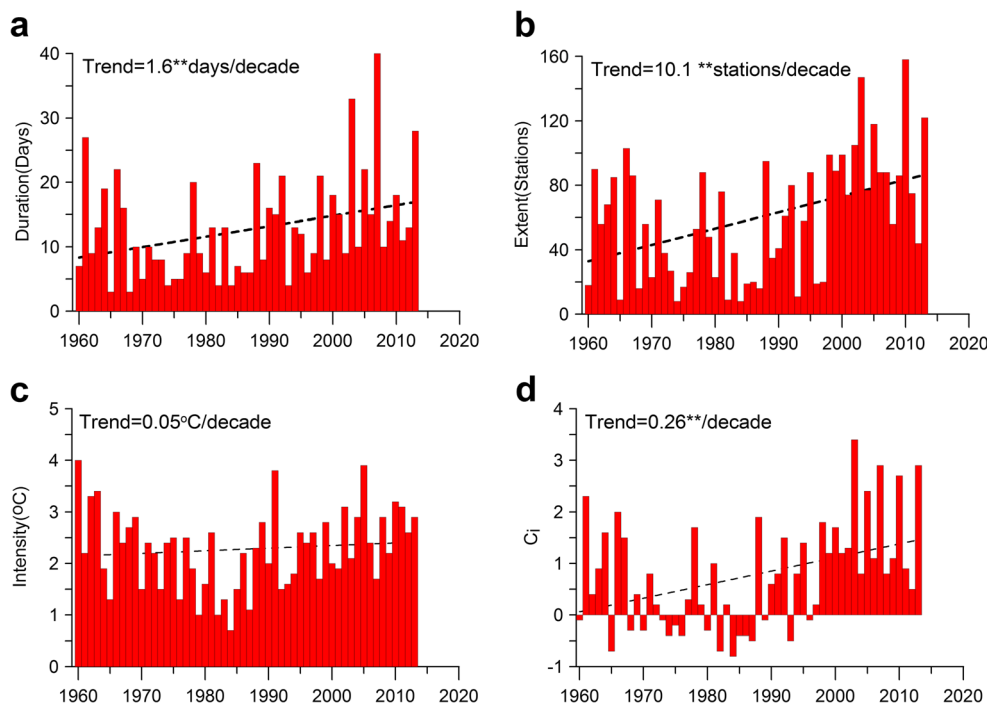
Distribution of the daily mean temperature anomaly on 17th of August was shown in Fig. 11c. The positive temperature anomalies were observed at 61 stations from the lower reaches of the Yellow River to the mid-lower reaches of the Yangtze River. Stations with temperature anomaly above 2 °C were located within the same regions. Temperature anomaly above 4 °C existed at 18 stations in the lower

reaches of the Yellow River, with the maximum temperature anomaly (6.0 °C) at Nanyang (33.0°N, 112.6°E) in Henan province. Figure 11d shows the distribution of the daily mean temperature anomaly on the 6th of August. Seventy-eight stations with positive temperature anomaly were mainly located in East China. The maximum temperature anomaly (5.5 °C) on the 6th
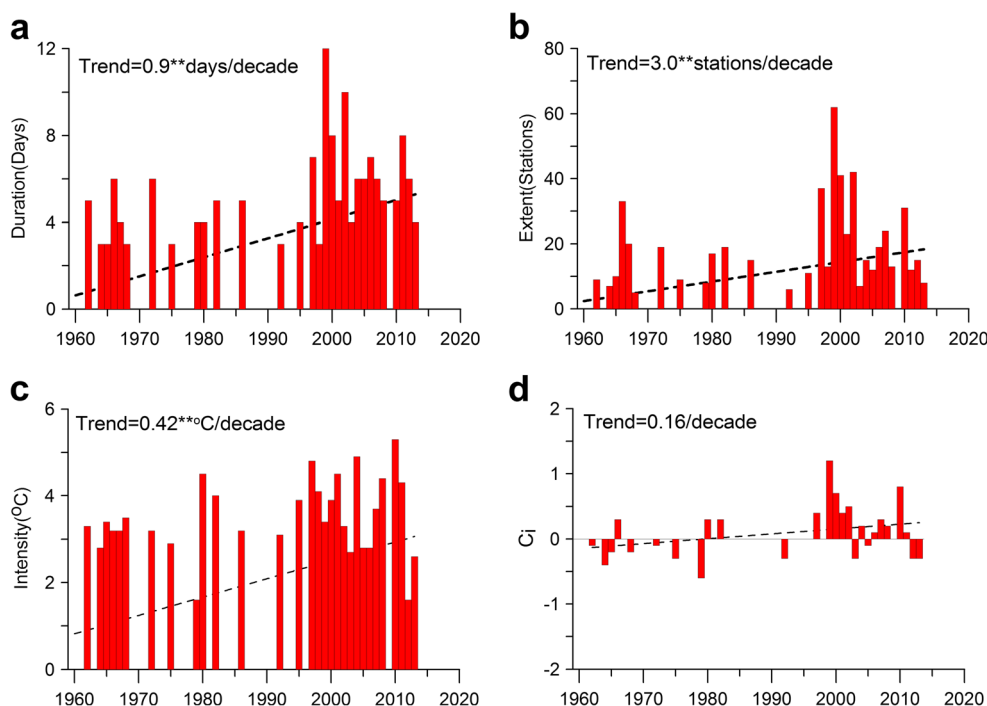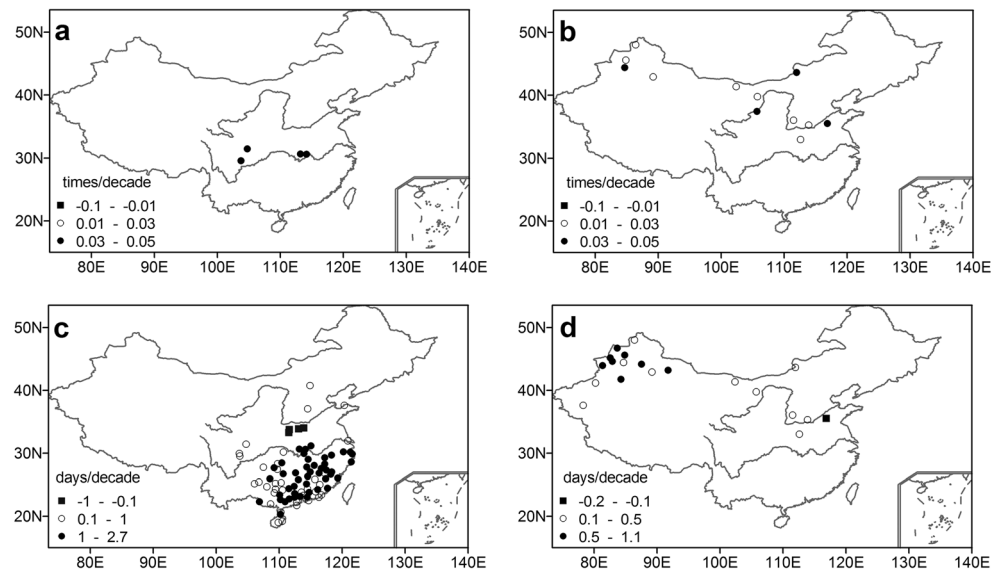
Fig. 9 As with Fig. 8, but for dry events

Fig. 10 Stations with significant linear trends at the 0.05 level under the *t*test to the regression equation during 1960–2013, for the series of **a** frequency of wet HWs (times per decade), **b** frequency of dry HWs (times per decade), **c** annual number of days for wet HWs (days per decade), and **d** annual number of days for dry HWs (days per decade)

of August was observed at Cixi (30.2°N, 121.3°E) in Zhejiang province.

The most severe wet HW event of the 54 years occurred in the summer of 2003, as listed in Table 1. Extreme hot weather causing heat-related deaths, record-breaking electricity consumption, and great losses of rice, cotton, and corn was documented (Chen and Lu 2014a; b; Tan et al. 2006). For comparison, results for the wet HW in the summer of 2003 were shown in Fig. 12. The HW extended from the lower reaches of the Yellow River southward to the mid-lower reaches of the Yangtze River, the south of the lower reaches of the Yangtze River, and to South China (Fig. 12a). The evolution of average daily mean temperature anomalies of stations and station numbers during the duration was plotted in Fig. 12b. The maximum average daily mean temperature anomaly (2.1 °C) was observed on the 2nd of August, on

which the maximum number of stations affected by the HW was also noticed. Figure 12c shows the distribution of the 130 stations with positive temperature anomalies on the 2nd of August. Stations with temperature anomaly above 2 °C were located in the mid-lower reaches of the Yangtze River and the south of the Yangtze River and above 4 °C at four sites along the Yangtze River. The maximum temperature anomaly (4.4 °C) on the 2nd of August was observed at Hefei (31.8°N, 117.3°E) in Anhui province.

In July to August in 2003 and 2013, the western North Pacific Subtropical High was stronger and extended more westward than in normal years. Strong subsidence motion associated with the positive anomalies at 500 hPa was observed in eastern China. The long persistence of large geopotential height anomalies lead to HWs in eastern China in the two summers. Comparing the wet HW events in 2013

Fig. 11 Results for the wet HW in 2013 for **a** distribution of the maximum impacted stations from 23rd July to 19th August, **b** temperature anomalies (*bar*) and station numbers (*black line*), **c** daily mean temperature anomaly on the 17th of August (degrees Celsius), **d** daily mean temperature anomaly on the 6th of August (degrees Celsius)
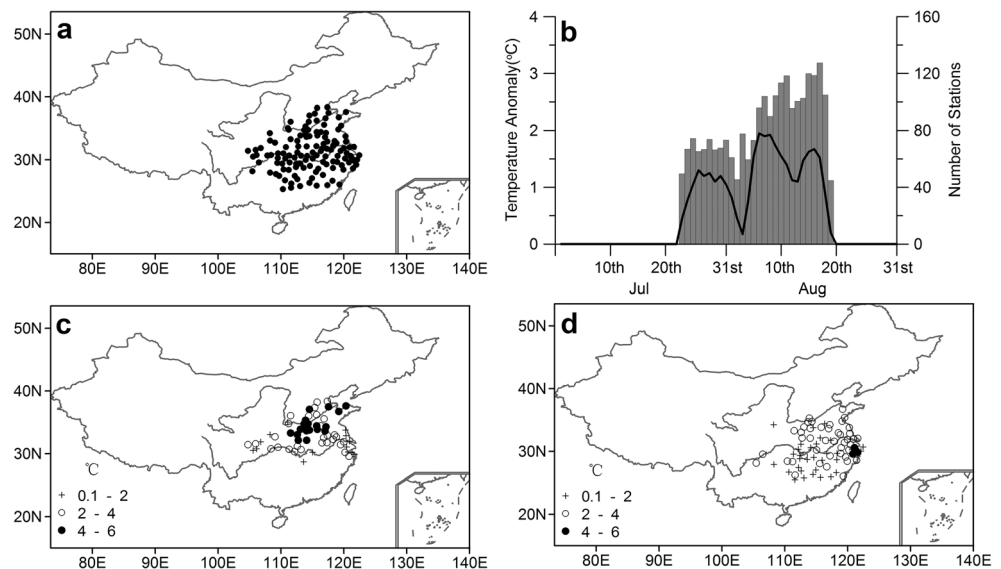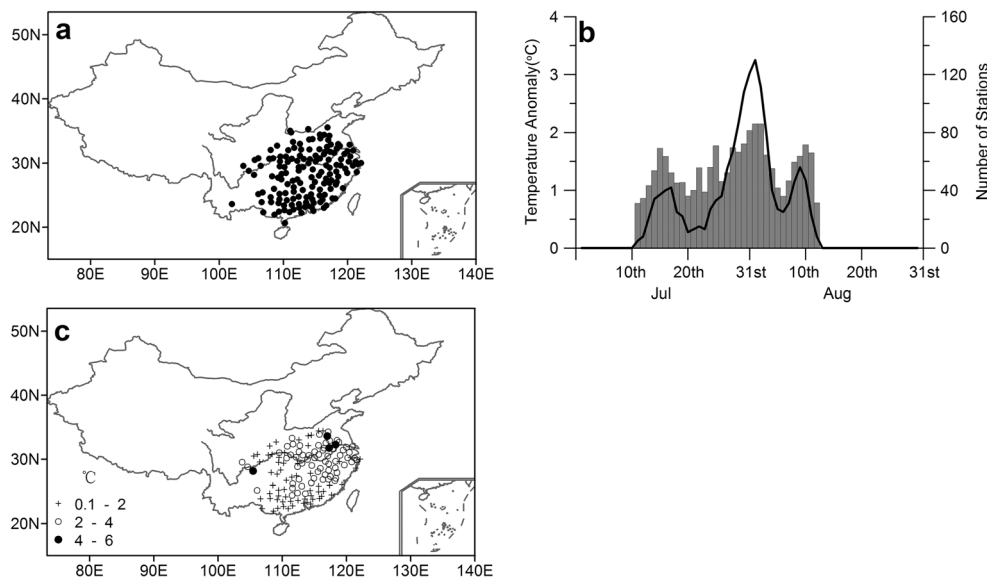
Fig. 12 Results for the wet HW in 2003 for **a** distribution of the maximum impacted stations from 11th July to 12th August, **b** temperature anomalies (*bar*), and station numbers (*black line*), and **c** daily mean temperature anomaly on the 2nd of August (degrees Celsius)

and 2003, both events occurred in East China from July to August with mean RH about 60 % during the HW. The HW event in 2003 lasted 33 days (rank 2), which was longer than that in 2013 (lasting 28 days, rank 3). The extent of the HW in 2003 (147 stations, rank 2) was larger than that in 2013 (122 stations, rank 3), as listed in Table 1. Comparing Figs. 11a and 12a, South China was affected by the extreme HW in 2003 but not in 2013. The daily peak number of stations during the 2003 HW was 130, which was also larger than that in 2013 (78 stations). However, the HW event in 2013 was more intense than that in 2003, with the intensity index 2.3 °C in 2013 and 1.6 °C in 2003. The maximum average daily mean temperature anomaly in 2013 (3.2 °C) was higher than that in 2003 (2.1 °C), and the maximum daily mean temperature anomaly in 2013 for the single site in 2013 (5.5 °C) was also higher than that in 2003 (4.4 °C). The C_i value in the HW of 2003 (3.37) was larger than that of 2013 (2.85), and this may indicate more severe impact in the 2003 HW than in the 2013 HW.

7 Conclusions

Based on station daily temperature and humidity data in China during the period 1960–2013, the present study described the climatology of HW events and analyzed the trend of HWs in China. The geographical patterns and temporal variations of wet HWs and dry HWs in China have been investigated and compared. The main conclusions of the study are summarized as follows.

On the basis of the absolute criteria (35 °C) and the relative criteria (the 80th percentile), a quantitative approach was used to identify HW events in China. Wet HWs and dry HWs were distinguished by mean RH for the duration of a HW event without overlap. Duration, extent, and intensity were

developed as quantitative criteria to quantify the severity of HWs. Totally, 211 wet HW events and 64 dry HW events in China were obtained and compared. All wet HW and dry HW events were classified into three groups: strong, moderate, and weak, respectively, according to their C_i values.

Regionally, wet HW events (more than 0.3 times per year) occurred mostly in East China in the monsoon area, including the lower reaches of the Yellow River, the mid-lower reaches of the Yangtze River, and South China while high frequencies of dry HW events were observed in the northwestern part of China and North China; neither dry HWs nor wet HWs were found in the northeast part of Northeast China and Southwest China. Dry HW events mainly occurred from May to August with one peak in June, while wet HW events occurred from April to September and mostly in July and August. The frequency was highest for the strong wet HWs and dry HWs in July, and the peak of C_i value for the wet HWs also appeared in July. The average duration of strong, moderate, and weak wet HW events was longer than those of dry HWs for the corresponding groups, while the average intensity of the wet HWs for the three groups was lower than those of dry HW events.

The annual frequency of wet HW events and dry HW events showed significant positive trends, with magnitudes of 0.54 and 0.34 times per decade, respectively. Significant transition points for the frequencies of the wet HWs and dry HWs were detected at 2002 and 1996, respectively. The mean frequencies before and after the transition points for wet HWs were 3.3 and 5.9 times per year, respectively, while for dry HWs 0.6 and 2.5 times per year, respectively. The mean duration of wet HW and dry HW events increased significantly with magnitudes of 0.47 and 0.63 days per decade, respectively. The C_i value for the wet HWs increased significantly in the 54 years, while increased slightly for the dry HWs. For the strong events, annual frequencies and C_i values for both wet HWs and dry HWs showed

significant positive trends. The trends of maximum duration and extent for wet HWs and dry HWs were also significantly positive. Stations with significant positive trends for the annual number of days of the wet HWs were widespread over southern China. The frequency and severity for both wet HWs and dry HWs increased remarkably in the recent decades.

The exceptional HWs in the summer 2003 and 2013 were among the top three wet HWs in the study period in China. The two events lasted from July to August and covered large area in East China, including the mid-lower reaches of Yangtze River and the south of the Yangtze River. South China was affected by the extreme HW in 2003 but not in 2013. The HW event in 2003 lasted longer and affected more areas than that in 2013 but was less intense. Comprehensively, the 2003 HW was more severe than the 2013 HW and was the top one wet HW event in the 54 years.

The increase in the frequency and severity of the dry HWs and the wet HWs in China might be easily attributed to the global warming, but the phenomenon seems to be more complex than that. Changes in extreme events may differ from changes in the corresponding mean (Rummukainen 2013). The variations in regional HW events in China were not parallel to those of mean climate warming. The dry HW in northwestern China was linked with the westerly ridge, while the wet HW in East China was associated with the western North Pacific Subtropical High. Different variations in the dry and wet HW events existed, as the variations in regional atmospheric circulation patterns were different. The results of this study are not sufficient to predict whether the frequency of the HWs may increase and whether the HW will become more severe in different regions in China in the future. The extreme high temperature event in 2013 was not as severe as the exceptional HW in summer 2003 but should be regarded as one more extreme climatic phenomenon with great impact on adverse biometerological conditions, serious economic impacts, and human health. Further analyses are needed to study how frequent and how severe the extreme HWs will be, and whether the extreme 2003 and 2013 HWs were just rare meteorological events or a first glimpse of climate change to come.

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