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A comparison of heat wave climatologies and trends in China based on multiple definitions

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Abstract Heat waves (HWs) can have disastrous impacts on human activities and natural systems, and are one of the current foci of scientific research, particularly in the context of global warming. However, there is no standard definition of a HW, which makes assessment of temporal trends a challenge. In this study, based on daily mean, maximum and minimum temperature, and relative humidity datasets from China Meteorological Administration, the patterns, trends and variations of HW in China during 1961–2014 are investigated. Sixteen previously published HW indices (HIs) are calculated, which are divided into two types using relative and absolute threshold temperatures, respectively. During 1961–2014, both relative and absolute threshold HIs show the highest number of HW in Jianghua and South China, geographically consistent with the climate characteristics of China. The majority of HIs shows negative/positive trends of HW days before/after 1990 over the whole of China, but especially in Jianghua and South China, which reflects rapid warming since 1990. There are significant correlations among different HIs in the same type (both absolute and relative), but correlations are weak between relative and absolute threshold HIs. Because relative and absolute HIs show contrasting trends, the choice of HI is therefore critical for future analysis

Keywords China · Heat wave · Multiple heat wave indices

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1 Introduction

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), global mean surface temperature has increased by 0.85 (0.65–1.06) °C during 1880–2012 (IPCC 2013), and each of the last three decades has been successively warmer at the Earth's surface than any preceding decade (IPCC 2013). Warming leads to an increase in heat wave (HW) occurrence in terms of magnitude, frequency and duration (Meehl and Tebaldi 2004), and it is likely that the frequency of HWs has increased in large parts of Europe, Asia and Australia (IPCC 2013). Previous studies have shown that HWs have great social and environmental impacts (Anderson and Bell 2011; Habeeb et al. 2015; Perkins 2016; Wang et al. 2015). For example, HWs are associated with increased levels of human morbidity and mortality (Anderson and Bell 2011; Meehl and Tebaldi 2004; Tan et al. 2007), and influence ecosystems, agriculture production and forest fire frequency etc. (Unal et al. 2013). Thus there have been frequent studies of HW changes (Smith et al. 2013; Tan et al. 2007; Wu et al. 2012b).

Although there is no universally accepted definition of a HW, there are numerous studies analyzing the patterns, trends, and occurrences of HWs on regional and global scales, especially in heavily populated regions. Studies include those in Europe (Carril et al. 2007; Della-Marta et al. 2007; Fischer and Schär 2010; Kyselý 2010;

Table 1 Definitions of heat wave indices (HI) including temperature metric, threshold, duration and HI type

Heat wave indices (HI)	Temperature metric	Threshold	Duration	References	HI type
HI1	T_{mean}	>90th Percentile	2+ Consecutive days	Anderson and Bell (2011)	Relative
HI2	T_{mean}	>95th Percentile	2+ Consecutive days	Anderson and Bell (2011)	
HI3	T_{min}	>95th Percentile	2+ Consecutive days	Anderson and Bell (2011)	
HI4	T_{max}	>95th Percentile	2+ Consecutive days	Anderson and Bell (2011)	
HI5	T_{max}	T1: >81st percentile T2: >97.5th percentile	Everyday, >T1; 3+ consecutive days, >T2; avg T_{max} > T1 for whole time period	Meehl and Tebaldi (2004); Peng et al. (2011)	
HI6	T_{max}	>90th Percentile	6+ Consecutive days	Fischer and Schär (2010)	
HI7	T_{max}	>97.5th Percentile 97.5th percentile >=29 °C	6+ Consecutive days	Ye et al. (2013)	
HI8	AT_{max}	>90th Percentile	1 day	Steadman (1984)	
HI9	AT_{max}	>95th Percentile	1 day	Steadman (1984)	
HI10	T_{max}	>35 °C	3+ Consecutive days	Chen et al. (2013); Tan and Huang (2004)	Absolute
HI11	T_{max}	>32 °C	3+ Consecutive days	Chen et al. (2013); Tan and Huang (2004)	
HI12	T_{max} and T_{min}	T_{min} > 26.7 °C; T_{max} > 40.6 °C	≥1 Threshold; 2 + con- secutive days	Robinson (2001)	
HI13	HI_{max}	>80 °F	1 day	Steadman (1979)	
HI14	HI_{max}	>90 °F	1 day	Steadman (1979)	
HI15	HI_{max}	>105 °F	1 day	Steadman (1979)	
HI16	HI_{max}	>130 °F	1 day	Steadman (1979)	

12 HIs follow the methods of Smith et al. (2013). Temperature metrics are daily mean temperature (T_{mean}), daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily maximum apparent temperature (AT_{max}) and daily maximum heat index (HI_{max})

Pongrácz et al. 2013; Tomczyk and Bednorz 2016), North America (Bumbaco et al. 2013; Wu et al. 2012b), central and southern Africa (Lyon 2009), China (Sun et al. 2014; Wu et al. 2012a), and Australia (Cowan et al. 2014; Lewis and Karoly 2013; Tryhorn and Risbey 2006). The synoptic causes of HWs are also examined by many researchers, including the 2003 European HW (Schär et al. 2004), the exceptionally warm summer of 2010 in eastern Europe and large parts of Russia (Barriopedro et al. 2011; Trenberth and Fasullo 2012), and that in eastern China in the summer of 2013 (Sun et al. 2014). Both the 2003 European and 2010 Russian HW broke numerous temperature records, and are considered mega-HWs, due to their unprecedented magnitude (Fischer 2014; Perkins 2016). Thus, the topic has received worldwide attention in recent decades.

As HWs have considerable impact on natural processes and human activities, any increasing trends would have important consequences for environmental policy and management (Barriopedro et al. 2011; Meehl and Tebaldi 2004; Perkins 2016; Schär et al. 2004). In recent decades, China has been one of the countries, arguably most influenced by climate change due to its pronounced monsoonal characteristics, with marked increases in extremes of temperature being observed (Qian and Lin 2004; Ren et al. 2011;

Wang et al. 2015; You et al. 2011). Recent studies (Chen et al. 2013; Sun et al. 2014; Wu et al. 2012a) have pointed out that reduced snow cover in the western Tibetan Plateau and its association with high pressure over Mongolia could encourage the occurrence of HWs in northern China on the one hand, while the anthropogenic influence has increased the likelihood of extreme 2013 summer HW in eastern China on the other. However, few studies have investigated the characteristics of HW occurrence at a nationwide scale in China over a longer period. The objective of this study therefore is to analyze the climatological patterns and trends of HWs in China during 1961–2014 from multiple indices used in previous studies (Fischer and Schär 2010; Robinson 2001; Smith et al. 2013). To investigate the spatial variability of HWs in China, the frequency, duration, and intensity of HWs in sub-regions in China are all examined (Table 1).

2 Dataset and method

2.1 Homogenized temperature dataset

Daily maximum temperature (T_{max}), mean temperature (T_{mean}), minimum temperature (T_{min}) and relative humidity
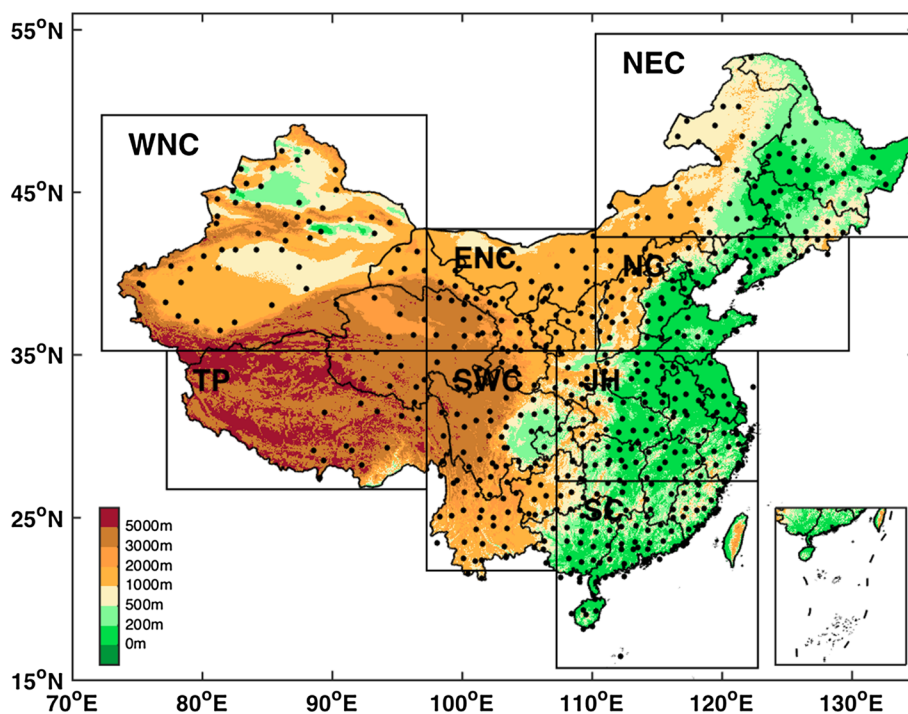
Fig. 1 Distribution of stations used in this study, and the eight sub-regions in China. *Dots* denote the locations of observed stations. The *lower right corner* of the figure is the South China Sea islands. Eight sub-regions include Northeast China (NEC, 42.25°N–54.75°N, 110.25°E–135.25°E), North China (NC, 35.25°N–42.25°N, 110.25°E–129.75°E), Jianghuai (JH, 27.25°N–35.25°N, 107.25°E–122.75°E), South China (SC, 15.75°N–27.25°N, 107.25°E–122.75°E), Southwest China (SWC, 21.75°N–35.25°N, 97.25°E–107.25°E), Tibetan Plateau (TP, 26.75°N–35.25°N, 97.25°E–107.25°E), West of Northwest China (WNC, 35.25°N–49.75°N, 7.25°E–97.25°E) and East of Northwest China (ENC, 35.25°N–42.75°N, 97.25°E–110.25°E), respectively

(RH) from 574 stations in China (Fig. 1) for 1961–2014 are obtained from National Meteorological Information Center, China Meteorological Administration. Daily temperatures have been adjusted for homogeneity and abrupt discontinuities have been corrected (Li and Dong 2009; Li et al. 2004). Among the 574 stations, most have very small amounts of missing data (Fig. 2). For example, 11, 17.9 and 17.1 % of stations for T_{mean}, T_{max} and T_{min} respectively only have 1 missing day in the 54-year period, and it is rare for there to be more than 10 missing days in total. In view of the fact that missing data can constrain most HWs definitions, missing values <3 days duration are interpolated with the average of the values at day −1 and day +1, while missing values over periods longer than 3 days are interpolated with the long-term average over 54 years. The dataset continually updates in real time and is frequently used in climate change assessments (Li et al. 2014; Wu and Gao 2013). Eight sub-regions of China are defined using the boundaries shown in Fig. 1.

2.2 Multiple definitions of heat wave

There is no consensus on the definition of a HW at present (Perkins and Alexander 2013; Robinson 2001). Because HW definitions differ in past studies, this can make it challenging to compare results. It is important to make clear whether patterns and trends reported by one definition are comparable with those obtained using other definitions. Climate change and its impacts is only fully evaluated by comparing many different definitions. Thus sixteen HW indices (HIs) are used in our study shown in Table 2, with twelve of them used by Smith et al. (2013). The HIs can be categorized into relative and absolute threshold types.

2.2.1 Relative thresholds

The relative threshold types (HI1 through HI9) of HW are characterized by a certain number of consecutive days above a fixed percentile of the temperature distribution during the warm season May to September (defined over 1961–1990). Generally, these definitions differ in (1) the metric used, e.g., T_{mean} (HI1-2), T_{min} (HI3), T_{max} (HI4-7) and apparent temperature (AT, HI8-9), (2) which percentile used, e.g., 95th in HI1, and (3) the consecutiveness constraint applied, e.g., 2 days in HI1.

Indices HI01-04 are drawn from Anderson and Bell (2011) and were used for the analysis of mortality risk during HW days compared with non-HW days. HI05 was used

Fig. 2 The distribution of the number of missing days of daily mean temperature (T$_{mean}$), maximum temperature (T$_{max}$), minimum temperature (T$_{min}$) and relative humidity (RH) in the 654 station records
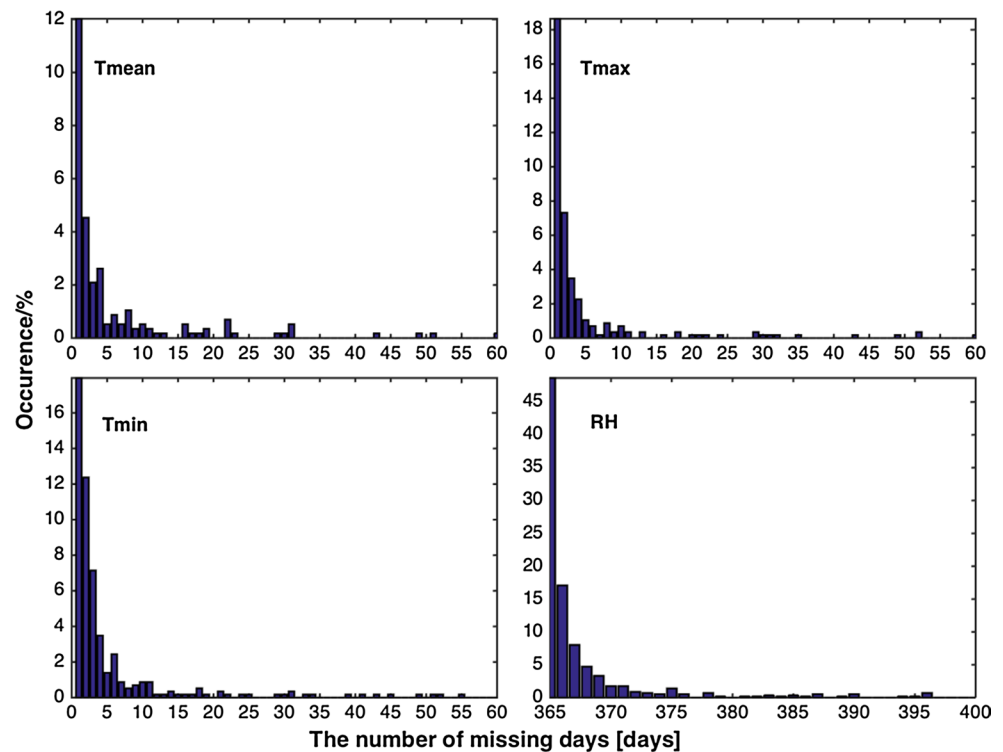

Table 2 Average number of annual heat wave days over eight sub-regions in China during 1961–2014 for each heat wave index (HI)

	NEC	NC	JH	SC	SWC	TP	WNC	ENC	Entire China
HI1	16.41	15.55	15.70	18.00	15.86	**18.94**	15.45	16.75	16.58
HI2	8.09	7.62	8.17	9.60	8.07	**10.13**	7.57	8.64	8.49
HI3	7.73	7.35	8.07	**9.59**	8.33	8.47	6.04	7.32	7.86
HI4	6.40	6.33	7.16	**7.80**	7.22	7.66	7.03	7.37	7.12
HI5	3.58	3.49	**5.51**	4.76	4.48	5.25	4.22	4.29	4.45
HI6	3.31	3.18	**5.86**	5.37	4.38	5.35	3.75	4.00	4.40
HI7	0.39	0.46	**1.10**	0.82	0.66	0.07	0.39	0.62	0.56
HI8	11.91	12.19	12.23	12.20	11.82	11.01	**13.36**	12.47	12.15
HI9	5.14	5.47	5.43	5.48	5.33	4.86	**6.27**	5.56	5.44
HI10	0.31	1.48	**12.37**	10.49	2.87	0.00	9.40	1.45	4.80
HI11	2.94	10.29	39.42	**56.72**	12.42	0.00	28.73	8.44	19.87
HI12	0.00	0.20	5.82	**8.15**	0.52	0.00	0.95	0.03	1.96
HI13	71.06	91.56	118.43	**138.94**	83.14	55.28	90.65	73.81	90.35
HI14	25.64	47.88	91.77	**124.61**	46.67	22.81	37.13	22.30	52.35
HI15	3.80	13.85	55.01	**88.48**	18.60	7.77	5.53	1.98	24.38
HI16	0.08	0.77	11.69	**11.88**	2.11	1.27	5.40	0.09	3.52

Values in bold indicate the sub-region with the highest frequency of heat waves days for each HI

by Meehl and Tebaldi (2004) to detect the extreme HW in the twenty-first century. Similarly, HI06 was used by Fischer and Schär (2010) to assess the future changes of HW in Europe. HI07, developed based on the significant increase in the mortality, was used by Ye et al. (2013) to detect the spatial and temporal characteristics of HWs in China. AT are used in HI8 and HI9 from Steadman (1984), defined as at least 1 day with AT exceeding the 90th and 95th percentile,

respectively. AT represents heat stress on the human body by accounting for the additional effects of relative humidity and incorporates the nonlinear nature of heat stress.

2.2.2 Absolute thresholds

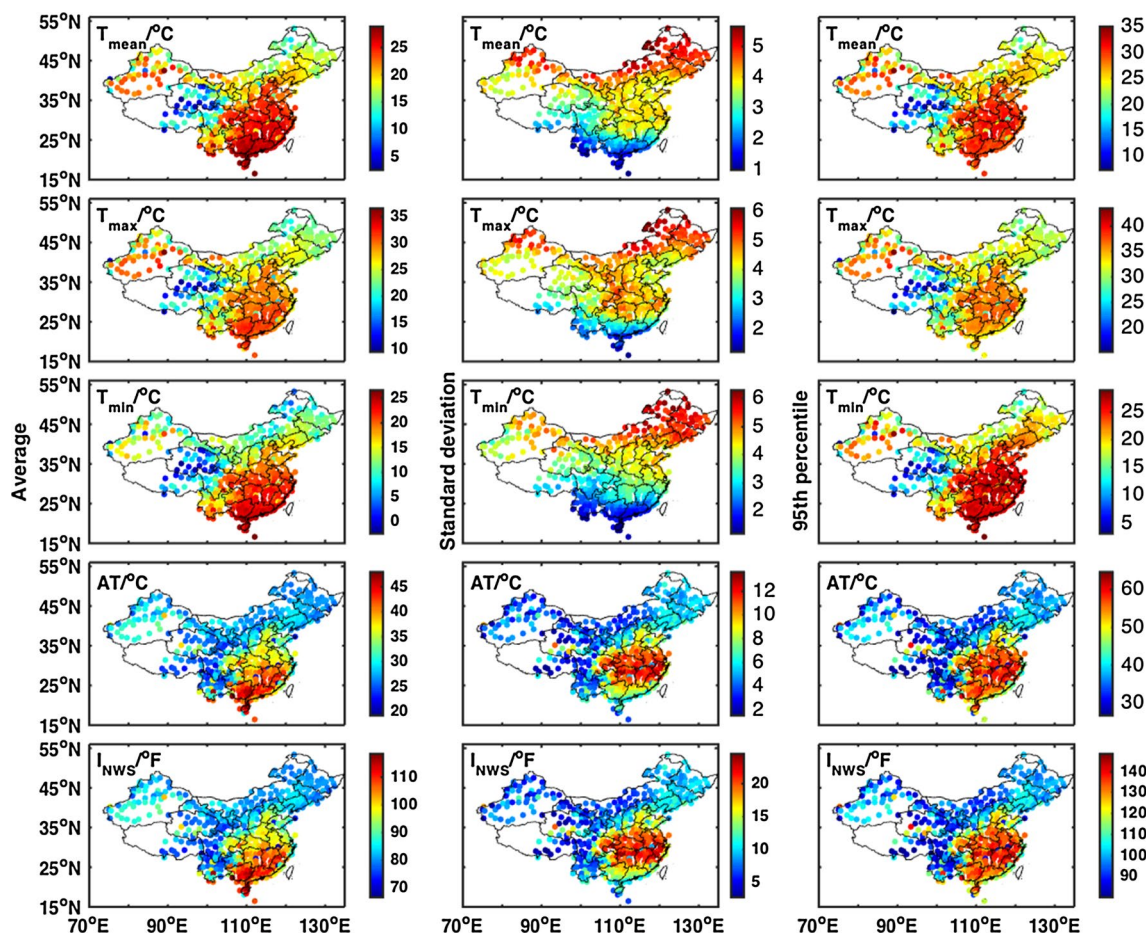The absolute threshold types (HI10 through HI18) indicate days exceeding fixed absolute values of temperature.

Fig. 3 Average (*left panel*), standard deviation (*middle panel*) and 95th percentile (*right panel*) of five temperature metrics in China during 1961–1990: daily mean temperature (T_{mean}/°C), maximum temperature (T_{max}/°C), minimum temperature (T_{min}/°C), apparent temperature (AT/°C) and the National Weather Service's (NWS) heat index (I_{NWS}/°F)

Similarly, these definitions differ in (1) the metric used, e.g., T_{max} (HI10-12) or HI_{max} (HI13-16), (2) the magnitude of threshold, e.g., 35 °C in HI10, and (3) the consecutiveness constraint applied, e.g., 3 days in HI10. 35 °C is used in HI10 as the threshold that corresponds to issued Chinese Meteorological Administration heat warnings. HI11 is similar to HI10 but with 32 °C as the threshold. HI12 considers the combined effects of daily maximum and minimum temperature, which is able to detect whether daytime heat can be relieved through nighttime (minimum) temperature. HI13 through HI16 follow the procedures of Steadman (1979), using the National Weather Service's (NWS) heat index (I_{NWS}). I_{NWS} in °F is calculated using temperature and relative humidity. Other factors such as vapor pressure, wind speed and, characteristics of human activity levels, sweating rate etc. were used in the original study to parameterize the equation (Smith et al. 2013). The daily maximum heat index is classified into one of four categories: (1) Caution: >80 °F (HI13), (2) Extreme Caution: >90 °F (HI14), (3) Danger: >105 °F (HI15), and (4) Extreme Danger: >130 °F (HI16) (Smith et al. 2013; Steadman 1979).

2.3 Trend calculation

The Mann–Kendall (MK) test for trends and Sen's slope estimates (Sen 1968), which are widely used to compute trends in hydrological and meteorological series (Joshi and Pandey 2011; You et al. 2015). However, the persistence in hydrological and meteorological time-series can contaminate the raw MK test results, so in this study we use the modified MK (MMK) (Hamed and Rao 1998) which considers the lag-1 autocorrelation (Hamed and Rao 1998; Zhang et al. 2011). A trend is considered to be statistically significant if it is significant at the 5 % level.

3 Results

Figure 3 shows the average (left panel), standard deviation (middle panel) and 95th percentile (right panel) of five temperature metrics based on the climatological reference period 1961–1990: T_{mean}, T_{max}, T_{min}, AT (°C) and I_{NWS}
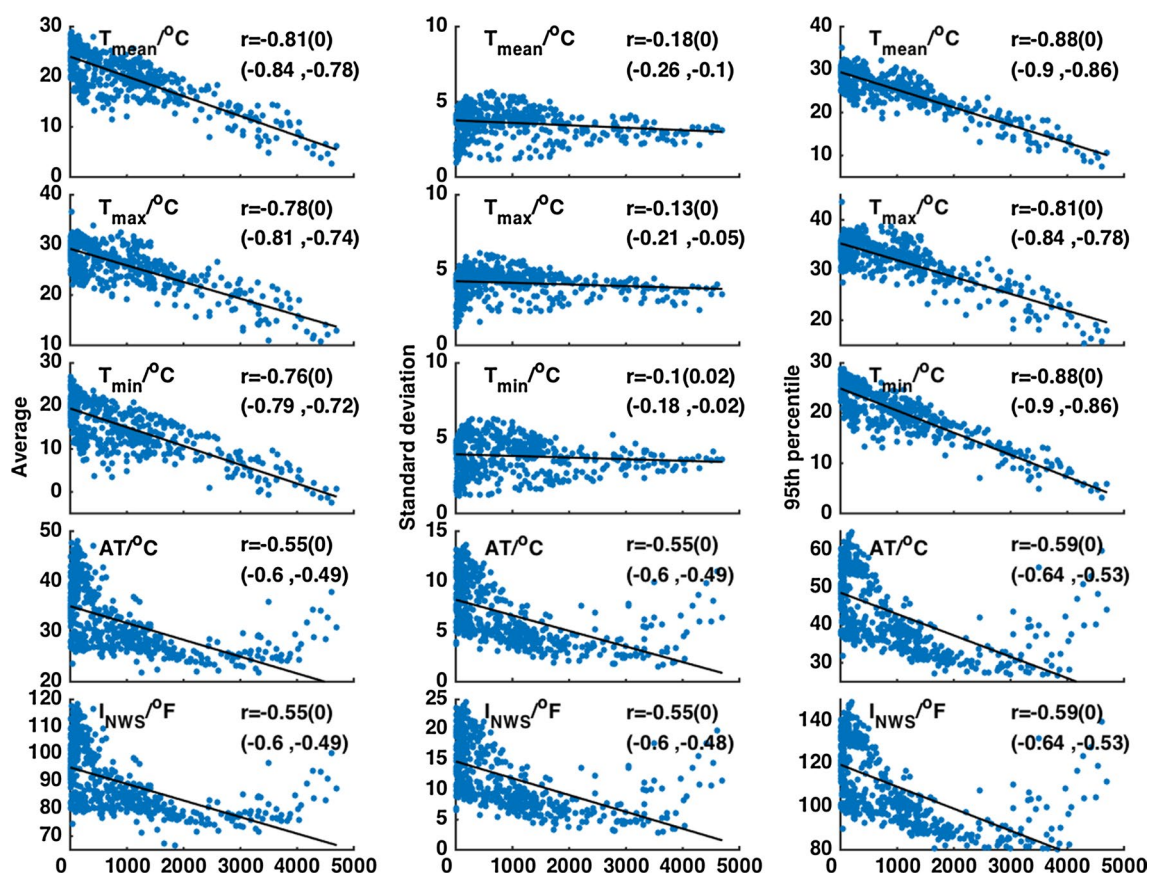
Fig. 4 Correlation coefficients between average (*left panel*), standard deviation (*middle panel*) and 95th percentile (*right panel*) of five temperature metrics in China during 1961–1990 and the elevation (m) of stations in China. Five temperature metrics are daily mean temperature (T_{mean}/°C), maximum temperature (T_{max}/°C), minimum temperature (T_{min}/°C), apparent temperature (AT/°C) and the National Weather Service's (NWS) heat index (INWS/°F). Texts are correlation coefficients with its *P* values and 95 % confidence interval (in *parentheses*)

(°F). The five temperature metrics have similar climatological patterns with higher values in eastern China and lower values in the west. This pattern provides the climate background to define relative HIs. Figure 4 presents the correlation coefficients between several statistics (correlation coefficients, standard deviation and 95th percentile) of these five temperature metrics and station elevation in China. For the climatologies, a significant negative relationship can be seen (left panel) because the temperature tends to decrease with increasing altitude. However, there is an unusual increase of AT and I_{NWS} within the 4000–4500 m elevation range. The standard deviation of the five metrics also tends to decrease with elevation for T_{max}, T_{mean}, and T_{min}, suggesting that variability of temperature is reduced at high elevations. However, prominent negative correlations with elevation are still detected for the standard deviation of AT and I_{NWS}. The results using the 95th percentile of temperature metrics are similar to those using the average.

Figure 5 shows the annual average of HW days in China defined using the 16 HIs during 1961–2014. The scale bars vary depending on the definition so as to accentuate the spatial patterns. The average number of annual HW days over eight sub-regions in China during 1961–2014 is summarized in Table 2.

Using different definitions, the annual average number of HW days during 1961–2014 varies from 0.56 (HI7) to 90.35 (HI13). Three HIs have annual averages below 3 days (HI7, HI12 and HI16), and six have annual averages above 10 days (HI1, HI8, HI11, HI13, HI14 and HI15).

Despite large differences in absolute frequencies, the spatial patterns for most HIs are broadly similar. The highest frequency of HW occurrence is usually in either the JH or SC sub-region (for sub-region definition see Fig. 1). For instance, four HIs (HI5–HI7, and HI10) have the largest frequency in the JH sub-region, and eight HIs (HI3–HI4, and HI11–HI16) in the SC sub-region. The NEC and TP sub-regions experience the lowest frequencies in most HIs. On the other hand, HI8–HI9 show the largest annual average of HW days in the WNC region, and HI1–HI2 in the TP region. This suggests that not all HIs agree and potentially
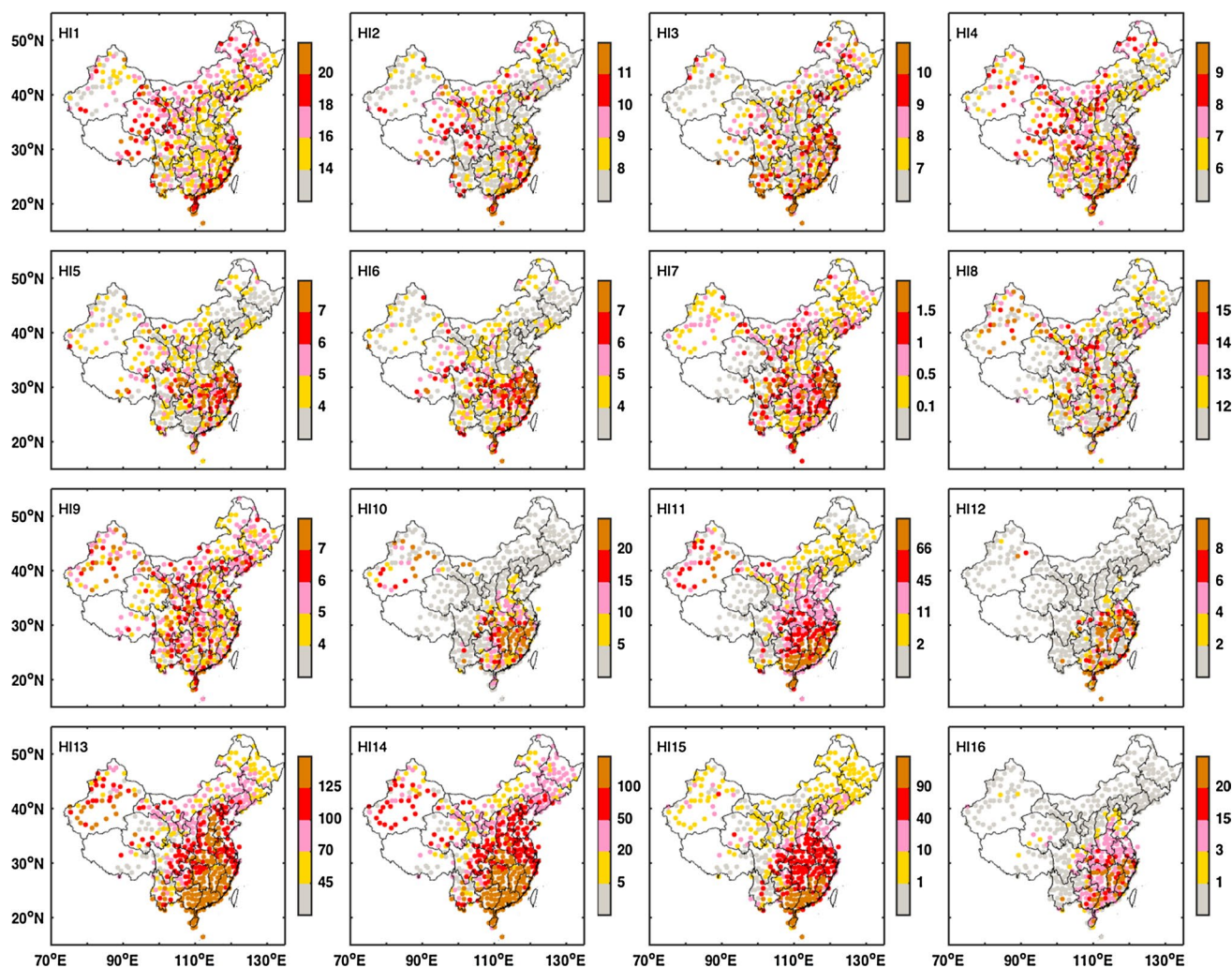
Fig. 5 Average annual number of heat wave days in China during 1961–2014 according to the sixteen HIs defined in the text

identify contrasting characteristics of HW occurrence in China.

Figure 6 shows the time series of average HW days (upper panels) and Z values with modified MK trend test (lower panel) over the whole of China during 1961–2014 for each HI. It is clear that most time series show decreased trends before 1990s and rapid increases afterwards, leading to positive trends overall during 1961–2014. Figure 7 summaries trend magnitudes and significance for all HIs in all sub-regions during 1961–2014, 1961–1990 and 1991–2014, respectively. The spatial patterns of these trends during the same three periods are presented in Figs. 8, 9 and 10, respectively.

The general findings from Fig. 7 are that most HIs show an increase over the whole period (first of the three columns in each case), but sometimes there is a significant decrease during 1961–1990 followed by a rapid increase during 1991–2014. Although there are exceptions to these generalizations, the absolute indices (H10–H16) often show strong decreases in the first half of the record and the most statistically significant increases tend to be in the relative indices (H01–H09) in JH, SC and SWC, especially over recent decades.

Examining the whole period (1961–2014), the majority of 16 HIs shows significant warming in each region, except HI16 (Fig. 8). The first four HIs show strong increases over most of China, particularly HI1 and HI3. The strongest trends are in the southern regions. Unusually, the NC region has experienced a significant decreasing trend for some indices (HI10, and HI16) and decreasing trends also occur in JH and TP regions for HI8 and HI9. Although relatively small areas, these do cover large centers of population, and so we cannot assume that HWs are increasing in frequency everywhere in China, even over the longest period. Moreover, it is notable that five (NC, JH, SC, TP, WNW) of eight regions all experienced a significant decreasing trend for
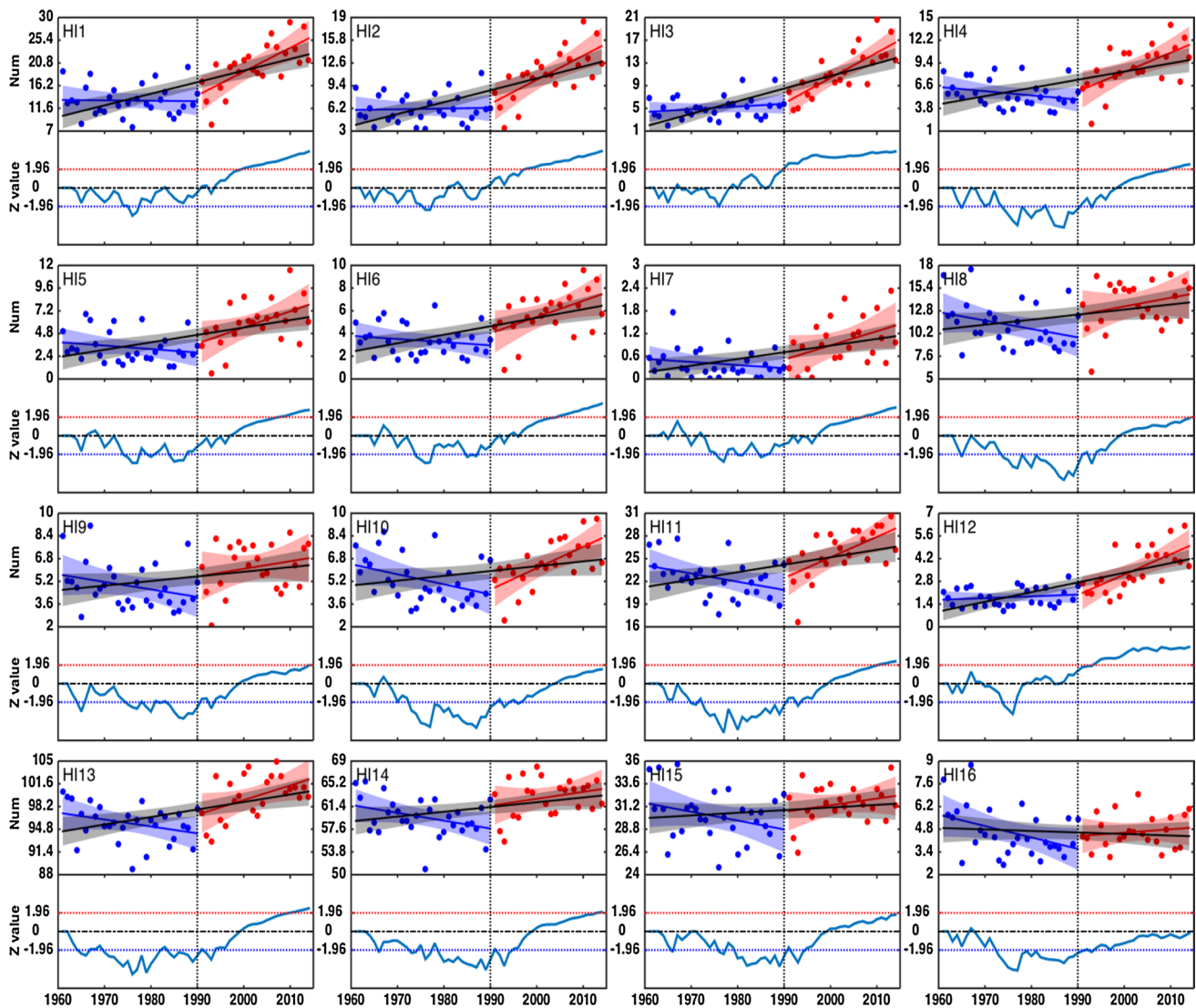
Fig. 6 Time series of average annual heat wave frequency (*upper panels*) and Z values with modified Mann–Kendall trend test (*lower panels*) over the whole of China during 1961–2014 for each heat wave index (HI). The *black line* denotes the generalized linear model regression (GLM) for the number of heat wave days during 1961–2014, *blue* denotes GLM for 1961–1990, *red* denotes GLM for 1991–2014, respectively. The *shading* represents the 95 % confidence level

HI16 that may be related to a decreasing trend of relative humidity in China over recent decades.

Over the period 1961–1990 (Fig. 9), decreasing trends are dominant and have been found for all HIs in NC, JH and ENC regions. The strongest decreases are usually reported in the JH region. There are exceptions to the general pattern with an increasing trend detected for eleven HIs in WNW, four in NEC, seven in SC, three in SWC and six in the TP region (also see Fig. 7).

During the most recent period (1991–2014) there has been a strong turnaround in HW days with strong increases in all regions and for all HIs (Fig. 10). Particularly rapid increases were detected in JH for HI1, HI3, and HI11; SC for HI1, HI2, HI3 and HI11; and SWC for HI1-HI4.

Decreasing trends were only detected for HI8 in NC and WNC; HI9 in WNC and ENC; HI15 in NC, TP, WNW and ENC; and HI16 in NC and ENC. To summarize, both relative and absolute HIs show decreasing trends up until 1990 (particularly in the JH region) but there has been a strong reversal since 1990. Although these contrasting trends could weaken the longer-term trends during 1961–2014 to some extent, nevertheless there are still significant increases over the longer-term period in the majority of regions.

Table 3 summarizes the correlation coefficients between the annual HW days calculated for each HI. It is clear that correlations among HIs in the same type are strongly positive, but those between HIs in the two different types

	NEC			NC			JH			SC			SWC			TP			WNC			ENC		
	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014	1961-2014	1961-1990	1991-2014
HI1	2.77	1.53	5.84	2.14	-2.71	5.25	2.45	-3.95	5.74	4.14	4.57	8.74	3.28	0.15	7.96	4.73	3.22	9.88	2.68	1.74	6.89	2.91	-1.24	6.67
HI2	1.65	1.54	4.07	1.34	-1.42	3.35	1.76	-2.26	4.94	2.67	2.43	6.64	2.02	0.28	5.44	2.97	1.99	7	1.8	0.92	5.22	1.95	-0.8	4.64
HI3	1.75	1.49	4.35	1.44	-0.6	3.33	1.98	-0.75	5.13	3.23	2.11	8.71	2.79	0.76	7.38	2.86	0.86	8	1.71	1.09	4.62	1.86	-0.33	5.46
HI4	1.02	-0.68	2.87	0.83	-1.65	2.37	1.6	-1.91	3.75	2.05	1.15	5.44	1.57	-0.11	4.55	1.4	1.24	3.09	1.26	0.54	3.27	1.36	-0.87	4.53
HI5	NaN	NaN	0.71	NaN	NaN	1.55	1.26	NaN	3.36	0.72	-0.88	4.32	0.29	NaN	2.75	0.31	NaN	3.72	0.39	NaN	0.82	0.02	NaN	2.33
HI6	NaN	NaN	1.25	NaN	NaN	NaN	1.44	-0.19	2.85	1.06	-0.23	4.59	0.11	-0.31	2.35	0.4	NaN	4.75	0.03	0.85	0.74	0.1	NaN	1.88
HI7	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
HI8	0.95	-0.97	4.02	0.48	-2.32	-1.44	-0.41	-3.17	0.63	1.24	-0.57	2.28	1.31	-0.84	5.6	-0.2	-0.02	4.49	1.95	0.86	-3.2	1.05	-1.31	0.44
HI9	0.26	0.82	1.55	0.52	-1.48	0.64	-0.13	-1.71	0.33	0.72	-0.66	1.57	0.66	-0.7	3.21	-0.17	-0.84	2.1	1.14	0.67	-2.11	0.64	-0.42	-0.56
HI10	NaN	NaN	NaN	-1.67	-2.03	1.75	1.28	-3.53	5	2.03	-0.92	6.06	1.14	-1.31	6.54	NaN	NaN	NaN	1.75	1.07	3.41	0.84	-1.42	NaN
HI11	0.78	-0.4	1.7	1.03	-3.6	0.93	1.06	-5.96	7.62	4.69	4.74	8.47	1.92	-4.46	7.05	NaN	NaN	NaN	2.72	-1.2	6.58	1.36	-2.27	5.3
HI12	NaN	NaN	NaN	NaN	NaN	NaN	1.67	-1.18	4.56	2.7	2.24	7.37	0.75	-0.68	3.27	NaN	NaN	NaN	0.28	NaN	2.89	NaN	NaN	NaN
HI13	2.28	-3.58	5.64	1.74	-3.58	2.18	1.77	-2.96	3.47	0.79	-1.48	3.29	2.53	-1.44	7.43	-0.54	1.35	0.65	1.55	0.12	2.44	1.41	-2.89	2.85
HI14	1.66	-2.64	4.83	1.69	-3.27	1.75	1.34	-3.47	3.51	0.58	-2.4	1.72	1.51	-1.04	5.13	-1.44	-0.24	-1.34	2.91	1.33	-2.8	0.86	-2.47	-0.51
HI15	-0.15	-0.01	0.27	0.04	-2.57	-2.71	0.04	-4.35	3.35	2.19	0.38	4.58	0.96	-2.66	3.54	-1.6	-0.59	-4.85	1.02	1.23	-1.93	-0.07	-0.68	-1
HI16	NaN	NaN	NaN	-0.4	-1.17	-0.17	-0.96	-3.28	0.23	-0.2	-1.83	1.36	0.02	-0.9	2.17	-0.37	0.5	2	-0.56	-2.22	-1.1	NaN	NaN	-0.71

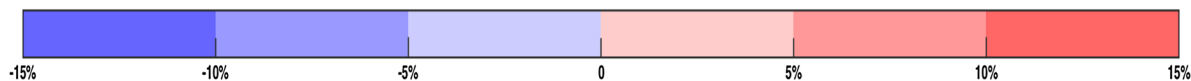-15%　　-10%　　-5%　　0　　5%　　10%　　15%

Fig. 7 Trends (days/decade) in the number of annual heat wave days over eight sub-regions in China for each heat wave index (HI) during the periods 1961–2014, 1961–1990 and 1991–2014, respectively. NaN means the trends failing the significant test. The *color* of the cell represents positive (*red*) and negative (*blue*) trends. The *shades of red/blue* represent the station percentage covered by this significant trend given by the *scale bar*

(absolute vs relative) are weak and even negative in some cases. Moreover, spatial patterns and trends observed in relative threshold HIs (HI1–HI9) are not always consistent with absolute threshold HIs (HI10–HI16). This means the selection of HI has important consequences. The two types of HI show different impacts and significant differences exist, evident in contrasting trends of duration, intensity and frequency of HW events. Relative thresholds are commonly used to detect the evolving statistics of extremes using a probability of exceedance in some metric, and a fixed percentile of the temperature distribution (Smith et al. 2013). On the other hand, absolute thresholds encompass more absolute or fixed aspects of human physiology,

acknowledging that many thermo-physiological functions are fundamentally the same among all populations. Common heat alerts are based on absolute thresholds (Amengual et al. 2014; Smith et al. 2013).

4 Discussion and conclusions

HWs are of great environmental concern for numerous reasons, including their influence on local drought and desertification (Meehl and Tebaldi 2004; Schär et al. 2004; Wu et al. 2012a) which can lead to water shortages and a worsening ecological environment. Therefore, the
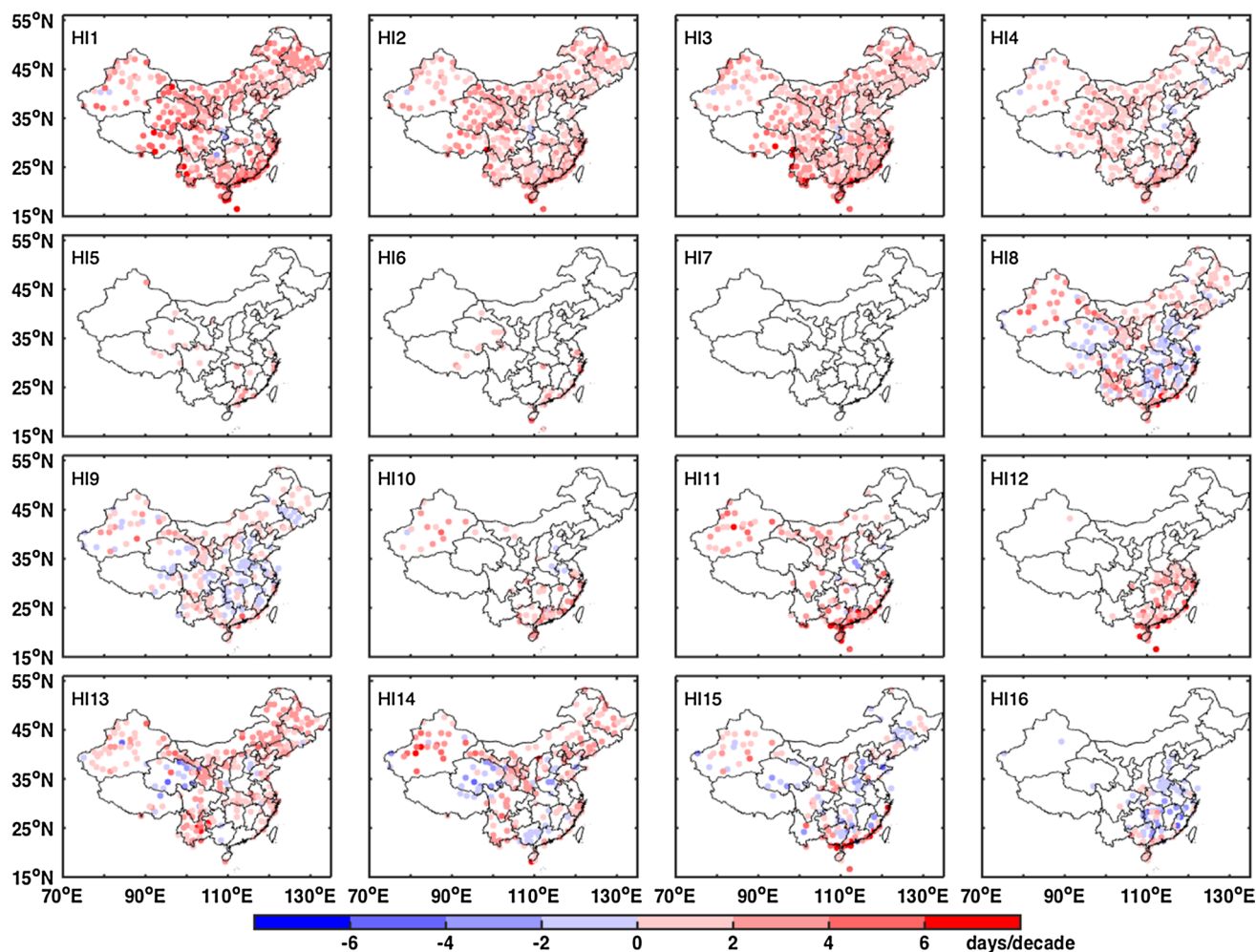
Fig. 8 Spatial distribution of trends in the number of annual heat wave days over eight sub-regions in China during 1961–2014 for each heat wave index (HI)

understanding of HWs trends in China is essential to understand why there are discrepancies between HW definitions for climate scientists, health researchers, and the general public. We compare results based on multiple definitions (Meehl and Tebaldi 2004; Perkins 2016; Smith et al. 2013; Wu et al. 2012b) in this study.

In this study, sixteen HIs have been compared and results are generally consistent with warming observed in previous studies (Qian and Lin 2004; Ren et al. 2011; Sun et al. 2014; You et al. 2011). During 1961–2014, the frequency of HW days has increased over nearly all of China, and the majority of HIs show similar patterns. The largest positive trends have occurred in JH, SC and SWC regions where there are large population centers and already high levels of heat stress. Because of varying definitions of HWs, the geographical patterns of HW days are varied among the HIs. Usually there are higher values located in the south of China and lower values in the north, but this pattern is strongest for the absolute indices (H10–H16). The relative

indices can show contrasting spatial distributions. In addition, HI8 and HI9 are calculated from apparent temperature which includes both temperature and relative humidity, and the geographical patterns of high HW days from both these indices correspond with high humidity (i.e. focused in the east of China). Similar research in the United States (Smith et al. 2013) has shown that the spatial range in average number of HW days is greater for absolute than for relative HIs which is also shown in our study (note the particularly high ranges for HI13 and HI15).

From the trend analysis, it is apparent that most HIs decrease up until 1990 and increase afterwards, which is in line with the rapid warming after the 1990s in China (Li et al. 2014; Qian and Lin 2004; Ren et al. 2011). Over the longer 1961–2014 period, the JH and SC regions have experienced both the largest magnitude and most widespread increases in HWs in most HIs. In a previous study, Wu et al. (2012a, b) applied HI06 to northern China, and showed increased HW days in recent decades, connected
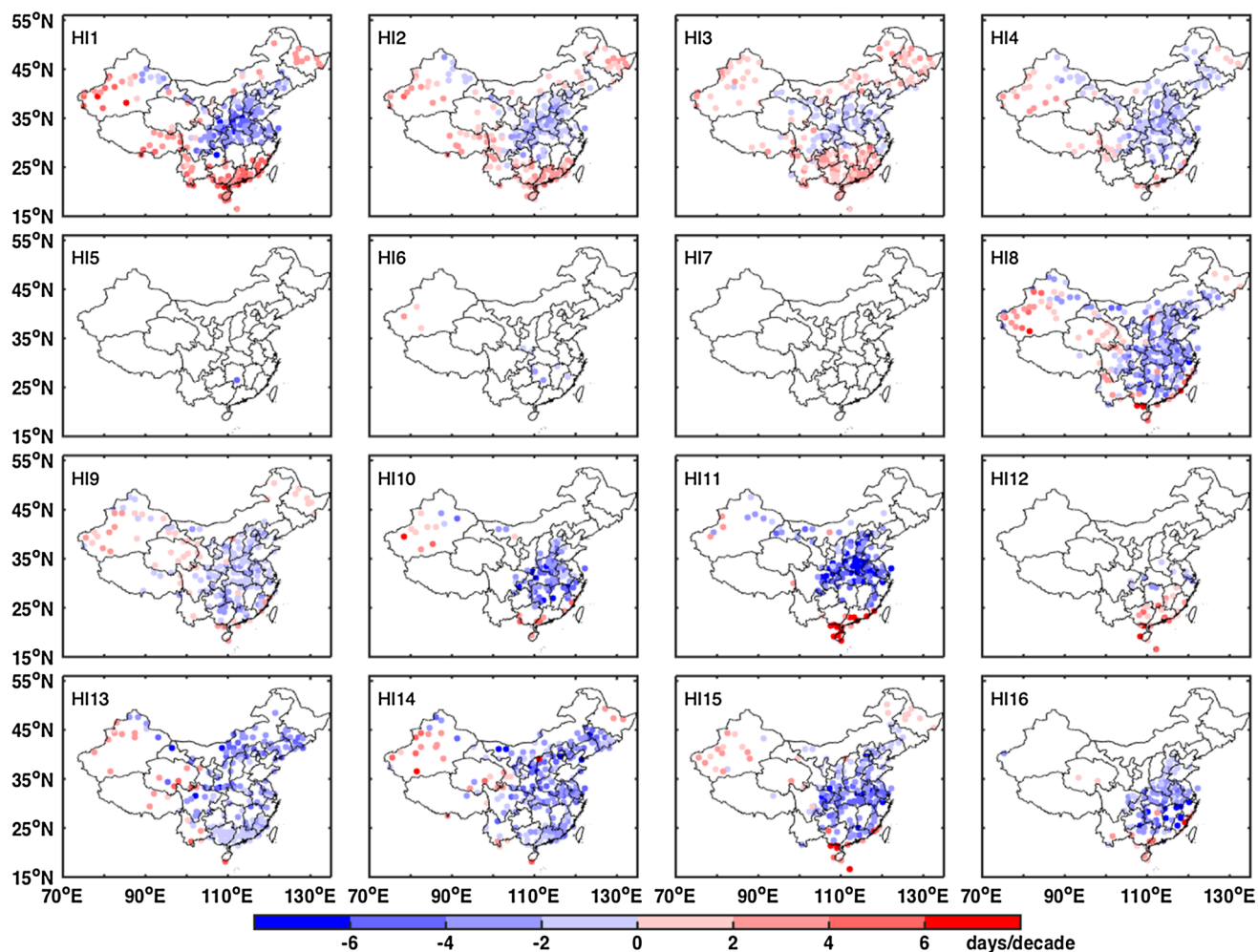
Fig. 9 Same as Fig. 8 but for the period 1961–1990

with variability in the western Tibetan Plateau snow cover. Wang et al. (2015) defined a hot spell as a day with T_{max} higher than the 95th percentile threshold of T_{max} during 1961–1990 (not one of the HIs used in this paper), and studied the changes of hot spells during 1960–2005 from both observations and CMIP5 model output. In another study, which used HI11, intensified HWs were shown to occur in eastern China associated with changes in large scale circulation. In many cases an abnormally intense summer subtropical high developed over eastern China, is connected to a west-drifted west Pacific subtropical high and a weakened India–Burma trough (Tan and Huang 2004; Tan et al. 2007; Ye et al. 2013). Beyond these case-study examples, it is difficult to compare studies, because differences in the period of analysis, data sources, the number of stations, and HWs definitions can all contribute to inconsistencies

in results (Smith et al. 2013). Unfortunately, this can lead confusion in assessments of the magnitude and geography of HW trends.

Since there is no standard definition for a HW (Table 4), we have applied analysis of observations in China to compare patterns and trends across sixteen previously published HIs. The choice of HIs has been shown to be critically important to the resulting analysis of patterns and trends (Fig. 9). In future work similar index comparisons could be translated easily to different datasets, in particular if a focused local analysis is required. Similar comparisons should therefore be performed using other meteorological datasets and for future climate model projections in order to explore the full range of potential HW impacts associated with climate variability and change (Fischer 2014; Fischer and Schär 2010; Meehl and Tebaldi 2004; Smith et al. 2013).
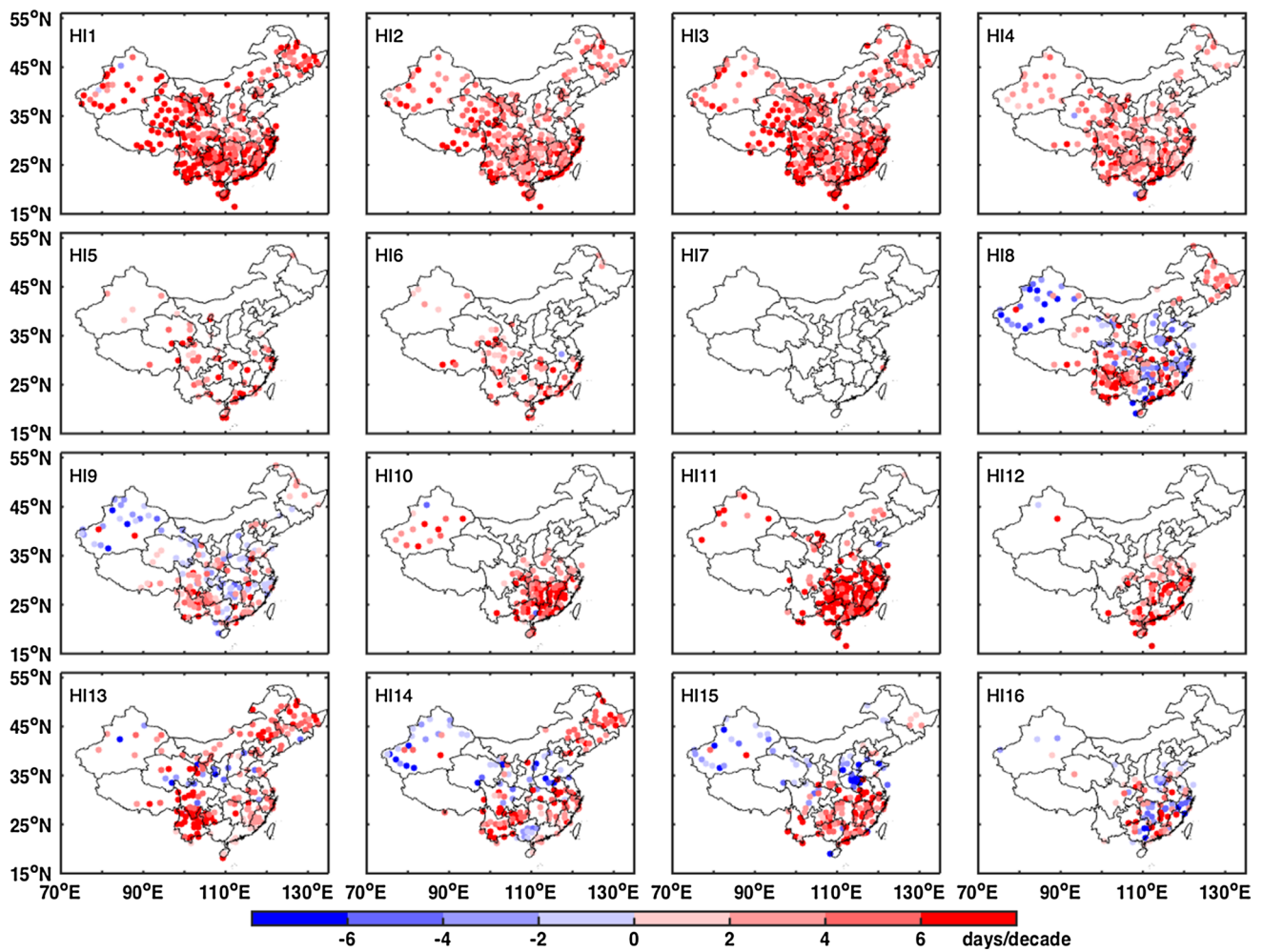
Fig. 10 Same as Fig. 8 but for the period 1991–2014

Table 3 Correlation coefficients between average numbers of annual heat wave days for each heat wave index (HI)

	HI1	HI2	HI3	HI4	HI5	HI6	HI7	HI8	HI9	HI10	HI11	HI12	HI13	HI14	HI15	HI16
HI1	1.00															
HI2	0.93	1.00														
HI3	0.60	0.61	1.00													
HI4	0.50	0.56	0.27	1.00												
HI5	0.35	0.46	0.24	0.76	1.00											
HI6	0.41	0.50	0.31	0.73	0.88	1.00										
HI7	0.16	0.27	0.21	0.52	0.68	0.67	1.00									
HI8	0.09	0.05	−0.09	0.42	0.20	0.18	0.21	1.00								
HI9	0.12	0.08	−0.09	0.45	0.25	0.22	0.20	0.94	1.00							
HI10	−0.15	−0.08	−0.07	0.02	0.24	0.25	0.25	−0.08	−0.06	1.00						
HI11	−0.07	0.00	0.04	0.08	0.20	0.27	0.29	−0.06	−0.05	0.82	1.00					
HI12	0.26	0.29	0.26	0.16	0.26	0.35	0.27	−0.06	−0.06	0.32	0.37	1.00				
HI13	0.00	0.05	0.13	0.06	0.16	0.24	0.35	0.05	0.05	0.55	0.77	0.39	1.00			
HI14	0.05	0.11	0.21	0.10	0.21	0.33	0.35	−0.05	−0.05	0.58	0.84	0.47	0.93	1.00		
HI15	0.09	0.17	0.24	0.14	0.25	0.39	0.35	−0.14	−0.13	0.58	0.85	0.48	0.78	0.94	1.00	
HI16	−0.05	0.04	0.10	0.09	0.30	0.39	0.36	−0.19	−0.17	0.70	0.76	0.24	0.57	0.69	0.80	1.00

Table 4 Summary of past studies of trends and patterns of heat waves on regional and worldwide scales

Continent	Region/country	Heat wave index	Study period	References
Europe	Ukraine	A period of more than 5 consecutive days with $T_{max} \geq 5$ °C above the mean T_{max} for the normal climatic period 1961–1990	1951–2011	Shevchenko et al. (2014)
	Hungary	$T_{mean} \geq 25$ °C, 1 consecutive day	1961–2100	Pongrácz et al. (2013)
	Turkey	HI9	1965–2006	Unal et al. (2013)
	Entire Europe	HI6	1961–2100	Fischer and Schär (2010)
	Western Europe	The number of consecutive 3-day periods that exceed the long-term daily 80th percentile of T_{max}	1880–2003	Della-Marta et al. (2007)
	Czech Republic	HI5	1961–2100	Kyselý (2010)
	Central Europe	T_{max} above the 95th annual percentile		Tomczyk and Bednorz (2016)
	Western Europe	periods of at least 3 consecutive days of extremely high daily maximum temperature affecting at least 30 % of western Europe	1979–2100	Schoetter et al. (2015)
America	Continental US	Multiple HI	1979–2011	Smith et al. (2013)
	Pacific Northwest	Three or more consecutive days above the 99th percentile for the maximum (9.5 °C) or minimum (4.6 °C) temperature anomalies	1901–2009	Bumbaco et al. (2013)
	North America	HI6	1958–2010	Wu et al. (2012b)
	50 large US cities	Similar to HI08, but for 85th percentile	1961–2010	Habeeb et al. (2015)
Asia	China	HI6	1968–2009	Wu et al. (2012a)
	China	HI7	1961–2010	Ye et al. (2013)
	China	Similar to HI4, but for one consecutive day	1960–2005	Wang et al. (2015)
	Shanghai	HI7	1873–2010	Chen et al. (2013)
	Japan	HI6	1979–2003 and 2075–2099	Nakano et al. (2013)
Australia	Entire Australia	T_{max} exceeds a 90th percentile for three or more consecutive days, and T_{min} exceeds a 90th percentile on the second and third days	2006–2100	Cowan et al. (2014)
	Southern Australia	T_{max} exceeds a 90th percentile for three or more consecutive days, and T_{min} exceeds a 90th percentile on the second and third days	1979–2008	Pezza et al. (2012)
	Australia	Three or more consecutive days above one of the following: the 90th percentile for T_{max}, the 90th percentile for T_{min}, and positive extreme heat factor conditions.	1951–2008	Perkins and Alexander (2013)
Africa	Southern Africa	Daily T_{max} values exceeded the 90th percentile for at least 3 consecutive days	1961–2100	Lyon (2009)

The definition of the heat wave is given in full if not one of the sixteen used in this study

The temporal evolution of different HIs appears to be reasonably coherent, and efforts should be made to obtain a clearer understanding of the underlying physical mechanisms which explain HW occurrence. The scientific understanding of HWs has been summarized into three main drivers: synoptic systems, soil moisture and land surface interactions, and climate variability (Perkins 2016). In China, it is mentioned that circulation anomalies are a key factor behind extreme HWs (Lu and Chen 2016). Synoptic-scale characteristics and associated atmospheric circulation anomalies within extreme HWs in southeastern, southwestern, and eastern China are investigated by Wang et al. (2016). These are the regions where the highest frequencies of HWs are also detected among most HIs in this study. During the studied period, the sixteen HIs have negative correlations with Pacific Decadal Oscillation (PDO) index in most cases (Table 5). From 1960 to 1990, the PDO was in a positive phase, which will weaken the East Asian summer monsoon, and decrease the frequency of extreme high temperature events in China. Thus it is suggested that the PDO may contribute to the variability of HWs in China. In addition, many studies have also pointed out that Western North Pacific Subtropical High and the South Asian High, as the major components of the East Asian Monsoon system, play an important role in the variability of high temperatures in China (Wang et al. 2014; Zhang et al. 2005). Thus, synoptic

Table 5 Correlation coefficients between Pacific Decadal Oscillation (PDO) index and 16 heat wave indices during 1961–2014

	HI1	HI2	HI3	HI4	HI5	HI6	HI7	HI8	HI9	HI10	HI11	HI12	HI13	HI14	HI15	HI16
Before detrend	−0.22	−0.17	−0.13	−0.22	−0.18	−0.17	−0.08	**−0.31**	**−0.25**	**−0.32**	**−0.33**	−0.09	**−0.29**	**−0.34**	**−0.32**	**−0.25**
After detrend	**−0.45**	**−0.40**	**−0.41**	**−0.38**	**−0.30**	**−0.30**	−0.17	**−0.38**	**−0.31**	**−0.38**	**−0.46**	**−0.29**	**−0.42**	**−0.42**	**−0.35**	**−0.24**

Correlation coefficients with significance at the 5 % level are in bold

systems and circulation anomalies associated with extreme HWs in China are a focus of ongoing study, necessary for a deeper understanding of HWs in China.

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