Li Yi, Ding Yihui, and Li Weijing, 2017: Observed trends in various aspects of compound heat waves across China from 1961 to 2015. J. Meteor. Res.,

31(x), XXX—XXX, doi: 10.1007/s13351-017-6150-2.(in press)

Observed Trends in Various Aspects of Compound Heat Waves across China from 1961 to 2015

Li Yi^{1,2,3} (李 怡), Ding Yihui³ (丁一汇), and Li Weijing^{2,3} (李维京)

1 Chinese Academy of Meteorological Sciences, Beijing 100081

2 Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044

3 Laboratory for Climate Studies, National Climate Center, Beijing 100081

(Received September 2, 2016; in final form November 8, 2016)

Supported by the National Basic Research and Development (973) Program of China (2013CB430203 and 2012CB417205), the China Meteorological Administration Special Public Welfare Research Fund (GYHY201306033), the National Natural Science Foundation of China (41275073), the Program of Science and Technology Development in Sichuan Meteorological Bureau (2014-09), and the Project for Postgraduate Scientific Research and Innovation of Jiangsu Province (Grant No. KYLX16_0933).

Corresponding author: <u>liviant@126.com.</u> ©The Chinese Meteorological Society and Springer-Verlag Berlin Heidelberg 2017

ABSTRACT

Based on combined thresholds of daily maximum and minimum temperatures, a compound heat wave is defined, and then changes in multiple aspects of such heat waves in China are estimated between 1961 and 2015. Our results intriguingly indicate that severe compound heat waves in northern China are characterized by excessively high intensity within short duration, while long duration determines great disaster-causing potential of severe events in the south. In the past few decades, large areas of China have experienced longer, stronger, and more frequent compound heat waves. Northern China has witnessed dramatic intensity increases, with a maximum amplification over 5 °C decade⁻¹; while remarkable lengthening in duration has been mostly recorded in the south, with a maximum trend over 1 day decade⁻¹. The spatial extent affected by compound heat waves has significantly expanded since the 1960s, with the largest expanding rate over 6% decade⁻¹ detected in North China and Northeast China.

These systematic assessments serve to deepen our understanding of observed changes in compound heat waves across China, and may further shed some light on future adaptations and mitigations against an increasingly warming climate. **Key words:** heat wave, climate change, duration, intensity, spatial extent

1. Introduction

During summer, heat wave-induced morbidity and mortality among temperature-sensitive groups, like infants, the elderly and cardiovascular patients are alarmingly high. Such high impacts of heat waves have been reinforced by numerous literatures during the past few decades (Basu and Samet, 2002), and was punctuated by a record-breaking case in 2003, which hit vast areas of Europe and led to approximately 40,000 deaths (Garc *n*-Herrera et al., 2010). Furthermore, heat stress accumulated during heat waves could result in massive electricity shortages, higher risks of forest fire, and lower productivity of crops (Garc *á*-Herrera et al., 2010). In general, heat waves (HWs) are commonly recognized as a spell of consecutive warm days, but concrete definitions differ among various sectors (Perkins et al., 2012). On a warming globe, increasing occurrences of warm days in many regions have elevated risks of heat waves (IPCC, 2013). In fact, most parts of the world have not only witnessed increased frequency, but also experienced higher intensity and longer duration of heat waves, especially after 2000 (Perkins et al., 2012; Smith et al., 2013; Kuglitsch et al., 2010). Increased frequency was largely ascribed to increased mean summertime temperature (Della-Marta et al., 2007), while amplified intensity resulted more from enhanced temperature variability (Fischer and Schär, 2010). Some climate model projections imply that these increases in mean and variability of summertime temperature will continue or even accelerate, so more HWs with unprecedented duration and intensity will possibly happen by the end of the 21st century (Meehl and Tebaldi, 2004; Guo et al., 2016).

While one-day extremes of warm days/nights were widely investigated, comparably little work has been done to assess HWs comprehensively (IPCC, 2013), notably in China. In China, a finite number of studies concerned on definitions and changes of heat waves, in which consideration of HWs was mostly confined to high daytime heat (Jiang et al., 2012). However, long-lasting extreme weathers tend to trigger severer disasters, so indices measuring duration and intensity are also warranted (Zhang et al., 2011). It is now well-acknowledged that heat waves have significantly increased in China since the latter part of the 20th century (Ding et al., 2010; Ding and Qian, 2011; Wei and Chen, 2011; Wang et al., 2012). The frequency of hot weather events in Shanghai was much larger in the first decade of the 21st century than at any time since 1873 (Chen et al., 2013; Xia et al., 2016). In contrast, the US, European and Australian scientific communities and governments are more concerned about compound heat waves composed of both warm days and nights, which may severely disturb human body thermoregulation and energy supply (Patz et al., 2005). Furthermore, in existing studies in China, changes in HW frequency seemed the primary concern, while other equally important indicators, such as duration, spatial coverage and intensity, were substantially under-emphasized (Ding et al., 2010; Guo et al., 2016). In this context, a systematic estimation of compound HWs in China is still desirable. Our study therefore aims to narrow above-mentioned gaps of heat wave studies in China. Specifically, quantitative assessments would be performed with respect to changes of various aspects of compound HWs, including their frequency, number of days involved, duration, intensity, and spatial extent.

2. Data and methods

2.1 Data preparations

Summertime (June-August) daily maximum temperature (Tmax) and daily minimum temperature (Tmin) between 1961 and 2015 are selected from a dataset covering 756 stations across China. This dataset is gained from the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). Before being released, it has gone through fastidious quality control by the NMIC, with some missing observations completed, suspect/wrong values rectified, and temporal-spatial inconsistencies due to new instrumentations and site relocations reconciled (documentation available online <u>http://edc.cma.gov.cn/home.do)</u>. Having been validated in many studies (Li et al., 2013; Ren et al., 2014; Chen and Zhai, 2013), this dataset is recognized as one of the best tools currently available for climate research in China. Apart from the above quality controls, we have performed some additional pretreatments to ensure that:

(1). missing data for Tmax and Tmin account for less than 5% of total records in every year between 1961 and 2015;

(2). any horizontal relocation of stations throughout the entire period is within 20km-radius; and elevation relocation is less than 50m vertically;

These procedures aim to guarantee the continuity and greatest homogeneity. This dataset covers almost all national reference climate stations (first-class stations) and national basic meteorological stations (second-class stations). The variables observed in each station represent meteorological elements within 20km-radius around it, so a relocation threshold of 20km is routinely applied to minimize inhomogeneity from site displacements (Ren et al., 2014). Particularly, site relocation doesn't mean significant changes in surface cover types, since environment (e.g. buildings and trees) in the vicinity of observational fields is universal stipulated by the CMA. 376 stations are finally retained for subsequent analyses (as distributed in Fig. 1.), and these stations turn out well-distributed in eastern China, but sparsely dotted in the West.



Fig. 1. Spatial distribution of 376 stations (as marked by black triangles) under quality control procedure. Different regions are divided by red curves and labelled with blue letters, A for Northeast China, B for Huang-Huai, C for Yangtze River Valley, D for South China, E for Southwest China, F for North China, and G for Xinjiang.

2.2 Methods

Many studies defined heat waves merely based on Tmax (Ding et al., 2010; Wang et al. 2012). In fact, consecutive hot days without relief from nighttime cooling

are more devastating to human health (Meehl and Tebaldi, 2004; Karl and Knight, 1997). It is therefore necessary to define a heat wave with both daytime high and overnight low taken into account (Robinson, 2001). In this study, a heat wave is defined as a spell of three or more consecutive hot days and nights. Such kind of heat wave is referred to as a "compound heat wave" hereafter. Three-day is adopted as a minimum duration to guarantee necessary persistency. Particularly, two independent heat waves is required to be sandwiched by at least two consecutive non-extreme day $(Tmax < 90^{th} percentile or Tmin < 90^{th} percentile)$. A hot day/night is defined as one with a Tmax/Tmin above 90th percentiles of their respective long-term counterparts (1961-2015). Following the method introduced by Della-Marta et al. (2007), daily 90th percentile of Tmax/Tmin for each day during June-August is calculated from corresponding units of data samples, each of which contains 15 days (composed of the specific day and respective seven days before and after it) in a given year; then these sample units for days between 1961 and 2015 are assembled (i.e. total samples $15 \times 55 = 825$ days). A less critical threshold (90th percentile) for hot day/night is rationally adopted (Della-Marta et al., 2007), because an at-least 3-day duration and extreme Tmax/Tmin are required simultaneously. Identifications with higher percentiles (95th or 99th) substantially reduce the number of HWs, leading to many HW-undetected (figure not shown) years. Few HW samples would impair the reliability of the following linear trend estimations. In existing studies, 90th percentile algorithm was also widely applied to represent the rareness of temperature extremes (Fischer and Sch är, 2010).

Figure 2 shows some illustrating examples depicting differences in identification based on daily percentiles and traditional seasonal percentiles. Daily 90th percentiles exhibit pronounced intra-seasonal variation, with lower thresholds in early and late summer, which is consistent with temporal evolution of observed Tmax/Tmin. Under a fixed seasonal percentile, early-summer (before 20 June) HWs are likely to be ignored (as shown in Fig. 2a-b), a problem prevailing over 90% of all stations. However, despite lower intensity, these early-summer HWs can be more health-damaging than mid-summer ones (Kalkstein and Smoyer, 1993). Early-summer HWs can trigger a greater death toll among susceptible populations who are overwhelmed by sudden scorching weather at so early stages (Laurence et al., 2008). By contrast, in mid-later summer, vulnerable groups may have become more adapted physiologically and behaviorally after long-time exposure to high ambient temperatures (Basu and Samet, 2002). During mid-summer, similar HWs (Fig. 2b) can be identified by daily percentiles and seasonal thresholds in some stations. However, in many cases, identified peak-summer HWs by seasonal percentiles fail to meet daily percentiles' criteria, which tend to be more critical, as shown in Fig. 2c. In other words, in terms of intensity, daily percentiles may yield severer mid-summer HWs. The percentile-based threshold also enables HW changes comparable among regions of different prevailing climates (Robinson, 2001). So, events identified by daily percentiles represent extremely hot anomalies, with respect to normal conditions from both temporal and spatial perspectives.

The definition doesn't entail an absolute threshold either (30 $^{\circ}$ C or 35 $^{\circ}$ C), as

recommended by the CMA. In a warming climate, temperatures in some regions frequently exceeded these prescribed thresholds with no disastrous consequences to health or agriculture, thanks to technological (e.g. air conditioning and irrigation) or physiological precautions made in response to high temperature alerts. Based on varying daily percentiles, our HW definition, not only represent extremity statistically, but also emphasizes potential adverse impacts of these extremes (e.g. agricultural disasters, power outages, and water supply shortages) in the context of increasingly warming climate.

çc



Fig. 2. Examples of heat wave identification by daily and seasonal thresholds. Solid blue (green) lines and dashed blue (green) lines represent seasonal (daily) 90th percentiles of Tmax and Tmin respectively; solid red lines and dashed red lines stand for Tmax and Tmin series; Heat wave days identified by daily and seasonal 90th percentiles have been respectively labeled with *" and "+".

Four indices are designed to quantify heat waves:

Heat wave number (HWN) – the occurrence frequency of heat wave events;

Heat wave day frequency (HWF) - the total number of days involved in all heat wave

events;

Heat wave duration (HWD) - the length of each heat wave;

Heat wave intensity (HWI) – the amplitude of a heat wave calculated as accumulated exceedances of both Tmax and Tmin above thresholds during its duration,

$$HWI = \sum_{t=1}^{t=Duration} (T \max(t) - T \max_{threshold(t)}) + (T \min(t) - T \min_{threshold(t)}), (1)$$

HWN considers the heat wave as a whole, while the HWF tallies all extreme warm days/nights up during heat waves. For example, if there are 2 heat waves in a year, with one lasting for 3 days and the other for 5 days, then the annual HWN, HWF, and mean HWD are 2, 8 days, and 4 days respectively. A great HWI, according to Eq.1, may result from long duration and/or large exceedances above thresholds (Kuglitsch et al., 2010).

In addition to above four indictors, an index measuring spatial extent of compound HWs is also constructed. To avoid possible uncertainties and inaccuracies brought in by interpolation, a method called "frozen grid" based on raw station observations, rather than gridded data, is employed (Jones, 1986). Firstly, mainland China is divided into 2.5 °longitude by 2.5 °latitude boxes. Assuming there are totally ns(i) stations located within box-*i*, and among ns(i) stations, nh(i,t) stations record at least one heat wave during summer in year-*t*, the spatial coverage of HWs in year-*t* (for the whole country or a specific region) should be :

Spatial
$$_coverage(t) = \sum_{t=1}^{i=number} \frac{nh(i,t)}{ns(i)} \times 2.5 \times 2.5 \times 110 \times 110 \times cos(latitude), (2)$$

in which "110" denotes the approximate distance per unit longitude/latitude, and "number" represents the total number of boxes in the target region. Considering variation of box area with latitude, the spatial extent is also weighted by central latitude of each box. If simply represented by the number of affected stations, the spatial coverage in regions with sparse stations (e.g. Xinjiang and North China) would be much smaller than that in the East, an area boasting dense observational networks. Via the "frozen grid" scheme, the spatial coverage of compound HWs in different regions could be impartially compared by the percentages of stations recording HWs in boxes. So the frozen grid method serves to minimize the influences of uneven station distribution on spatial extent evaluation (Chen and Zhai, 2013). Our sensitive tests indicate that selection of 2° , 2.5° and 3° for the box scale does not significantly affect estimated spatial coverage, or the following trend analyses. Considering varying box number among sub-regions (see Section 3), in addition to absolute changes (km² decade⁻¹), estimated spatial coverage of HWs is also normalized (divided) by respective total areas to yield percentages (% decade⁻¹) for further comparisons.

To evaluate linear trends of different parameters, Kendall's tau slope estimator (Sen, 1968) is employed----this nonparametric method is sufficiently insensitive to potential outliers, and it does not assume any distributional forms of the original data. Significance of linear trends at the 0.05 level is also estimated via the Kendall's tau test. The probability density function (PDF) is evaluated with kernel density estimation scheme, which is also detached from any prescribed assumption of distributional forms of the original data. rsion'

3. Results

3.1 Basic features of HWs

During the past 55 years, compound HWs occurred most frequently in the Yangtze River Valley (YRV) and South China (Fig. 3a), with a maximum accumulated occurrence of 80 recorded in Yin-Xian station in the YRV. Northern China also witnessed frequent HWs, with total occurrences of 30-40. During mid-summer (21 June-10 August), daily 90th percentiles of Tmax in central-eastern China, South China and Northwest China usually exceed 35 $^{\circ}$ (Fig. 3b; Fig. 2a and 2c). Coincidently, daily 90th percentiles of Tmin in these regions are higher than 20 $^{\circ}$ C or even 25 ℃, meeting "tropical nights" criterion (Tmin≥20°C, Fischer and Schär, 2010). Consistent with intra-seasonal variations revealed in Fig. 2, daily percentiles in early summer (Fig. 3c) and late summer (Fig. 3d) are not as high as those in peak summer. During early summer, the configuration between extremely high daytime and nighttime percentiles mainly exist over northern parts of eastern China and Xinjiang area, while during late summer combined high percentiles mainly prevail in the south of the Huai-River. Identified HWs based on such combined thresholds (Tmax≥35°C and Tmin≥20°C) reportedly accounted for excessive mortality (Grizea et al., 2005). Remarkably, the adoption of daily percentiles explicitly accentuates regions with high

risks of severe compound heat waves during different summer stages.

Monthly distribution of HWs can also be revealed owing to utilizing daily percentiles (figure omitted). During June, HWs mainly hit the middle reach of the Yangtze River and coastal regions of South China. By contrast, July often witnesses HWs in the lower reaches of the Yangtze River, Northern and Southern China. Long-lasting (over 5 days) HWs mainly concentrate during July, notably in mid-lower reaches of the Yangtze River. During August, the number of long-lasting HWs drops substantially, and high-frequency regions are distributed more dispersedly along the Yangtze River and southern coastal regions.



Fig. 3. (a) total number of HWs during 1961-2015, (b)-(d) mean 90th percentiles of Tmax and Tmin in peak summer (during 21 June-10 August), early summer (during 1 June-20 June), and late summer (during 11 August-31 August), in which only stations

with Tmax (Tmin) percentiles above 30 °C (20 °C) are presented.

3.2 Linear trend estimations

Significant increases of nationwide HWN, HWF, HWD, and HWI (0.10±0.04 frequency decade⁻¹, 0.56±0.20 days decade⁻¹, 0.10±0.06 days decade⁻¹ and 0.75 ± 0.52 °C decade⁻¹) were observed, which indicate more occurrences, longer duration and greater intensity of HWs across China during the past few decades. Specifically, significant increases of the HWN are mainly detected in northern China (north of 35 N) and southern China (south of 30 N), sandwiched by a band of insignificant weak negative trends (Fig. 4a). The stations with a positive HWN trend of 0.4 frequency decade⁻¹ or greater are mainly located in the Yangtze River Valley and South China. The HWN doubled in large swaths of China over the last decade, compared to that during the 1960s. The HWN in Southwest China increased dramatically, from 0.60 per year in the 1960s to 1.53 per year in the last decade (figure not shown). Increasingly frequent HWs may partly account for severer droughts across Southwest China since 1995 (Wang et al., 2016). More heat wave days (HWF) were also observed in most parts of China, which constitute a spatial pattern similar to that of HWN (Fig. 4b). The most significant increases in HWF are observed in the Yangtze River Valley and South China, with the largest linear trends above 3 days decade⁻¹. Compared to the corresponding figure during the 1960s, the HWF in the Yangtze River Valley, Northeast China and Southwest China nearly tripled after 2000 (figure omitted). The mean duration of HWs in each year can be

deduced via $\frac{HWF}{HWN}$, in which both indices increased over most stations as discussed above. The lengthened duration in Fig. 4c suggests greater magnitude of growth in HWF than in HWN, and also implies an amalgamating trend between increasing warm days/nights. Mean HWI increases of 3 $^{\circ}$ decade⁻¹ or above are mainly detected in northern China (Fig. 4d). Also greatly amplified (above 4 $^{\circ}$ decade⁻¹) is the mean intensity of HWs in the Yangtze River Delta dotted with several fast-developing metropolises, such as Shanghai. Trends for intensity in this densely-populated area are two-three times larger than those in neighboring regions, implying possible anthropogenic contributions to heat wave intensification there. Representing accumulated exceedances above thresholds during HWs, the HWI is determined by both duration and intensity of Tmax and Tmin. The magnitude of duration increase in northern and southern China are similar (Fig. 4c), so much sharper increases of HWI in northern China arise more from greater growth in daily maximum and minimum temperatures at higher latitudes (Serreze et al., 2000). Frequent HWs with greater HWI have accelerated desertification and grassland degradation in Northern China, posing a great threat to local ecosystem and economy (Xue, 1996).



Fig. 4. Linear trends for (a) HWN (frequency decade⁻¹), (b) HWF (days decade⁻¹), (c) mean HWD (days decade⁻¹), and (d) mean HWI ($^{\circ}$ C decade⁻¹). The filled dots indicate trends significant at 0.05 levels.

Remarkably, in contrast to significant positive trends in above regions, insignificantly negative and weak trends of all HW indices were observed in regions between the Huang River and the Yangtze River, which mainly resulted from significant decreases in hot days (Fig. 5a). Also revealed by Ding et al. (2010) and Ye et al. (2013), such drastic reductions in hot days led to significant decreases in Tmax-based heat waves in this area. Apparent differences in magnitude, significance or even signs (positive/negative) of linear trends for compound HWs and Tmax-based HWs further justify the necessity of separately assessing diverse heat wave types. A pan-China pattern of significant increases of hot nights (Fig. 5b) across China indicate

a more sensitive response of nighttime low to climate warming, which may arise from natural variability and/or anthropogenic influences.



Fig. 5. Linear trends for (a) hot days frequency (days decade⁻¹), (b) hot nights frequency (days decade⁻¹). The filled circles indicate trends significant at 0.05 level.

As shown in Fig. 4, trends for heat wave indices display distinctive regional peculiarities, matching well with climate zones classified by summer temperature (Liu and Zhai, 2013; Zou et al., 2005). Based on a comprehensive consideration of regional features of HW indices and climate zones, China is then divided into several sub-regions as shown in Fig. 1. All the indices are then evaluated at regional scales as presented in Table 1. In general, greater increases of HWN, HWF and mean HWD are found in South China, Southwest China, and Yangtze River Valley. The largest increases of both HWN and HWF are observed in the Yangtze River Valley with respective linear trends of 0.24 ± 0.10 frequency decade⁻¹ and 1.13 ± 0.52 days decade⁻¹. The most obvious lengthening in duration is registered in Southwest China with a linear trend of 0.49 ± 0.18 days decade⁻¹. Larger increases in HWI are detected in

northern China. In Huang-Huai region, changes for all four indices are weak and insignificant.

The spatial extent of HW increased nationwide at a linear trend of $41.16\pm12.66\ 10^4\ km^2\ decade^{-1}$. From another perspective, such increased trend can be translated into that compound HWs swept larger portions $(4.43\%\pm1.36\%\ decade^{-1})$ of mainland China, where few events of this type were registered in the past. Such phenomenon of heat wave expansion is also manifested in each sub-region, as listed in Table 1. The maximum expansion of spatial coverage is detected in Northeast China and North China, with about extra 6% intact territory in these regions scorched by compound heat waves per decade after 1961. Of particular note is that despite no significant increases or even slight decreases in occurrences of compound heat waves in the Huang-Huai region, spatial coverage show significant positive trend there. Such phenomenon implies that compound heat waves tend to appear more evenly across the Huang-Huai region, rather than repeatedly occurred in some specific stations. Multi-model projections of heat wave coverage imply that the regions suffering compound HWs would further expand (Guo et al., 2016).

Table 1. Linear trends for domain-averaged HWN (frequency decade-1), HWF (days decade⁻¹), mean HWD (days decade⁻¹), mean HWI (°C decade⁻¹), and spatial extent (104 km2 decade-1, % decade-1 for the values in bracket) during 1961-2015

	YRV	South	Xin Jiang	North	Northeast	Huang Huai	Southwest
		China		China	China		China
HWN	0.24±0.10	0.19±0.06	0.16±0.07	0.12±0.08	0.14±0.08	-0.01±0.92	0.19±0.06
HWF	1.13±0.52	0.93±0.29	0.74±0.29	0.58±0.34	0.56±0.30	-0.06±0.37	0.89±0.26

HWD	0.32±0.23	0.21±0.13	0.42±0.19	0.18±0.21	0.28±0.22	-0.06±0.24	0.49±0.18
HWI	1.24±0.69	0.80±0.35	2.01±0.81	1.28±1.01	1.81±1.18	0.43±0.88	1.78±0.69
Extent	3.71±2.52	4.79±1.89	3.99±1.69	9.12±4.29	4.48±1.15	3.71±2.95	3.99±1.57
	(5.92±4.02)	(3.44±1.35)	(4.44±1.88)	(6.40±3.01)	(6.73±1.73)	(3.38±2.69)	(3.96±1.56)

Note: Trends in bold indicate a significance level of 0.05. The error estimates are 95% confidence intervals based on the standard error of the Kendall's tau estimator. The linear trends of the "Extent Index" are further normalized (divided) by respective total areas of each sub-region, as listed in the second row of "Extent".

3.3 Severe HWs

Severe heat waves, characterized by long duration and/or high intensity, would result in serious casualty and economic damage. D'Ippoliti et al. (2010) concluded that in some European cities, the mortality was up to 3 times greater during severe HWs than moderate HWs. To further assess severe HWs, linear trends for the annual longest duration and maximum intensity of HWs are explored (as displayed in Fig. 6). Sharpest lengthening of the longest duration mainly occurred in Yangtze River Valley and South China, while the largest increase of maximum intensity (above 3 $^{\circ}$ C decade⁻¹) was mainly observed in North China. The Tmax and Tmin in most days during strongest HWs exceed their 95th or even 99th percentile, although they were originally identified based on their respective 90th percentiles. Within each sub-region, events with the longest duration and the maximum intensity are selected among all stations to intuitively demonstrate the severity of these high-impact HWs (Fig. 7). The lengthening trend of the longest duration and increases of the maximum intensity are clearly revealed in Fig. 7 and validated in Table 2. Fig. 7 shows a general consistency between durations of the strongest HWs (dashed lines) and the longest-lasting events (red bars), which highlights long duration's role in extraordinary heat stress

accumulation. In the Yangtze River Valley and southern China, the longest duration usually exceeds a week. A typical case is that a 22-day compound HW affected South China in 1998. In such long-lasting heat waves, duration plays a more critical role than intensity in elevating mortality. Mortality grows non-linearly (but rather, exponentially) with duration in long-lasting HWs (Hajat et al., 2006), with an estimate of 2.5–4% extra deaths per day beyond the first three HW days (Anderson and Bell, 2011). By contrast, events with duration longer than 7 days were rarely reported in northern China, especially before 1996. In spite of shorter duration, severe HWs in North and Northeast China can be characterized by an intensity equivalent to or even greater than that of most longer-lasting HWs in the South. For example, the intensity of an 8-day event in Northeast China in 2010 (Fig. 7e) exceeded 70 °C, greater than the intensity accumulated over 20 days in the Yangtze River Valley and South China. Great heat stress accumulated during a concentrated spell would swiftly damage agriculture, human thermoregulation, and local power supply. As for events with short-lasting HWs and extremely high intensity, the intensity is the ringleader of high mortality. A small rise in intensity was reportedly responsible for considerable increases in mortality in the UK and US, with an estimate of 2.47% to 4.23% of

unnatural death for every extra degree above the threshold (Anderson and Bell, 2011).

What is worth noticing is that linear trends of longest duration and maximum intensity are much larger than those for mean duration and intensity (comparing Table 1 and Table 2). In other words, severe events have been getting even substantially severer. Consistent with variations in mean intensity and duration, increasing rate of longest duration is larger in southern China, while amplification of maximum intensity are greater in northern China. Particularly, the Yangtze River Valley, though located in southern China, experienced greatest amplification of maximum intensity. Such exception may be attributed to rapid urbanization and anthropogenic emissions (Du et al. 2016).



Fig. 6. Linear trends for (a) longest duration (days decade⁻¹), (b) the maximum intensity ($^{\circ}$ decade⁻¹) in every station. The filled circles indicate trends significant at the level.

Table 2. Linear trends for longest duration (days decade⁻¹), and the maximum

NY	YRV	South	Xin Jiang	North	Northeast	Huang	Southwest
		China		China	China	Huai	China
Longest	1.11±0.80	1.47±0.50	0.93±0.28	0.89±0.43	0.63±0.36	-0.04±0.46	1.17±0.31
duration							
Maximum	6.10±3.32	4.71±1.33	4.99±2.07	5.25±3.22	4.81±2.44	1.80±2.32	4.77±1.59
intensity							

i	ntensity ($^{\circ}$ decade ⁻¹) in si	ub-regions	during	1961	-2015
---	------------	---------------------------------	---------	------------	--------	------	-------

Note: Trends in bold indicate a significance level of 0.05. The error estimates are 95% confidence intervals based on the standard error of the Kendall's tau estimator.



Fig. 7. Severe heat waves with longest duration (red bars and left y-axis) and maximum intensity (blue bars, right y-axis) in each sub-region. The durations for strongest events (left y-axis) are illustrated by based lines.

Changes in the mean and variability of temperature may account for variations of HW indices (Fischer and Sch ä, 2010). As presented in Fig. 7, the intensity and duration of severe HWs show marked decadal shifts, with greater duration and intensity most frequent over the last two decades. Thus, decadal variations in the mean and variability of temperature are examined via comparing PDF (probability density function) curves (Figure 8). Increases in both mean Tmax and Tmin are characterized by positive shifts of PDF curves in most sub-regions, excluding Huang-Huai region. The most obvious shift, as recorded in Southwest China, brought more hot days and nights, which narrowed temporal gaps between isolated warm events and further lengthened HWs. This may explain why the largest increase of duration was observed in Southwest China. Generally, the shape of PDF curves in northern China is wider and flatter, indicating greater temperature variability there, notably during the last two decades. Such variation entails more frequent appearance of excessively high Tmax/Tmin. These analyses imply that the recent frequent severe HWs with higher intensity in northern China were jointly contributed by increased variability and mean Tmax/Tmin, the latter of which dominated in inducing increasing occurrences of severe HWs with longer duration and greater intensity in southern China over the past two decades.



Fig. 8 Decadal changes in Probability Density Function (PDF) of Tmax and Tmin in most-affected sub-regions

4. Discussions and conclusions

4.1 Limitations and discussions

Some conclusions still need interpreting cautiously, though a proper slope estimator (Kendall's tau) and rigorous significance tests are applied in this study. Main estimations have been made favorably via linear trend analyses, but this approach may get stuck with HW indices with strong decadal oscillations, which possibly exist in stations with insignificant weak trends (Della-Marta et al., 2007). Moreover, linear trend analyses are also sensitive to the periods selected, the diversity of which may account for the differences between estimated trends in different studies. In addition to the uncertainties above, there are punchy evidence suggesting accelerating urbanization may lead to severer heat waves and hence higher mortality (Bian et al., 2015). Particularly, city expansions may raise risks of compound heat waves downtown by favoring warm nights and dampened winds (Lemonsu et al., 2015). So municipal interventions and precautions should mitigate such elevated risks (Vanos et al., 2015). It is also imperative to further partition the impacts of anthropogenic activities and natural variabilities on heat waves (Sun et al., 2014).

The simultaneous consideration of Tmax and Tmin was intended to link HWs with heat-relate mortality. However few long-term mortality data is currently available for analyses in China. Very short records (usually after 2005) in limited big cities, such as Shanghai and Guangzhou, were used in previous study (Gao et al., 2015). So, data for long-term heat-related mortality in other cities/stations needs collecting to support follow-up studies (Chen et al., 2015). In 19 stations located in mountains or plateaus, though exceeding 90th percentile, Tmax/Tmin may still lower than 25 C/15 C, especially during early summer. In these stations, early-summer events should be more exactly referred to as "hot spells" instead of heat waves.

The PDF curves presented in Section 3.3 qualitatively depicted decadal variation of the mean and variability of Tmax/Tmin. Quantitative estimation only discovered insignificant changes of kurtosis coefficients for the curves in all the sub-regions. Sch är et al. (2004) revealed a nonlinear correlation between increases in temperature variability and HW intensity in Europe. Such correlation has also been found in other regions, where very trivial and insignificant changes of kurtosis corresponded to substantial increases of HW intensity (Simolo et al., 2011).

In terms of heat waves changes, responses to global warming vary regionally. For instance, inland China's increases in HWF are similar to those in eastern America (0.5-2 days decade⁻¹, Smith et al., 2013), while rises in duration across eastern Mediterranean region (2 days decade⁻¹, Kuglitsch et al., 2010) are much larger than those in our study. Climate model projections aiming at compound HWs are further needed to tell whether these changes HWs will continue. A deeper understanding of HW trends may and their future behaviors could provide scientific supports for precautions against heat-related disasters.

4.2 Conclusions

Our study focuses on features and trends for compound heat waves across China during 1961-2015. Compound heat waves are defined by a combined threshold of daily maximum temperature (Tmax) and minimum temperature (Tmin), with both meteorological extremity and health impacts taken into consideration. Few studies have been conducted with respect to such kind of heat waves in China.

Compound heat waves are quantified by four indices, namely HWN (number), HWF (day frequency), HWD (duration) and HWI (intensity), whose significant increase are observed in most parts of China, except for Huang-Huai region. The sharpest lengthening in duration was recorded in southern China, with a maximum trend of 0.49±0.18 days decade⁻¹ in Southwest China. The intensity of the identified HWs rose dramatically in northern China, coastal regions along South China, and the Yangtze River Valley. The HWs in northern China, compared to those in southern China, are characterized by larger increases in intensity but smaller lengthening in duration. Spatial extent of HWs has expanded across China since 1961, especially in northern China. Similar increasing trends can also been found when severe HWs with longest duration and/or maximum intensity are investigated. In terms of intensity, severe HWs in northern China could be, despite a much shorter duration, comparable to or even stronger than their counterpart in the south.

This study has provided a systematic evaluation of trends for compound heat waves in China, with an attempt to narrow the gap of understanding about such devastating heat wave type in China and in the rest of the world.

References

Anderson, G. B. and M. L. Bell, 2011: Heat waves in the United States: mortality risk

28

during heat waves and effect modification by heat wave characteristics in 43 US communities. *Environmental health perspectives*, 119, 210-218.

- Basu, R. and J. M. Samet, 2002: Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiologic reviews*, 24, 190-202.
- Bian, T., G. Ren, B. Zhang, et al., 2015: Urbanization effect on long-term trends of extreme temperature indices at Shijiazhuang station, North China. *Theor. Appl. Climatol.*, 119, 407-418.
- Chen, K., Bi J., J. Chen, X. D.Chen, et al., 2015: Influence of heat wave definitions to the added effect of heat waves on daily mortality in Nanjing, China. *Science of the Total Environment*, 506, 18-25.
- Chen, M., F. H. Geng, L. M. Ma, et al., 2013: Analyses on the heat wave events in Shanghai in recent 138 years. Plateau Meteorology, 32, 597-607.
- Chen, Y., and P. M. Zhai, 2013: Persistent extreme precipitation events in China during 1951-2010. *Climate Research*, 57,143-155.
- Della Marta, P. M., M. R. Haylock, J. Luterbacher, et al., 2007: Doubled length of western European summer heat waves since 1880. *J. Geophys. Res. Atmospheres*, 112, D15103 doi 10.1029/2007JD008510.
- Ding, T., W. Qian, Z. Yan, 2010: Changes in hot days and heat waves in China during 1961–2007. *Int. J. Climatol.*, 30,1452-1462.
- Ding, T., W. Qian, 2011: Geographical patterns and temporal variations of regional dry and wet heatwave events in China during 1960–2008. *Adv. Atmos. Sci.*, 28,

322-337.

- D'Ippoliti, D., P. Michelozzi, C. Marino, et al., 2010: The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environmental Health*, 9, 37-45.
- Du, H. Y., D. D. Wang, Y. Y. Wang, et al., 2016: Influences of land cover types, meteorological conditions anthropogenic heat and urban area on surface urban heat island in the Yangtze River Delta Urban Agglomeration. Science of the *Total Environment*, 571, 461-470.
- Fischer, E., C. Schär, 2010: Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, **3**, 398-403.
- Gao, J. H., Y. Sun, Q. Liu, et al., 2015: Impact of extreme high temperature on mortality and regional level definition of heat wave: A multi-city study in China. Science of the Total Environment, 505, 535-544.
- Garc á-Herrera, R., J. D áz, R. Trigo, et al., 2010: A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40, 267-306.
- Grizea, L., A. Hussa, O. Thommena, et al., 2005: Heat wave 2003 and mortality in Switzerland. Schweiz Med Wochenschr, 135, 200-205.
- Guo, X. J., J. B. Huang, Y. Luo, et al., 2016: Projection of heat waves over China for eight different global warming targets using 12 CMIP5 models. *Theor. Appl. Climatol.*, doi:10.1007/s00704-015-1718-1.

Hajat, S., B. Armstrong, M. Baccini, et al., 2006: Impact of high temperatures on

mortality: is there an added heat wave effect? *Epidemiology*, 17, 632-638.

- Jiang, Z. H., J. Song, L. Li, et al., 2012: Extreme climate events in China: IPCC-AR4 model evaluation and projection. *Climatic Change*, 110, 385–401.
- Jones, P., S. Raper, R. Bradley, et al., 1986: Northern Hemisphere surface air temperature variations: 1851-1984. J. Climate Appl. Meteor., 25, 161-179.
- Kalkstein, L. S., and K. E. Smoyer, 1993: The impact of climate change on human health: some international implications. *Experientia*, 49, 969-979.
- Karl, T. R. and R.W. Knight, 1997: The 1995 Chicago heat wave: How likely is a recurrence? *Bull. Amer. Meteor. Soc.*, 78, 1107-1119.
- Kuglitsch, F. G., A. Toreti, E. Xoplaki, et al., 2010: Heat wave changes in the eastern Mediterranean since 1960. *Geophys. Res. Lett.*, 37, L04802.
- Laurence, S. K., J. Greene, D. Mills, et al., 2008: Analog European Heat Waves for
 U.S. Cities to Analyze Impacts on Heat-Related Mortality. *Bull. Amer. Meteor. Soc.*, 89, 75–85.
- Li, X., L. Wang, D. L. Chen, et al., 2013: Near-surface air temperature lapse rates in the mainland China during 1962–2011. J. Geophys. Res.: Atmospheres, 118, 7505–7515.
- Liu, J., and P. M. Zhai, 2013: Changes in climate regionalization indices in China during 1961-2010. *Adv. Atmos. Sci.*, 31, 374-384.
- Lemonsu A, V. Vigui é, M. Daniel, V. Masson, 2015: Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). *Urban Climate* 14, 586-605.

Meehl, G. A. and C., Tebaldi, 2004: More intense, more frequent, and longer lasting

heat waves in the 21st century. Science, 305, 994-997.

- Patz, J. R., D. Campbell-Lendrum, T. Holloway, et al, 2005: Impact of regional climate change on human health. *Nature*, 438, 310-317.
- Perkins, S., L. Alexander, J. Nairn, 2012: Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophys. Res. Lett.*, **39** (20).
- Ren, G. Y., and Y. Q. Zhou, 2014: Urbanization effect on trends of extreme temperature indices of national stations over mainland China, 1961–2008. J. *Climate*, 27, 2340:2360.
- Robinson, P. J., 2001: On the definition of a heat wave. J. Appl. Meteor., 40, 762-775.
- Schär, C., P. L. Vidale, D. Lüthi, et al., 2004: The role of increasing temperature variability in European summer heatwaves. *Nature*, 427, 332-336.
- Sen, P. K., 1968: Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63, 1379-1389.
- Serreze, M. C., J. E. Walsh, F. S. Chapin Iii, et al., 2000: Observational evidence of recent change in the northern high-latitude environment. *Climatic change*,46, 159-207.
- Simolo, C., M. Brunetti, M. Maugeri, et al., 2011: Evolution of extreme temperatures in a warming climate. *Geophys. Res. Lett.*, 38, L16, 701 doi:10.1029/2011GL048437.
- Smith, T. T., B. F. Zaitchik, J. M. Gohlke, 2013: Heat waves in the United States: definitions, patterns and trends. *Climatic change*, 118, 811-825.

Stocker, T. F., D. Qin, G. K. Plattner, et al. IPCC, 2013: climate change 2013: the

physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 2013.

- Sun, Y., X. Zhang, F. W. Zwiers, et al., 2014: Rapid increase in the risk of extreme summer heat in Eastern China. *Nature Climate Change*, 4(12), 1082-1085.
- Vanos, J. K., L. S. Kalkstein, T. J. Sanford, 2015: Detecting synoptic warming trends across the US Midwest and implications to human health and heat-related mortality. *Int. J. Climatol.*, 35, 85-96.
- Wang, L. Y., X. Yuan, Z. H. Xie, et al., 2016: Increasing flash droughts over China during the recent global warming hiatus. *Scientific Reports*, doi:10.1038/srep30571.
- Wang, Z. Y., Y. H. Ding, Q. Zhang, Y. F. Song, 2012: Changing trends of daily temperature extremes with different intensities in China. Acta Meteorologica Sinica, 26, 399-409.
- Wei, K., W. Chen, 2011: An abrupt increase in the summer high temperature extreme days across China in the mid-1990s. *Adv. Atmos. Sci.*, 28, 1023-1029.
- Xia, J., K. Tu, Z. Yan, et al., 2016: The super heat wave in eastern China during July - August 2013: a perspective of climate change. International Journal of Climatology, 36(3), 1291-1298.
- Xue, Y., 1996: The impact of desertification in the Mongolian and the Inner Mongolian grassland on the regional climate. *J. Climate*, 9, 2173-2189.
- Ye, D. X., J. Yin, Z. H. Chen, et al., 2013: Spatiotemporal change characteristics of summer heat waves in China in 1961-2010. Adv. Climate Change Res., 9,

15-20.

inds

Zhang, X., L. Alexander, G. C. Hegerl, et al., 2011: Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: *Climate Change*, 2, 851-870.

Zou X. K., P. M. Zhai, Q.Zhang, 2005: Variations in droughts over China: 1951–2003. Geophys. Res. Lett., doi:10.1029/2004GL02185.

çc