(1) comments from Referee1

The manuscript is interesting, well written, well structured and easily understood by the reader. The authors introduce Heat Wave and Hot Year Indices in order to define and study heat waves in China. The statistical methodology is relatively simple, but useful and leads to interesting conclusions. However, I think that the authors could try to link the trends in heat waves to the corresponding variations/trends in the large-scale temperature and circulation characteristics over the region. For example, they could use grid point temperature, sea-level pressure and/or geopotential height data for the lower troposphere obtained from any of the known worlwide data sets (e.g NCEP/NCAR) in order to further support the justification analysis made in the last paragraph of the discussion section. This would be useful, taking into account that meteorological data obtained from surface meteorological stations located in (or near) cities are possibly affected by urbanization. I do not suggest an extensive analysis about this issue, taking into account that this case the manuscript would become huge, but 1-2 figures and a paragraph refering to such comparison could be useful.

Minor comments:

1. Page 5, Data and Methods, lines 112-115: Please explain more analytically the procedure used for the division of China into the 8 climate regions, or alternatively provide appropriate references.
2. Pages 6-8, Data and Methods, lines 143-180: Please provide a simple sensitivity analysis of the defined indices. For example, what are the ranges of the indices' values and how are these values affected by specific changes of CD, AD etc. The authors give some answers about this issue later in the results, but in my opinion the methodology section is the proper section to analyze this.
3. Figs 3 and 6: Please explain either in the caption or in the text what are the lines, boxes, points etc. in the diagram.
4. Lines 111 and 122: The number of the titles are the same (2.2). Please correct.

(2) Author's response:

1. The related reference about the division of China into the 8 climate regions are added in the part of Data and Methods, Pages 5, lines 113-114.
2. We have added a simple sensitivity analysis of the defined indices in the part of Data and Methods, Pages 7-8, lines 156-163 and lines 190-197.
3. The explains of the lines, boxes and points in the caption and the text of Fig 3 and 6 are added in Pages 23-24, lines 566-571 and lines 583-589.
4. The numbers of the titles are corrected in Pages 5-7, line 122, line 142 and line 173.

(3) Author's changes in manuscript

According to the reviewer's suggestion, we try to link the trends in heat waves to the corresponding variations/trends in the large-scale temperature and circulation characteristics over the region. Taking into account that this case the manuscript would become huge, we do not carry out a detailed analysis on the relationship of heat waves and the large-scale circulation; there are many literatures which have done extensive analysis about this issue and revealed the driving factors of heat waves in different regions of China. So we quoted the published results in the part of Discussion, Page 16-17, lines 378-387 to clarify the control factors of spatial distribution of heat waves.

For advice 1, we have cited the reference from Yang QY et al, which introduced the method, principle and process on the division of China into the 8 climate regions. The reference is as follow:

Yang, Q.Y., Wu, S.H., Zheng, D.,: A retrospect and prospect of researches on regional physio-geographical system (RPGS), Geo. Res., 21(4), 407-417, http://doi:10.1080/12265080208422884, 2002.

For advice 2, we have added the ranges of the indices' values and how are these values affected by specific changes of CD, AD etc. The content is as follow:

For HWI, there are two extreme situations. If there are no heat waves in one year, the value of HWI would be 1. If there are 92 continuous days of a year in which Tmax exceeds 40℃, the value of HWI would reach the biggest, 33792; for the real world, the second extreme situation would rarely occur except extreme catastrophe shocking. According to the statistics from 1955 to 2014 in China, the most serious heat wave event occurred in Changsha city in 2013 for which the value of HWI is no more than 140. The value of HWI is mostly determined by the number of continuous days in which Tmax exceeds 37℃, even 40℃. If the extreme hot days continue longer, HWI would be more serious.

For HYI, there are also two extreme situations. If there are no heat waves or hot days in one year, the value of HYI would be 1. The value of HYI is largely determined by the value of AHWI, which would reach 33792 at most; in other word, the intensity and frequency of heat wave events in one year is bigger, the hot year index would be more severe. There is insignificant impact on HYI for discontinuous days in which daily Tmax exceeds 35℃, comparing with heat wave events. According to the statistics, the hottest year is also in Changsha city in 2013, which contained the most serious heat wave event from 1955 to 2014 in China.

For advice 3, we have added explanation of the boxes, lines and points in the titles of Fig.3 and Fig.6. The content is as follow:

Fig. 3 Distribution of D_{35} in 29 cities from 1955 to 2014 (Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of D_{35} in 29 cities

Notes: There are no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.

Fig. 6 Distribution of amounts and frequencies of HWs in 29 cities from 1955 to 2014 (upper graph: amounts of HWs; lower graph: Frequency of HWs. Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of HWs frequencies and amounts in 29 cities

Notes: There is no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.

For advice 4, the title "2.2 Method" has been corrected into "2.3 Method"; the title "2.2.1 Heat wave index" has been corrected into"2.3.1 Heat wave index"; the title "2.2.2 Hot year index" has been corrected into"2.3.2 Hot year index".

(1) comments from Referee2

The manuscript proposes new indices for the study of heat waves and extreme temperature especially for cities in China. I find the manuscript to be interesting and the methodology is novel. Unfortunately, the proposed methodology is not well descripted, and more details should be added. I find the overall information presented in this paper below the standards of the Natural Hazards and Earth System Sciences and I believe that the paper requires entire modifications and needs to go through the review process again.

Indeed, there are some aspects that are weak. The main problem is the proposed methodology for the new indices. More specific: â˘A ´c The physical explanation of the index HWI (line 151, page 7) should be added. â˘A ´c I believe that there is a mistake in the equation of the first index, HWI, (line 151, page7). Is the multiplication sign correct of the first parameter for the CD35? I can not understand why it is multiplication and not sum. The rate CD35/92 should be change to AD35/92. â˘A ´c Moreover, I believe that an example should be added. I was tried to create an example for better understanding. Lets say that in a year there are 35 days with temperature greater than 35oC, from these days, there are 15 consecutive days with temp>35oC. Moreover from the initial 35 days, 15 days have temperatures greater than 37 oC (with 10 consecutive days greater than 37 oC) and 5 days have temperatures greater than 40 oC (with 10 consecutive days greater than 40 oC). Based on these data: HWI=(35/92 x 15/3+1)x(15/92+10/3+1)x(5/92+3/3+1) = HWI=(0.38x5+1)x(0.163+3.333+1) x(0.054+1+1)=2.9 x4.496x2.054=26.78 In case there is a mistake in the equation, HWI=6.38x4.496x2.054=58.92.

Based on the classification of Table 1, it is obvious that there is a mismatch for the range of the index. Please provide the appropriate modifications and explanations.

In the case of AHWI, there is a misunderstanding. It is not clear, how it is possible to be several HWI in a year. HWI use for its calculation the days with temperature greater than 35 (37/40) in the three months (June, July, August 92 days). Based on it, it is not possible to have more than one value per year. Please give some explanations. Based on the above comment, HYI (line 173, page 8) can be not defined with the proposed way. Below the Authors can find some minor comments and suggestions in case of resubmission. â˘A ´c Initially, I will suggest the description of the classification of the indices (table 1 and table 2) to be removed into methodology.

The analysis of figure 8 is not consistent with the figure 8. The scale of the diagram in figure 8 range from 0 to 900, the station Chongqing presents HWI equal to 800 while in the manuscript it is said ": : :sum value of HWIs in Chongqing reached 13.7: : :" (line 261, page 11). Similarly, the result about Changsha. Please made the appropriate modifications.

The section 3.1 can be changed to "variance of extreme temperature days" since in this paragraph it is analysed the trend of the extreme temperature days but the variance.

The quality of all figures is poor. The labels are too small, and it can not be read. â˘A ´c The authors should add more information about the secondary axis in figure 4 and 7.

The authors claim that the analysis is for 31 main stations in China, in figure 3, 6 and 5 are presented the results of 29 stations, while in figure 7 and 8 are presented the result of 26 stations. Similarly, in map of figure 9 is presented 29 station. Please provide the appropriate modifications.

(2) Author's response:

1. The explanation of the index HWI had been described in the manuscript (line 143-148, page 6) . HWI in this manuscript is established mainly based on statistical and empirical methods, which is created to compare the intensities and frequencies of heat wave events. The physical mechanism of heat waves is not the focal point in this manuscript.

2. The example of HWI is added in the part of Heat wave index (line 156-166, page 7). The equation of HWI has been checked for several times. The multiplication sign of the first parameter for the CD_{35} is correct. There is no mistake in the HWI equation. The differences in the three parentheses of HWI equation are to distinguish the importance of CD_{35}, AD_{37}, CD_{37}, AD_{40} and CD_{40}. For heat wave events, 3 continuous days are the shortest duration for HWs, in which daily Tmax exceeds 35℃. In other word, the continuous days in which daily Tmax exceeds 35℃are the basic requirement of heat wave events. The HWI values are mainly determined by AD_{37}, CD_{37}, AD_{40} and CD_{40}. The CD_{35} represents the continuous days in which daily Tmax exceeds 35℃, which is the same meaning of AD_{35}. The discontinuous days in which daily Tmax exceeds 35℃ are not belonged to heat wave events, which are not included in HWI equation; but these discontinuous days are exactly considered in HYI equation. According to the example that the reviewer had proposed, the value of CD_{35} should be 15, not 35; the values of AD_{37} and CD_{37} are 15 and 10; the values of AD_{40} and CD_{40} are 5 and 3. The calculation of HWI is, (15/92 x 15/3+1)x(15/92+10/3+1) x (5/92+3/3+1) =16.8.

3. The appropriate modifications on the classification of Table 1 has been done (line 553-554, page 21). We revise the description of each level of HWI, which becomes clear and easily understanding.

4. According to the definition of heat wave, the constant hot weather more than 3 continuous days in which daily Tmax exceeds 35℃ could be called one heat wave event. If the days (daily Tmax≥35℃) are not continuous, it could not be named one heat wave event. There may be several heat wave events occurring in one year. For example, in 2014, there were two HWs occurred in Chongqing city, separately lasting from 17 July to 31 July and from 2 August to 8 August. So the HYI index should contain all the HWs and the discontinuous days with extreme temperature (daily Tmax exceeding 35℃) in one year. We have checked AHWI and HYI equations and there are no mistakes in them. We believe that the description of the

classification of the indices (table 1 and table 2) should be in the part of Heat wave index (line 245-260, page 11; line 289-292, page 12-13) , which are close to the analysis process of HW index and HYI index.

5. We have checked the analysis of figure 8; it is consistent with the figure 8. The scale of the diagram in figure 8 range from 0 to 900, which represents the sum value of HWIs of 60 years from 1955 to 2014. In order to make it clearer, the description in the manuscript has been changed (line 278-287, page 12).

6. We have checked the content of section 3.1. It contains variance of extreme temperature days and trend of the extreme temperature days. It is more proper to use the current title "3.1 Trend of Extreme Temperature days".

7. We have developed the quality of all figure to resolve the problems. More information about the secondary axis in figure 4 and 7 are added.

8. There are no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities. So the results of the other 29 stations are presented in figure 3, 5 and 6. There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities. So the results of 26 stations are presented in figure 7 and 8. In order to be more clearer, we make appropriate modifications and add explanation in the titles of figure 3, 5, 6, 7 and 8.

(3) Author's changes in manuscript

For advice 1, there is no change in the manuscript. The interpretation has been given.

For advice 2, the example of HWI is added in the part of Heat wave index (line 156-166, page 7). The content is as follow:

For HWI, there are two extreme situations. If there are no heat waves in one year, the value of HWI would be 1. If there are 92 continuous days of a year in which Tmax exceeds 40℃, the value of HWI would reach the biggest, 33792; for the real world, the second extreme situation would rarely occur except extreme catastrophe shocking. According to the statistics from 1955 to 2014 in China, the most serious heat wave event occurred in Changsha city in 2013 for which the value of HWI is no more than 140. The value of HWI is mostly determined by the number of continuous days in which Tmax exceeds 37℃, even 40℃. If the extreme hot days continue longer, HWI would be more serious. Taking the most serious heat wave event in Chongqing city for example, it lasted from 25 July to 19 August, 2006; the value of CD35 reaches 26; the value of AD37 is 21; the value of CD37 is 19; the value of AD40 is 9; the value of CD40 is 7. According to the HWI equation above, the HWI of this heat wave event reaches 98.2.

For advice 3, the description of each level of HWI (line 553-554, page 21) has been revised to make it clearer and easily understanding. The content is as follow:

Tab.1 The classification of HW hazards by the values of HWI

Heat Wave Index	Level of hazard	Description
HWI =1.0	No hazard	There is no HW event occurred.
1.0＜HWI≤1.5	Low hazard	The HW event must last at least 3 continuous days and less than 12 continuous days, in which there is no days above 37℃or 40℃.
1.5＜HWI≤3.0	Moderate hazard	The HW event must last at least 3 continuous days and less than 24 continuous days, in which daily Tmax exceeds 35℃.
3.0＜HWI≤6.0	High hazard	The HW event must last at least 3 continuous days and less than 36 continuous days, in which daily Tmax exceeds 35℃.
6.0＜HWI	Extreme high hazard	The HW event must last at least 4 continuous days in which daily Tmax exceeds 40℃.

For advice 4, there is no change in the manuscript. The interpretation has been given.

For advice 5, in order to make it clearer, the description in the manuscript has been changed (line 278-287, page 12). The content is as following:

The sum value of HWIs in Chongqing is far bigger than other cities; the annual average value of HWIs in Chongqing reached 13.7. Changsha had been the second hard hit city with most serious HW hazards, in which the annual average value of HWIs reached 9.5. There were 6 cities that have been threatened by severer HW hazards, include: Hangzhou, Fuzhou, Nanchang, Xi'an, Wuhan and Haikou; the annual average value of HWIs in each city is between 4 and 9. There were 7 cities threatened by moderate severe HW hazards; these cities include: Hefei, Zhengzhou, Nanjing, Jinan, Shijiazhuang, Nanning, and Shanghai and the annual average value of HWIs in each city is between 2 and 4. The remaining 11 cities encountered lighter serious HW hazards in which the annual average value of HWIs is between 0 and 2. As mentioned above, there were no HW hazards in 5 cities.

For advice 6, there is no change in the manuscript. The interpretation has been given.

For advice 7, we have added more information of the secondary axis in figure 4 and 7 and developed the quality of figures. The figure 4 and 7 are showed as following:

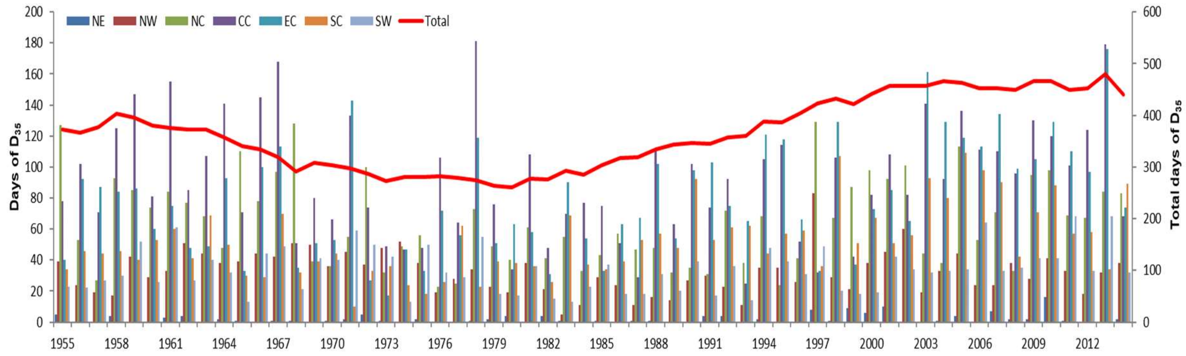

Fig. 4 Time series of D_{35} in different climate zones of China from 1955 to 2014

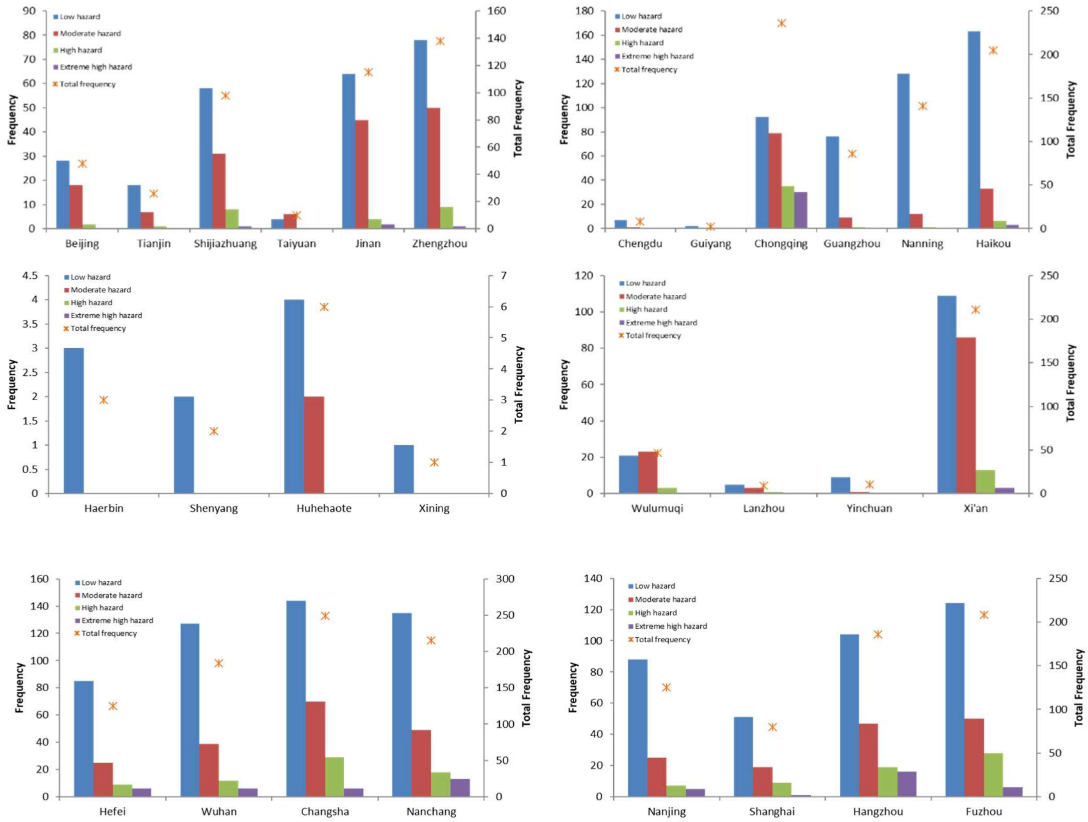

Fig. 7 Frequency of Low, Moderate, High and Extreme high HW hazards in 26 cities from 1955 to 2014 (Top left: NC; Top right: SW & SC. Middle left: NE; Middle right: NW & QT; Bottom left: CC; Bottom right: EC)

Notes: There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities in the past 60 years. Therefor there are 26 cities shown in this figure.

For advice 8, appropriate modifications and explanation in the titles of figure 3, 5, 6, 7 and 8 have been added. The content is as following:

Fig.3 Distribution of D_{35} in 29 cities from 1955 to 2014 (Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of D_{35} in 29 cities

Notes: There are no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities in the past 60 *years. Therefor there are 29 cities shown in this figure.*

Fig.5 Comparison between D35 and HWs per year in 29 cities of China from 1955 to 2014

Notes: There is no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.

Fig.6 Distribution of amounts and frequencies of HWs in 29 cities from 1955 to 2014 (upper graph: amounts of HWs; lower graph: Frequency of HWs. Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of HWs frequencies and amounts in 29 cities

Notes: There is no high temperature weather in which daily Tmax exceeds 35℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.

Fig.7 Frequency of Low, Moderate, High and Extreme high HW hazards in 26 cities from 1955 to 2014 (Top left: NC; Top right: SW & SC. Middle left: NE; Middle right: NW & QT; Bottom left: CC; Bottom right: EC)

Notes: There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities in the past 60 years. Therefor there are 26 cities shown in this figure.

Fig. 8 The sum values of HWIs in 26 cities from 1955 to 2014

Notes: There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities in the past 60 years. Therefor there are 26 cities shown in this figure.

Spatiotemporal Changes of Heat Waves and Extreme Temperatures in Main Cities of China from 1955 to 2014

Kuo Li, Gyilbag Amatus

Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China

Kuo Li, corresponding author Email: hqlk2000@163.com

Abstract: In the past decades, severe heat waves have frequently occurred in many parts of the world. These conspicuous heat waves exerted terrible influences on human health, society, economy, agriculture, ecosystem and so on. Based on observed daily temperatures in China, an integrated index of heat waves and extreme temperature days was established involving the frequency, duration, intensity, and scale of these events across large cities in China. Heat waves and extreme temperature days showed increasing trend in most regions except Northwest China from 1955 to 2014. After late 1980s, the increasing trend was more obvious than the past decades. The cities in the middle and lower reaches of the Yangtse river were threatened by the most serious hot events in the past 60 years, especially Chongqiang and Changsha. Due to the subtropical monsoon climate and special terrain, Chongqing would occupy the top of hot cities in a long period. In particular, there was obvious fluctuation for hot years in 31 cities, which were not continuously rising with the global warming; 21 cities mainly located in the eastern and southern regions of China had obvious rising trend; 8 cities had clear declining trend which mainly distributed in the western and northern regions of China; and there were no extreme temperature days in Kunming and Lasa in the past 60 years. The study revealed an obvious differentiation of hot events for 31 cities under climate change; hot threat in most cities is aggravating but declining or remained unchanged in the other cities. The trend is likely to intensify with global warming.

Keywords: Heat waves, Extreme temperature days, Hot Year Index, Climate change, China

1 Preface

In the past 100 years, global warming has been an apparent physical phenomenon in the whole world (Stocker et al, 2013). The extreme events (heat waves, flood, drought, typhoon) frequently break out in many parts of the world, which exert huge effects on normal functioning of agriculture, society, human health and ecosystem (Alexander et al., 2006; Diffenbaugh et al., 2016; Coumou and Rahmstorf, 2012). In the past decade, heat waves (HWs) engulfed many countries worldwide, impacting negatively on the whole population especially the elderly and children (Horton et al., 2015; Liu et al., 2012; Angélil et al., 2017; Peterson et al., 2013); for example, in 2003, the European continent experienced an extraordinary HW which was characterized by excessive long duration, unprecedented extreme temperature and vast spatial scale. This devastating HW took a heavy toll on human lives (at least 50,000 deaths) (Stott et al, 2004; Robine et al., 2008). In 2013, a similar HW visited most parts of China with increased intensity and duration resulting in significant economic loss (Sun et al., 2014).

Concrete definition and exact assessment of HW has become the main obstacles in developing mitigation and adaptation measures (Hajat et al., 2006; Perkins and Alexander, 2013). A HW is usually defined as an event that exceeds prescribed temperature thresholds over a few days (Robinson, 2001). Precise definitions are created in many literature which pay attention to different features of HWs (Bonsal et al., 2001; Klein et al., 2003; Jones et al., 2015). Climate scientists attach greater importance to how to evaluate the intensity and frequency of HWs; disaster scientists pay more attention to the vulnerability evaluation and risk assessment of HWs; sociologists mainly focus on the human health impact of HWs which attempts to estimate the probable heat-related mortality and morbidity of people; besides, there are many researchers who focus on the impact of HWs on agriculture, water resources, forestry, ecosystem and other sectors (Dike et al., 2015; Johnson et al, 2009; Dong et al., 2015; Buscail et al., 2012). On the whole, there are two research trends for HWs; one is about the characteristics analysis of HWs; the other is about the impact assessment and consequence analysis of HWs. The feature analysis of HWs is the basis for impact assessment on different sectors (Liang et al., 2014; Fouillet et al., 2006). But the realities of HWs in different continents are distinctive, so the definitions and thresholds of HWs are debatable for researchers.

In Canada and USA, the HW threshold is 40.5℃; when the time is more than 3 hours accumulated in 2 days in which the temperature is over 40.5℃, a HW could be confirmed; the other threshold of HW is 46.5℃, over which in any time of a day a HW would be confirmed (Oswald et al., 2014). In the Netherlands, the HW refers to a period of at least 5 days in which the extreme maximum temperature (Tmax) in each day exceeds 25℃; in the meantime, the Tmax exceeds 30℃ in at least 3 days of the above period (Uhe et al., 2016). For World Meteorological Organization (WMO), the threshold of HW is 32℃, which should be exceeded in at least 3 days (Klein et al., 2009). In China, a HW usually refers to a period of at least 3 days when the extreme maximum temperature (Tmax) in each day exceeds 35℃ (Liu et al., 2017; Chen et al., 2014). In China, the early warnings of HWs are gradually advanced with the intensity levels of HWs; when Tmax exceeds 35℃, the local meteorological departments would issue a Yellow Warning; when Tmax exceeds 37℃, the local meteorological departments would issue an Orange Warning; when Tmax exceeds 40℃, the local meteorological departments would issue a Red Warning. In a comprehensive view, the thresholds of HW in different regions are depending on the local climate conditions.

Unlike US and Europe, HWs assessment in China is primarily focused on occurrence frequencies of individual warm days with extreme temperatures (Huang et al., 2010; Zhang et al., 2005). The basic features of other equally important aspects for HWs, such as duration and intensity, are less emphasized (Li et al., 2010). Some recent studies in the US and the Europe began to separately assess diverse HW types (Gasparrini et al., 2015; Easterling et al., 2016), in which the temperature variable (Tmax or Tmin) was delimited into different categorizations but few studies have been able to integrate the different features of HWs for a holistic assessment. An integrated index is therefore desirable for systematic and quantitative evaluation of HWs in China, which includes multiple indicators – frequency, duration, intensity and so on. Moreover, current definition of HWs in China only considered the thresholds of Tmax, which is not enough for the precise assessment of HWs. For example, it is hard to evaluate the exact difference between a HW event (exceeding 35℃, 5 days) and the other HW event (exceeding 40℃, 3 days). For both scientific literatures and operational practices in China, it just shows the qualitative situation of scorching conditions, which would not easily give policy-makers and general public a clear picture of HWs for efficient precautions. As such, a more quantitative and precise evaluation should be done to distinguish different impacts of HWs, such as, human health, water resource supply burden, forest fires, ecology degeneration, among others.

This study therefore aims at building an integrated index of HWs and extreme temperature days. It would compare the observed basic features of HWs and extreme temperature events in the typical 31 cities of China during 1951-2014 and reveal the change trends of HWs and extreme temperature events in mainland China under climate change. Spatial distribution of HWs and extreme temperature days in the past 60 years in different cities would be estimated and mapped. The integrated index of HWs and extreme temperature events would provide an efficient tool for risk assessment of hot events under future climate change scenarios and support for further physical interpretation, attribution and mechanism of HWs.

2 **Data and Methods**

2.1 Data

Data from the National Meteorological Information Centre (NMIC) of the China Meteorological Administration (CMA), which is the first and most authoritative national homogenized temperature data set in China, was used. A database from 31 capital cities in all the provinces of China with historical daily temperature data from 1951 to 2014 was used, except Taiwan, Hongkong and Macao. At some stations the daily data was missing, especially in the years prior to 1955. In order to ensure consistency of temperature extremes and efficiency of the entire study, missing data up to 2% of the data points at each station in more than 50 years was rejected. The data of 31 stations over the period from 1955 to 2014 were ultimately selected for analysis.

2.2 Study area

According to the temperature and precipitation data, combined with the administrative boundaries of provinces, the whole China could be divided into 8 climate regions (Yang et al., 2002), including Northeast China (NE), North China (NC), East China (EC), South China (SC), Southwest China (SW), Northwest China (NW), Central China (CC) and Qinghai-Tibet Plateau (QT). Locations for the 31 cities and the climate zones in the study are presented in Fig.1. The total population of 30 capital cities currently stood at 278 million representing 20% of the total population of China and contributing 33.5% of the country’s GDP. These 31 capital cities were therefore chosen to reveal the trends of extreme temperature in China, which may influence policy directions in reducing extreme temperature disasters, protecting human health and enhancing crop production.

2.~~2~~3 Method

In this study, an integrated index is established for systematical and quantitative evaluation of HWs and extreme temperature events in China, which includes the frequency, duration and intensity of HWs and extreme temperature days. At first, we made clear two definitions: extreme temperature days and heat wave (HW). As stated earlier, when Tmax exceeds 35℃, it could be called a day with extreme temperature in China; when Tmax exceeds 35℃ in more than 2 consecutive days, it could be defined a heat wave (HW) event. The extreme temperature days are the base of a HW. In one year, there may be several HW events and discontinuous days with extreme temperature, which jointly decide the hot level of one region. So the integrated index would contain two aspects in this study, HWs and discrete days with extreme temperature.

According to the statistical data, the hot days with extreme temperature usually concentrate on June, July and August in China, which account for above 90% of all the hot days from 1955 to 2014 in 31 capital cities. In May and September, the hot days account for 9% and in the other months it accounts for no more than 1% (Fig.2). It is obvious that HW events mostly break out in June, July and August, which are the hottest months of the whole year in 31 capital cities. So we take the three months as the basic period for intensity assessment of HWs and extreme temperature days. There are totally 92 days in June, July and August. If one HW event lasts for 92 days in a year, it would be regarded as the most serious heat event.

2.~~2~~3.1 Heat wave index

For HW events, the frequency, duration and intensity should be considered. Firstly, if the HWs last for more days, the intensity of HWs would be bigger. Secondly, according to the definition of HW, 3 days are the shortest duration for HWs, in which daily Tmax exceeds 35℃. So the period of 3 days is made as one essential unit for evaluating the intensity of HWs. Thirdly, as mentioned above, when daily Tmax exceeds 37℃ or 40℃, especially the continuous days above 37℃ or 40℃ are increasing, the intensity of HWs would go up rapidly.

So in the study, Heat Wave Index (HWI) is established as the following formula.

$$\mathbf{HWI} = \left(\frac{\mathbf{CD_{35}}}{\mathbf{92}} \times \frac{\mathbf{CD_{35}}}{\mathbf{3}} + \mathbf{1}\right) * \left(\frac{\mathbf{AD_{37}}}{\mathbf{92}} + \frac{\mathbf{CD_{37}}}{\mathbf{3}} + \mathbf{1}\right) * \left(\frac{\mathbf{AD_{40}}}{\mathbf{92}} + \frac{\mathbf{CD_{40}}}{\mathbf{3}} + \mathbf{1}\right) \quad \textbf{(1)}$$

HWI represents the integrated intensity of HW events: CD_{35} represents the continuous days in which daily Tmax exceeds 35℃; AD_{37} represents the all days in which daily Tmax exceeds 37℃among CD35; CD_{37} represents the continuous days in which daily Tmax exceeds 37℃among CD_{35}; AD_{40} represents the all days in which daily Tmax exceeds 40℃among CD_{35}; CD_{40} represents the continuous days in which daily Tmax exceeds 40℃among CD_{35}.

For HWI, there are two extreme situations. If there are no heat waves in one year, the value of HWI would be 1. If there are 92 continuous days of a year in which Tmax exceeds 40℃, the value of HWI would reach the biggest, 33792; for the real world, the second extreme situation would rarely occur except extreme catastrophe shocking. According to the statistics from 1955 to 2014 in China, the most serious heat wave event occurred in Changsha city in 2013 for which the value of HWI is no more than 140. The value of HWI is mostly determined by the number of continuous days in which Tmax exceeds 37℃, even 40℃. If the extreme hot days continue longer, HWI would be more serious. Taking the most serious heat wave event in Chongqing city for example, it lasted from 25 July to 19 August, 2006; the value of CD_{35} reaches 26; the value of AD_{37} is 21; the value of CD_{37} is 19; the value of AD_{40} is 9; the value of CD_{40} is 7. According to the HWI equation above, the HWI of this heat wave event reaches 98.2.

For one year, there may be several HW events. The total intensity of Annual HWI (AHWI) should contain all HW events of the year. Based on HWI, AHWI is calculated as following.

$$\mathbf{AHWI} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{HWI_i} \quad \textbf{(2)}$$

AHWI represents the total annual intensity of HW events; n represents the total frequency of HW events in one year; i represents the sequence of HW events occurred in one year.

2.~~2~~3.2 Hot year index

As mentioned above, within one year, there are not only HW events, but also discontinuous days with extreme temperature. If the hot levels are compared between different cities in different years, the two aspects should be considered synthetically. The discontinuous days with extreme temperature above 35℃, 37℃ or 40℃ are not as serious as HW events in some cities. In other cities there may be few HW events in some years, in which the hot levels are mainly decided by the discontinuous days with extreme temperature. So based on AHWI established above, an integrated index for hot years is constructed, considering the discontinuous days with extreme temperature in one year. The formula is as follows:

$$\mathbf{HYI} = \mathbf{AHWI} + \frac{\mathbf{D_{35}} - \sum \mathbf{CD_{35}}}{\mathbf{92}} \times \frac{\mathbf{D_{35}} - \sum \mathbf{CD_{35}}}{\mathbf{3}} + \frac{\mathbf{D_{37}} - \sum \mathbf{AD_{37}}}{\mathbf{3}} + \frac{\mathbf{D_{40}} - \sum \mathbf{AD_{40}}}{\mathbf{3}} \quad \textbf{(3)}$$

HYI represents the integrated intensity of hot years in different cities. D_{35} represents the days of one year in which daily Tmax exceeds 35℃; $\sum CD_{35}$ represents the continuous days in which daily Tmax exceeds 35℃ in one year; D_{37} represents the days in one year in which daily Tmax exceeds 37℃; $\sum AD_{37}$ represents the all days in which daily Tmax exceeds 37℃ among CD_{35} in one year; D_{40} represents the days in one year in which daily Tmax exceeds 40℃; $\sum AD_{40}$ represents the all days in which daily Tmax exceeds 40℃ among CD_{35} in one year.

For HYI, there are also two extreme situations. If there are no heat waves or hot days in one year, the value of HYI would be 1. The value of HYI is largely determined by the value of AHWI, which would reach 33792 at most; in other word, the intensity and frequency of heat wave events in one year is bigger, the hot year index would be more severe. There is insignificant impact on HYI for discontinuous days in which daily Tmax exceeds 35℃, comparing with heat wave events. According to the statistics, the hottest year is also in Changsha city in 2013, which contained the most serious heat wave event from 1955 to 2014 in China.

3 Results

3.1 Trends of Extreme Temperature days

According to the historical statistics, Chongqing has been the most vulnerable province to disasters of extreme temperature in whole China, in which annual D_{35} exceeds 33 days in the past 60 years. Meanwhile, there is no extreme temperature day from 1955 to 2014 in Kunming and Lasa, which are the most comfortable places of the 31 capital cities in summer. There are 7 cities in which annual D_{35} is between 20-30 days (Fig.3), including Changsha, Fuzhou, Nanchang, Hangzhou, Haikou, Xi'an and Wuhan. With regards to climate zones, Central China had been threatened by the most frequent extreme temperature disasters in the past 60 years; annual D35 in: East China and South China was between 10-20 days; North China and Southwest China was between 1-12 days; Northwest China was about 8 days; and Northeast China and Qinghai-Tibet Plateau was less than 3 days.

Though the global climate has been continuously warming in the past 60 years, the trend of D_{35} in China is not increasing constantly. There are 3 main stages for the variation of D_{35} in China (Fig.4). From 1955 to early 1970s, the value of D_{35} in 31 cities of China averagely amounts to 372 days per year, signifying the high level of hot years in this stage; from early 1970s to late 1980s, the value of D35 in 31 cities of China averagely amounts to 280 days per year, which means that, these cities encountered a relatively cool years in this stage; from early 1990s to 2014, the value of D35 in 31 cities of China averagely amounts to 425 days per year, which is higher than the past 40 years. It means that the whole China is threatened by more and more serious extreme temperature events in the recent 20 years. However, there are obvious variation in the characteristics of D35 in different climate zones of China. The values of D35 in South China, East China and Northeast China are obviously going up from 1955 to 2014; the values of D35 in Central China, Southwest China and North China are slightly rising; however, the trend in the values of D35 in Northwest China have slightly declined in the past 60 years.

3.2 Trends of Heat Waves

Following the HWs definition in China, an average of 1.54 HW events occurred annually in each city from 1955 to 2014, which last for an average of 5.4 days for each HW event. It is obvious that, as the value of D35 gets bigger in each city, the amount and frequency of HWs also grow bigger (Fig.5). There is a positive correlation between D35 and HWs. Through the analysis of HWs in the 31 typical cities, Chongqing was the most threatened as HW rose up to 25.1 days annually; Changsha experienced the most frequent HWs in the past 60 years, almost 3.9 times per year; the intensities and frequencies of HWs in Nanchang, Fuzhou, Hangzhou, Haikou and Xi'an are smaller than Chongqiang and Changsha, but much bigger than other cities; there was no HW in Kunming, Lasa and Changchun but there were few HWs in Haerbin, Shenyang, Guiyang and Xining. For the other cities, the threat from HWs was in the middle level.

According to the statistics, the distribution of amounts and frequencies of HWs per year in the 31 cities were similar to the distribution of D35 (Fig.6). Comparing the different climate zones, Central China had been threatened by the most serious HWs in the past 60 years, in which the frequency and amount of HWs per year were the highest; in East China HWs have also been very serious; in South China and Southwest China the threat of HWs have been lower than the Central China and East China; in North China and Northwest China there were less annual HWs; in Northeast China and Qinghai-Tibet Plateau, there had been almost no obvious threat of HWs in the past 60 years.

3.3 Heat Wave Index

In order to do comparative analysis on the HWs occurrence in the different cities for the past 60 years, a Heat Wave Index (HWI) was established as mentioned above. The duration and intensity are the key factors of HWs that define the severity of hot events. So HWI is designed to refer to the number of days one HW event lasts and the maximum temperature one HW event reaches (Tab.1). HWI provides us a quantitative tool to distinguish the different HWs in 31 typical cities of China. According to the climate conditions and national standards of extreme temperature in China, HWs could be classified into 5 levels of hazard by the values of HWI. When the value of HWI is 1.0, it indicates that there is no continuous hot day in which Tmax exceeds 35℃. When the value of HWI is between 1.0 and 1.5, it indicates slight HW hazards in which the duration and intensity of HWs are minimal. When the value of HWI is between 1.5 and 3.0, it means HW hazards are not serious as there are few continuous days of Tmax exceeding 37℃. When the value of HWI is between 3.0 and 6.0, it indicates that the HW hazards are serious and the continuous days of Tmax exceeding 37℃ or 40℃ become frequent. When the value of HWI is above 6, it indicates that the HW hazards are very serious and the continuous days of Tmax exceeding 37℃ or 40℃ may last through the whole period of HWs.

According to the classification of HWI, the frequencies of HW hazards with different levels in the past 60 years in 31 typical cities of China are analyzed (Fig.7). In all, cities with low HW hazards were the majority accounting for 62.3% of all HWs; the moderate HW hazards accounted for 26.4%; the high HW hazards represented 7.7%; and the extreme high HW hazards accounted for 3.6%. For all the 31 cities, most of the HW hazards are not serious; only 1/10 of the HW hazards are of the greatest threats. No HW hazards occurred in Changchun, Shenyang, Guiyang, Kunming and Lasa from 1955 to 2014; no high or extreme high HW hazards occurred in Haerbin, Huhehaote, Xining, Yinchuan, Taiyuan and Chengdu; no extreme high HW hazards occurred in Beijing, Tianjin, Wulumuqi, Lanzhou, Guangzhou and Nanning; in the remaining 14 cities, there were all four levels of HW hazards occurred in the past 60 years. However, most HW events of high (0.57 per year) and extreme high (0.47 per year) levels occurred in Chongqing than the other cities; most HW events of moderate levels occurred in Xi'an, reaching 1.35 per year; and most HW events of low level occurred in Haikou, reaching 2.38 per year.

Based on the calculation of HWI, the sum of HWIs from 1955 to 2014 in each city is shown in Fig.8. It is obvious that Chongqing has been threatened by the most serious HW hazards in the past 60 years, in which the frequency, duration and intensity of HWs are the biggest of all the 31 cities. The sum value of HWIs in Chongqing is far bigger than other cities; the annual average value of HWIs in Chongqing reached 13.7. Changsha had been the second hard hit city with most serious HW hazards, in which the annual average value of HWIs reached 9.5. There were 6 cities that have been threatened by severer HW hazards, include: Hangzhou, Fuzhou, Nanchang, Xi'an, Wuhan and Haikou; the annual average value of HWIs in each city is between 4 and 9. There were 7 cities threatened by moderate severe HW hazards; these cities include: Hefei, Zhengzhou, Nanjing, Jinan, Shijiazhuang, Nanning, and Shanghai and the annual average value of HWIs in each city is between 2 and 4. The remaining 11 cities encountered lighter serious HW hazards in which the annual average value of HWIs is between 0 and 2. As mentioned above, there were no HW hazards in 5 cities.

3.4 Hot year Index

Based on Heat Wave Indexes, Hot Year Indexes in the 31 cities were calculated and analyzed, including HW events and discontinuous days with extreme temperature (Tab.2). The analysis revealed the heat levels of the cities in different years. In the study, the quantity of Hot Year Indexes for all cities added up to 1860 from 1955 to 2014.

The No-hot year represented 29.1% of the gross; Light hot year, 28.8%; Mild hot year, 20.3%; Moderate hot year, 13.7%; Serious hot year, 7.9%; and the Extreme hot year represented 0.3%. Chongqing has been threatened by the most severe heat, in which Serious hot year and Extreme hot year accounted for 50% of the 60 years; in Changsha, Nanchang, Hangzhou and Fuzhou, Serious hot year and Extreme hot year accounted for 25%. However, there was only slight heat threat or no heat threat in the past 60 years in most cities of Northeast China, Northwest China, Southwest China and Qinghai-Tibet Plateau, in which No-hot year and Light hot year accounted for more than 90%. For the remaining 14 cities, Mild hot year and Moderate hot year accounted for the most of 60 years. It is obvious that the west and north regions of China are much cooler than the east and south parts of China; the hottest regions are located in Central China and East China.

On the point of time series, there are 3 kinds of variation trends of HYI for all the 31 cities: uptrend, downtrend and no change. In 21 cities, the value of HYI had obvious rising trend; the remaining 8 cities had clear declining trend in the value of HYI. There were no extreme temperature days in Kunming and Lasa in the past 60 years, so there was no change of HYI in the two cities. There are two rising pathways for the 21 cities; one is rising directly; the other is firstly declining and then rising. In a comprehensive view, there are 3 stages for all the cities in the past 60 years. In the first stage from 1955 to the early years of 1970s, HYIs in most of cities were in a high level; the moderate hot years and serious hot years were frequent, which accounted for 27.0% of the first stage. In the second stage from the middle of 1970s to the end of 1980s, HYIs in most of the cities were in a low level; the moderate hot years and serious hot years were rare, which accounted for 11.7% of the second stage. In the third stage from the early years of 1990s to 2014, HYIs in most of cities were also in a high level; the number of moderate hot years and serious hot years accounted for 26.8%; but the severities of hot years in this stage are more serious than the first stage in most cities. In general, there was obvious fluctuation for hot years in the past 60 years in the 31 cities, which are not continuously rising with the global warming. There was obvious increasing trend for whole China, either the intensity or the frequency of HWs and extreme temperature days.

From figure 9, clear variations of HWI events existed in most cities across the main land of China. For example, in Northwest China, HYIs in Lanzhou and Yinchuan were so small that no serious hot events occurred in the past 60 years, but in Wulumuqi and Xi’an, HYIs were much pronounced as annual average value of HYIs from 1955 to 2014 in Xi’an reached 6.96. In North China, the annual average values of HYIs in Beijing, Tianjin and Taiyuan were between 1.2 and 2.4, in which light hot years represented 63% of the whole; but in Shijiazhuang, Jinan and Zhengzhou, the annual average values of HYIs were between 3.9 and 5.1 and mild hot years represented 43% of the whole. In Southwest China, there were few hot waves in Chengdu, Guiyang and Kunming making these cities as cool as Northeast China; however, in Chongqing, the annual average value of HYIs rose up to 15.0. This city had been threatened by the most severe hot events, as serious hot years represented 34% and the HYIs ranked first of the 31 cities in 27 years of the past 60 years. From a broader view, 3 types of regions were identified: Northeast China and Qinghai-Tibet Plateau composed of one type of the regions: HYIs of these cities were small and the annual average value was 1.02 in which No-hot years accounted for more than 60%, representing the coolest region in China; Central China, East China and South China also formed one type of regions: HYIs of most of these cities were higher than the other regions and the annual average value of HYIs rose up to 5.61, in which moderate hot years and serious hot years accounted for 40%; in Northwest China, Southwest

China and North China which formed the last type of the regions, HYIs of most these cities were in the middle and the annual average value of HYIs was 3.45, in which light hot years and mild hot years accounted for 54%.

In brief, there is an apparent feature that most of the cities that were threatened by serious hot events in the past 60 years gather in the middle and lower reaches of the Yangtse river; there were few hot events in NE, NW, SW and QT, except Chongqing, Xi'an and Wulumuqi; the threatened by hot events in SC is not striking, though the annual mean temperatures of 3 typical cities in this region is the highest of all 31 cities.

4 Discussion

With global warming, there have been a lot of researches focusing on HWs. Most of these studies paid more attention on a single factor of HW, especially on occurrence frequency. The other key indicators, such as duration, intensity, extent and timing, were usually neglected. There are few studies combining HWs with extreme temperature days to evaluate the annual hot events and compare the inter-annual changes of torridity degrees.

From our analysis, we established a statistical model involving the frequency, duration, intensity, and length of the HWs and extreme temperature days across large cities in China. By analyzing HWs and extreme temperature days in large cities of China, we are capturing the changes and spatial distribution in HWs and the extreme temperature events caused from climate fluctuation and climate change, as well as local changes from the urban environment.

The results presented in this study are consistent with previous findings on changes in extreme temperature days and HWs in recent decades across China due to global-scale drivers (Chen et al., 2017; Fang et al., 2016; You et al., 2013; Qi et al., 2012). HW is the basic element for evaluation of hot events which is taken into account in most of the researches across the whole world (Spinoni et al., 2015; Oswald et al., 2014; Santamouris et al., 2015; Gershunov et al., 2009). However, the discontinuous extreme temperature days are usually ignored which play an important role on evaluation of annual hot events. The common influences caused by HWs and extreme temperature days exhibit the overall scene of hot events in different cities. The increase in the number of HWs and extreme temperature days in China, are consistent with all other global or regional studies that show that the occurrence of warm days increased (Rusticucci et al., 2012; Nemec et al., 2013; Pingale et al., 2014). The abrupt changes in the trends of HWs and hot years mainly occurred in the 1970s and 1980s; there was a period from early 1970s to late 1980s, in which the number of HWs and extreme temperature days were relatively lower than the other years; the changes are in accordance with the former findings put forward by other researchers (Zhou and Ren, 2011; Xu et al., 2013).

The cities distributed in the middle and lower reaches of Yangtze River had been threatened by the most serious HWs and hot years in the past 60 years, especially Chongqing and Changsha. The long-term anticyclones and the special topography are most responsible for this trend of change; Chongqing is a located in a valley surrounded by mountains and Changsha is located in the valley of Xiangjiang river, which are both affected by subtropical monsoon climate. At the mean time, the location, scope and intensity of HWs and extreme temperature events in southern China are closely influenced by the Western North Pacifica subtropical high (WNPSH) and the East Asia jet stream (EAJS); the poleward displacement of the EAJS and an enhanced WNPSH over the midlatitudes of eastern China usually result in a “heat dome” over the region, and the heat waves extend northward or westward to cover a larger area of Eastern China or Southwest China (Wang et al., 2015). In North China, the threat by HWs and hot years in the past 60 years is relatively mild, except Xi’an and Zhengzhou. The main cause is due to the anticyclone circling over the Lake Baikal; positive height anomalies at 500 hPa covering the north of China and easterly anomalies at 850 hPa in northwestern China were corresponding to anomalous high frequencies of HWs (Ding et al., 2010). For most cities in western and northern China, the high latitudes and high altitudes remarkably restrict the occurrence of HWs and extreme temperature events, in which the threat is slight and there is no obvious increase in the past 60 years (Zhou and Ren, 2011). It is therefore worthwhile to explore how the atmospheric circulation patterns change in future which would reveal the spatiotemporal trends of HWs and extreme temperature events in China. On the other hand, the elaborate depiction and accurate evaluation of HWs and extreme temperature events in more cities of China would be meaningful for planning of disaster prevention and mitigation.

5 Conclusions

This study established an integrated index which contained the duration, intensity, extent and timing of HWs and extreme temperature days. It showed the whole picture of hot threat in 31 main cities from 1955 to 2014.

(1) Both HWs and extreme temperature days showed increasing trend from 1955 to 2014 in NC, CC, NE, SW, EC and SC; there was a slight decreasing trend in NW. For whole China, HWs and extreme temperature days exhibited an obvious upward trend in the past 60 years with a rapid increase after late 1980s.

(2) The hottest regions were located in CC and EC over the past 60 years; the cities in SC and NC were faced with middle level of threat; there were low threat of heat events in most of the cities from NE, NW and SW, except Chongqing and Xi'an. More especially, Chongqing had been threatened by the most serious HW hazards, much heavier than the other cities.

(3) There was obvious fluctuation for hot years in 31 cities over the past 60 years, which were not continuously rising with the global warming; 21 cities mainly located in the eastern and southern regions of China had obvious rising trend; 8 cities had clear declining trend which mainly distributed in the western and northern regions of China; however, there

were no extreme temperature days in Kunming and Lasa in the past 60 years. More specially, there were 3 stages for all 31 cities and the abrupt changes occurred separately in early 1970s and late 1980s.

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Data availability: The historical weather data (1955-2014) that support the analysis in this study is from the National Meteorological Information Centre (NMIC) of the China Meteorological Administration (CMA), which is publicly available online at http://data.cma.cn/.

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Tab.1 The classification of HW hazards by the values of HWI

Heat Wave Index	Level of hazard	Description
HWI =1.0	No hazard	There is no HW event occurred.
1.0＜HWI≤1.5	Low hazard	The HW event must last at least 3 continuous days and less than 12 continuous days, in which there is no days above 37℃or 40℃.
1.5＜HWI≤3.0	Moderate hazard	The HW event must last at least 3 continuous days and less than 24 continuous days, in which daily Tmax exceeds 35℃.
3.0＜HWI≤6.0	High hazard	The HW event must last at least 3 continuous days and less than 36 continuous days, in which daily Tmax exceeds 35℃.
6.0＜HWI	Extreme high hazard	The HW event must last at least 4 continuous days in which daily Tmax exceeds 40℃.

Tab.2 The classification of Hot Years by the values of HYI

Hot Year Index	Level	Grades	Description
HYI =1	No-hot year	0	There are neither HWs nor hot temperature days (>35℃) occurred in one year.
1＜HYI≤2	Light hot year	1	There is one HW or a few hot days occurred in one

			year, which are small and slight.
2＜HYI≤5	Mild hot year	2	There are a few HWs or hot days occurred in one year, which are usually small.
5＜HYI≤10	Moderate hot year	3	There are several HWs or some hot days occurred in one year.
10＜HYI≤50	Serious hot year	4	There are some HWs in high level or many hot days occurred in one year.
50＜HWI	Extreme hot year	5	There are some extreme HWs or a lot of hot days occurred in one year.

Fig.1 Distribution of the weather stations in 31 cities and climate zones in Mainland of China (The climate zones includes: NE, NW, NC, CC, EC, SC, SW, QT)

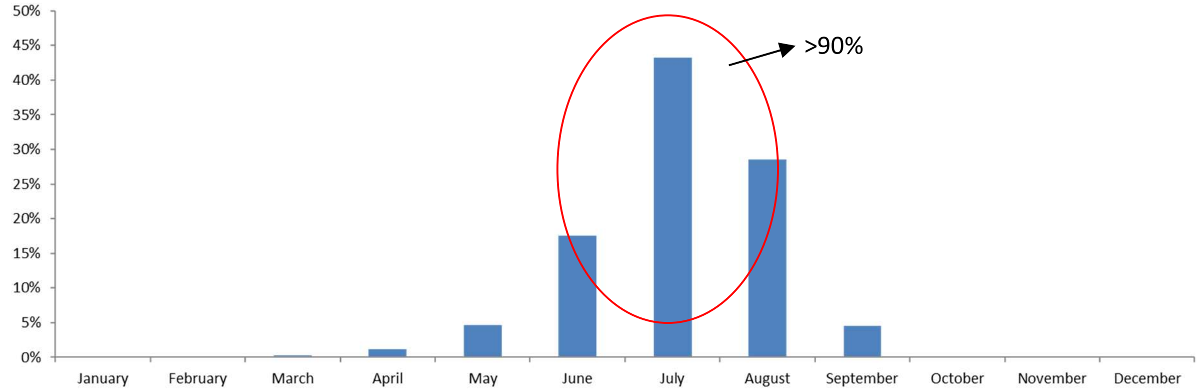


Fig.2 The proportion distributions of hot days in 12 months from 1955 to 2014 in 31 capital cities in China

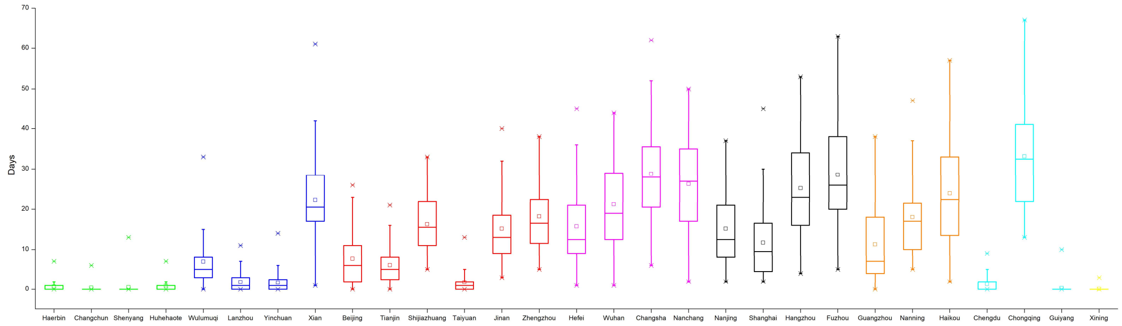
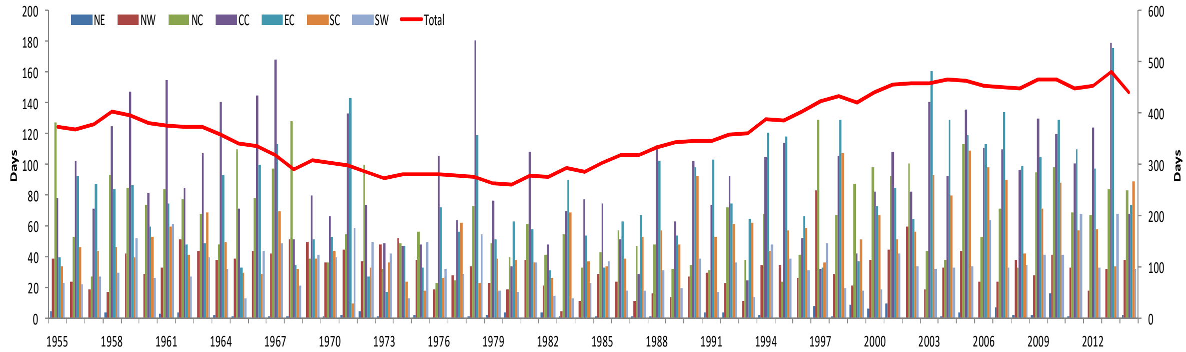


Fig. 3 Distribution of D_{35} in 29 cities from 1955 to 2014 (Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of D_{35} in 29 cities

Notes: There is no high temperature weather in which daily Tmax exceeds 35 ℃ in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.



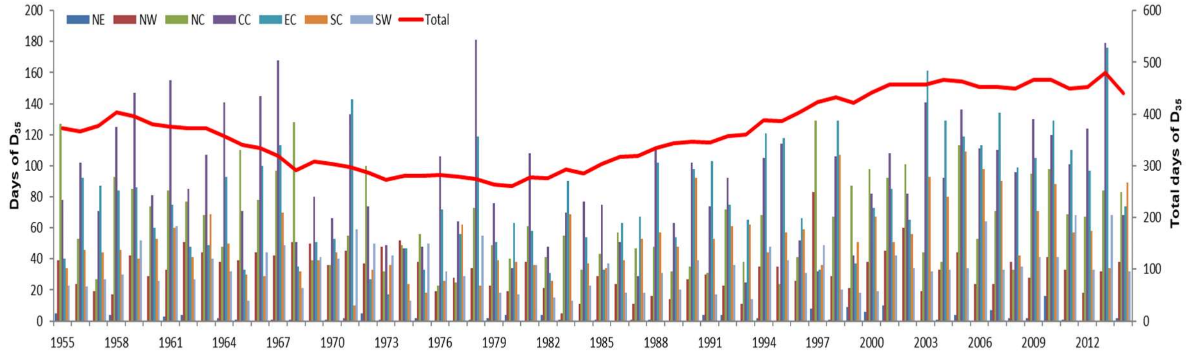


Fig. 4 Time series of D_{35} in different climate zones of China from 1955 to 2014

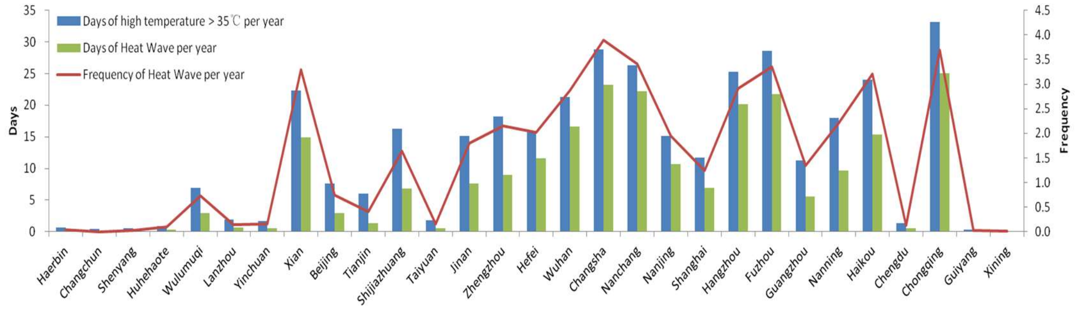


Fig. 5 Comparison between D_{35} and HWs per year in 29 cities of China from 1955 to 2014

Notes: There is no high temperature weather in which daily Tmax exceeds 35 ℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.

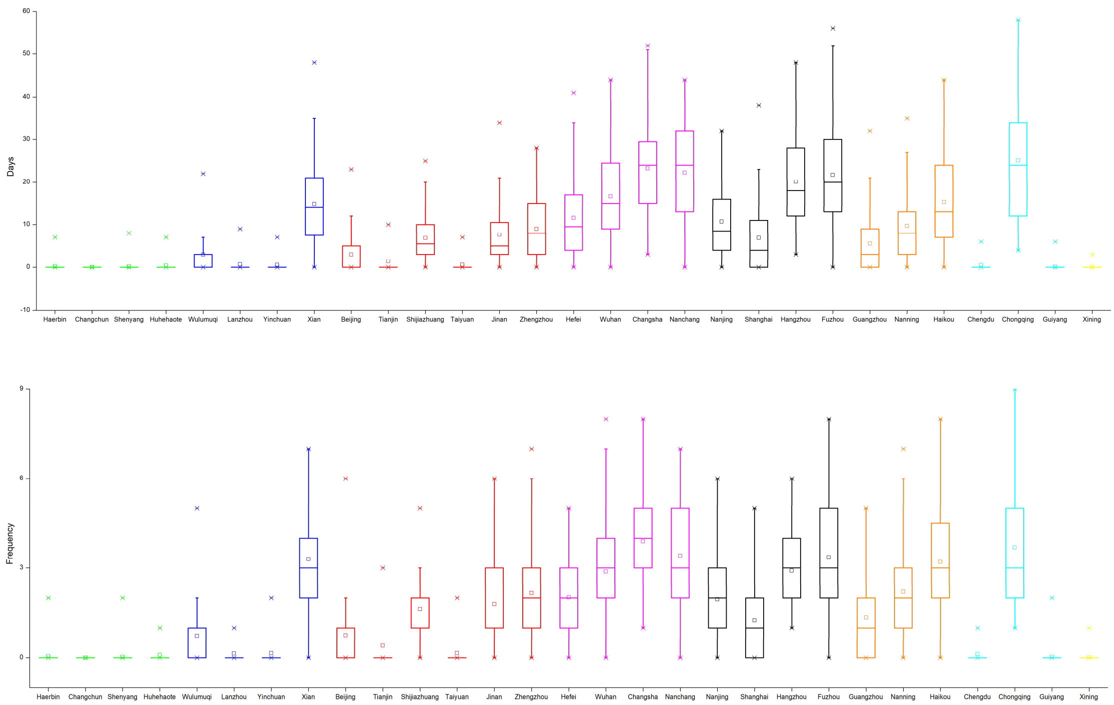
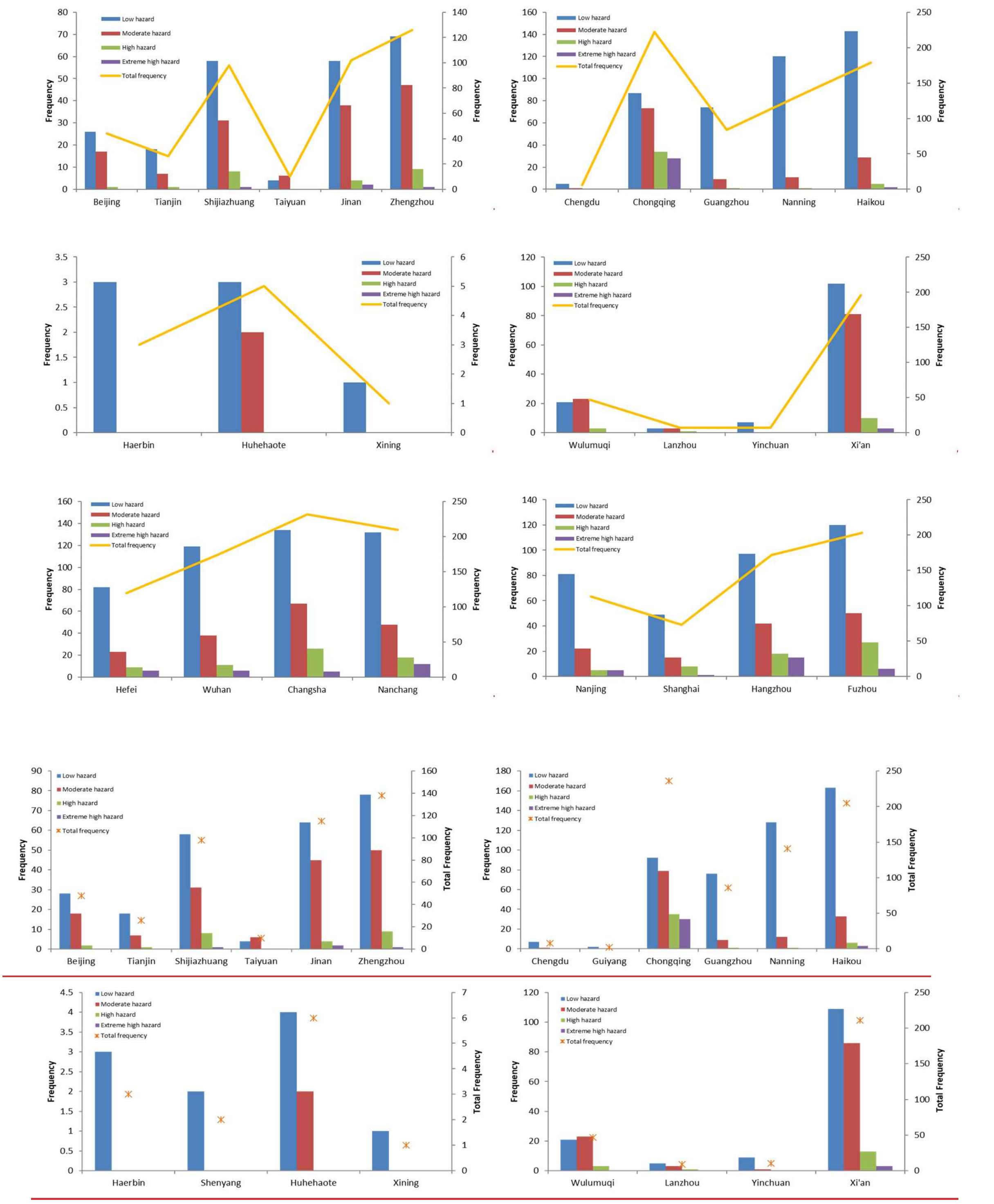


Fig. 6 Distribution of amounts and frequencies of HWs in 29 cities from 1955 to 2014 (upper graph: amounts of HWs; lower graph: Frequency of HWs. Green color: NE; Blue color: NW; Red color: NC; Purple color: CC; Black color: EC; Orange color: SC; Cyan color: SW; Yellow color: QT); Boxes indicate the interquartile spread (25th and 75th quantiles) with the horizontal line indicating the ensemble median and the whiskers showing the extreme range of HWs frequencies and amounts in 29 cities

Notes: There is no high temperature weather in which daily Tmax exceeds 35 ℃in Kunming and Lasa cities in the past 60 years. Therefor there are 29 cities shown in this figure.



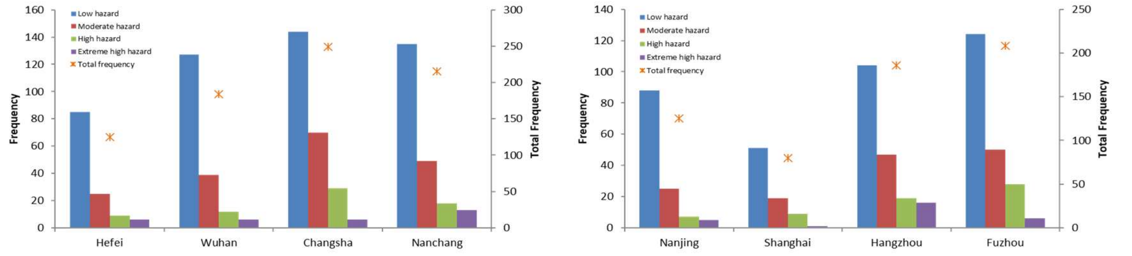


Fig. 7 Frequency of Low, Moderate, High and Extreme high HW hazards in 26 cities from 1955 to 2014 (Top left: NC; Top right: SW & SC. Middle left: NE; Middle right: NW & QT; Bottom left: CC; Bottom right: EC)

Notes: There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities in the past 60 years. Therefor there are 26 cities shown in this figure.

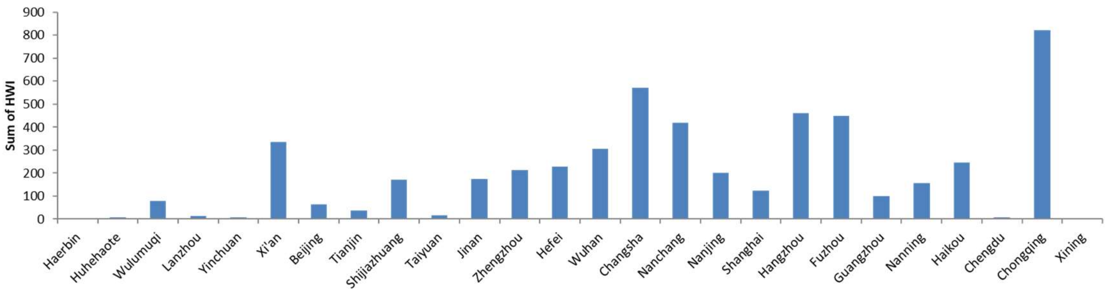


Fig. 8 The sum values of HWIs in 26 cities from 1955 to 2014

Notes: There are no HWs in Changchun, Shenyang, Guiyang, Kunming and Lasa cities in the past 60 years. Therefor there are 26 cities shown in this figure.

Fig. 9 Classification of Annual Average of HYIs from 1955 to 2014 in 31 cities in Mainland of China (The climate zones includes: NE, NW, NC, CC, EC, SC, SW, QT; The upper blue line: the Yellow River; The below blue line: the Yangtse River)