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ORIGINAL PAPER

# Identification of multiple climatic extremes in metropolis: a comparison of Guangzhou and Shenzhen, China

**Yanxu Liu[1] · Shuangshuang Li[2] · Yanglin Wang[1] · Tian Zhang[1] · Jian Peng[1] · Tianyi Li[1]**

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**Abstract** Identifying historical trends in the integrated frequencies of various climate extremes is meaningful in climatic hazard research. However, the variation trends in regional climate extremes still need to be described by more effective indices, correlations among multiple climatic extremes and different regions need to be quantified, and the urban heat island backgrounds and thermal bioclimate conditions in which people live need to be noted. In this study, the threats of heat wave, heavy rain, strong wind, and Universal Thermal Climate Index (UTCI) stress were identified both by units of days using the 90th percentile threshold, and by an unscaled magnitude index derived from kernel density functions for Guangzhou and Shenzhen, China, in 1960–2013. The results show that both metropolises experienced an increase in heat wave threat and a decrease in strong wind threat, and the change amplitudes were higher for Guangzhou than Shenzhen. The correlation of heat wave threat between the two metropolises was significant, while the other correlations depended on the city and index. The heat wave threat was correlated with the UTCI stress in Guangzhou, while both heat wave threat and UTCI stress were correlated with strong wind threat in Shenzhen. The UTCI stress indicated that bioclimate conditions for human habitat have not deteriorated, especially in Shenzhen. In the daily-level results, the heat waves had close relationship between the two adjacent cities, and people suffered from hazard events were usually in high weighted indices of extremes.

**Keywords** Multiple climatic extremes · Heat wave · Heavy rain · Strong wind · UTCI · Cumulative density function · Urbanization in China

✉ Yanglin Wang
ylwang@urban.pku.edu.cn

Yanxu Liu
liuyanxu@pku.edu.cn

1 Laboratory for Earth Surface Processes of the Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

2 State Key Laboratory of Earth Surface Processes and Resource Ecology, Academy of Disaster Reduction and Emergency Management, Beijing Normal University, Beijing 100875, China

## 1 Introduction

The global landscape is increasingly affected by significant changes in climatic extremes. Fluctuations in temperature, wind, rain, snow, and ocean currents have significantly affected ecological patterns and processes in both marine and terrestrial systems (Helmuth et al. 2011; Holmgren et al. 2006; Stenseth et al. 2002; Williams et al. 2014), and in many regions of the world, people's lives are being threatened by the warming and precipitation trends, as evidenced by increased morbidity and mortality (Changnon 2011; Li et al. 2012; Patz et al. 2005, 2014). Future climate scenarios forecast by scientists show increasing trends in the occurrence of heat waves, heavy rains, and extreme wind speeds (Bell et al. 2004; Beniston et al. 2007; Garcia-Aristizabal et al. 2015; Groisman et al. 1999), and the losses in lives and assets caused by climatic extremes have aroused much social concern. Therefore, the study of hazards caused by climate extremes has become a hot spot in climate research, and identifying historical trends in the frequencies of climate extremes should be an important topic of research today.

Climate hazard does not usually occur as an independent event, since one event can trigger a chain of disasters. The recent global warming is coherently related to precipitation and circulation. For instance, a striking increase in rainfall of 9.5 % per degree of global warming for the Northern Hemisphere summer monsoon has been found (Wang et al. 2013a). Records show that multiple heat threats and storms appear to strike the same region within a year (Mekasha et al. 2014; Savic et al. 2014). Events such as hurricane winds and surges often combine to threaten coastal regions (Pei et al. 2014), and other hazards such as drought and heat waves are often coupled in arid regions (Lyon 2009). As extremes can be combined or correlated with one another (Gallant and Karoly 2010; Pfahl 2014), the study of integrated climate hazard should be a significant research direction (Amendola et al. 2008).

The evolution of climatic extremes under changing conditions of both temperature and precipitation can be identified in daily records from regional climate stations (Beniston and Stephenson 2004; Moberg et al. 2006; New et al. 2006). However, since the use of indices to identify changes in climatic extremes is still in progress, extreme days identified using different methods may not be in agreement (Benestad 2007; Jones et al. 1999; Perkins and Fischer 2013; Smoyer 1998). For example, more than a dozen indices exist just for the definition of a heat wave (Keramitsoglou et al. 2013; Pascal et al. 2013; Radinovic and Curic 2012; Smith et al. 2013; Zhang et al. 2012). When combinations or correlations are inferred based on inappropriate indices, the conclusions will be inaccurate. Thus, better definition of discriminating indices is necessary in climate hazard research.

In urban areas, climate hazards such as high temperature and waterlogging often trigger remarkable disaster events (Campion and Venzke 2013; Depietri et al. 2012; Ma et al. 2011). China, which is urbanizing at high speed, has experienced various climate-induced disasters resulting in remarkable regional losses (Xie et al. 2014). In Shanghai, precipitation extremes, summer high temperatures, haze, and typhoons have caused many casualties; for example, 618 people were injured by meteorological disasters in 1986 (Shi and Cui 2012). In Beijing, heavy rainstorms in July 2012 caused ¥11.64 billion of direct economic losses, and 79 people were drowned (Wang et al. 2013b, 2015). In Nanjing, high temperatures and their durations have been increasing, and the meteorological disasters have been shown to be related to the city's economic development (Guo et al. 2014; Liu et al. 2015). In Guangdong province, which already suffers from floods, drought is affecting more areas with increased losses, and the number of typhoon events has increased over the last half century (Zhang et al. 2011).

Based on a magnitude method for identifying climate extremes, we aim to answer four related questions. First, is there an increase in the threat of climate extremes in regional metropolises in China? Second, are the multiple climatic extremes consistent between spatially adjacent metropolises? Third, are the trends in interannual climatic extremes related? Fourth, has heat stress related to the complex climatic fluctuations really deteriorated the thermal bioclimate conditions for living? Finally, is the occurrence of extreme events happen in both cities simultaneously on day level, and are the extreme events certainly relate to actual hazards events? In this study, the analysis was divided into three parts. In the first part, the evolution of climatic extremes in temperature, precipitation, and wind records from 1961 to 2013 was examined to respond to the first three questions. In the second part, the Universal Thermal Climate Index (UTCI) was introduced to address the fourth question. In the last part, daily-level results in both cities were compared, and records of hazards events were introduced to testify the results.

## 2 Methodology

### 2.1 Study area and data source

Guangdong province is where two metropolises, Guangzhou and Shenzhen, are located. The two metropolises, located on the Pearl River Delta in southeastern China (Fig. 1), have a southern subtropical monsoon climate (Xie et al. 2013a). The monsoon climate results in

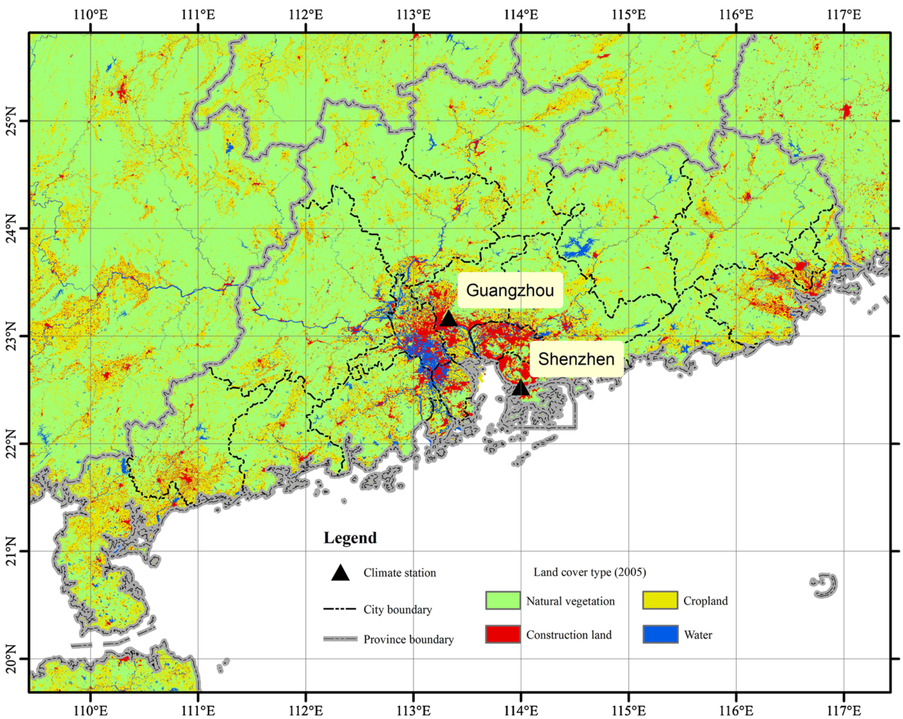


Fig. 1 Location of study area

both hot weather and typhoons, with heavy rainfall in the summer. The two cities rank in the top four of China's metropolises in terms of economy and have experienced rapid urban expansion and steady development since 1980, resulting in a dense population and impervious natural surface (Liu et al. 2013; Xie et al. 2013b). Accompanied with the population and economy blooming, high frequency of climate extremes has caused huge economic damage and threatens the lives of citizens. As the difference between the threats on the two cities is still not clear, a comparison between the climate extremes of Guangzhou and Shenzhen may be effective for identifying urban climate hazard in South China.

The daily climate station records of Guangzhou and Shenzhen were downloaded from the China Meteorological Data Sharing Service System. Three types of records, namely the maximum air temperature, daily precipitation, and maximum wind velocity, from 1/1/1960 to 12/31/2013 were extracted. Maximum wind velocity records begin from 1962 in Guangzhou and from 1970 in Shenzhen. As both of the two stations are urban stations surrounded by construction land, the longtime records may also act as a response of fast urbanization.

### 2.2 Definition of the extremes threshold

Because fixed values may not be appropriate for different regions, the 90th percentile has been found to be a reasonable threshold for determining climate extremes (Kioutsioukis et al. 2008; Tomozeiu et al. 2007; Yan et al. 2002). In this study, a sliding 31-day window was chosen to successively check the records with the reference period of 1981–2010. For each day, dates 15 days before and 15 days after were noted. Then, the climate records for the noted 31 days in 1981–2010 were extracted. If the value for this day was higher than the 90th percentile of extracted records, the day is considered an extreme day. Since a single hot day does not constitute a heat wave, and neither do warm winters, additional thresholds were set: The temperature higher than the 90th percentile should last for at least three consecutive days, and the daily maximum temperature value be higher than 33 °C for each of those days. Using this method, the successive hot summer days were identified. Likewise, light rain and gentle breeze are not hazards. The thresholds of extreme rain and extreme wind were 50 mm/d and 8 m/s as additional criteria. Then the values upper than 90th percentile were extracted. Finally, the extreme hot days were counted as a "heat wave," extreme rainy days were counted as "heavy rain," and extreme windy days were counted as "strong wind" for each year.

### 2.3 Heat stress of UTCI

Compared with heavy rain and strong wind, the urban heat island created by urbanization is a more common problem that directly alters local climate (Buyantuyev and Wu 2010; Connors et al. 2013). The temperature difference between urban and rural environments has attracted much attention, but whether the increasing temperature in urban settings has changed living conditions is not clear. In other words, with variations in wind and humidity, our sensation of heat is usually not in accord with the numerical value of the temperature. Thus, more attention should be paid to bioclimate conditions for the thermal comfort of citizens (Brode et al. 2012).

The UTCI was based on an advanced thermo-physiological model of human temperature regulation, which used real life data for clothing behavior (Havenith et al. 2012). By combining air temperature, wind, radiation, and humidity, the UTCI provides a deeper understanding of the principles of human thermoregulation (Jendritzky et al. 2012). In particular, the UTCI depends on four variables, namely the local air temperature, vapor pressure, wind speed, and mean radiant temperature (Saneinejad et al. 2014). In recent applications, the UTCI has been often used as an index of thermal stress (Cheung and Hart 2014).

In this study, the daily UTCI was calculated using the software BioKlima 2.6. In the same manner as the extraction of hot days, a numeric UTCI threshold of 30 °C was used to exclude warm winter days after the days were extracted using the 90th percentile threshold. The threshold was set at 30 °C in order to obtain a similar order of magnitude for the results of different indices.

### 2.4 Magnitude index from kernel density estimator

Nevertheless, identifying extremes as the number of days has a drawback, in that the intensity of the hazard could be concealed. For example, in a threshold of 33 °C, daily maximum temperatures of 28, 33, 33, 33, and 29 °C could be defined as a 3-day heat wave, but a temperature series of 32, 35, 38, 35, and 32 °C could also be defined as a 3-day heat wave. In order to separate the intensity of the hazard, an unscaled magnitude index has recently been proposed to reflect heat wave magnitudes (Russo et al. 2014). In the new index, a probability value between 0 and 1 is extracted by a cumulative density function, where the unit can be eliminated. This index could also suit numerous climate indices other than temperature.

In contrast to the original method that sums three daily maximum temperatures (Russo et al. (2014), in this study the calculation was simplified for daily records without summation, because the unit in our former extraction of extremes was days rather than a sum of days. In particular, the empirical (nonparametric) cumulative density function (ECDF) was fit to all the extreme hot days with unscaled magnitudes within the reference period 1981–2010. The values of the ECDF are obtained as (Silverman 1986):

$$\mathrm{ECDF}(T) = \frac{1}{N}\sum_{i=1}^{N}\int_{-\infty}^{T} K(T - T_i, h)\mathrm{d}T \quad (1)$$

where ECDF($T$) is the cumulative probability of extreme value $T$, $T_i$ is each extreme value in 1981–2010, and $N$ is the number of extreme days in 1981–2010; the kernel function $K$ is chosen here to be the Gaussian function; $h$ is the smoothing bandwidth calculated using the method of Sheather and Jones (1991).

Using this estimator, the unscaled magnitudes in every extreme can be built. For example, if a 100 mm/d rain event has the value 0.9 in ECDF, it means that 90 % of the rain extremes were lower than this event during the reference period; if another rain event of 50 mm/d has a value of 0.2 in ECDF, the two events should be well separated. In fact, these values act as weights on the counted days. Using the sum of unscaled magnitudes in every year, the yearly magnitude weighted index can be built in contrast to the yearly extreme days. All the calculations were performed in Matlab R2012a.

## 3 Results

### 3.1 Temporal variation of climate extremes

As the departures from the mean values show in Fig. 2, the climate extremes form inconsistent time series. Generally speaking, the threat of heat wave increased, the threat of strong wind decreased, and the threat of heavy rain fluctuated. The heat waves were

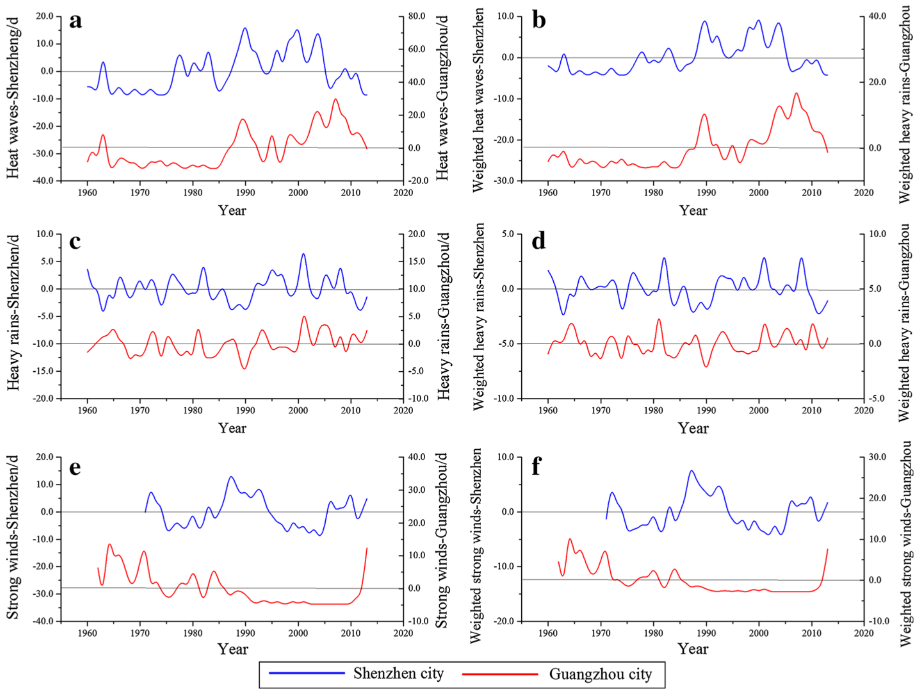


**Fig. 2** Departures of climate extremes from the mean value, in comparisons of two indices for Shenzhen and Guangzhou, 1960–2013; the weighted threats are unscaled in magnitude

consistent between spatially adjacent metropolises over some periods, but the other two extremes were not. There were some relationships among the trends of interannual climatic extremes, as the years with strong winds generally suffered fewer heat waves, but the relationships were not obvious between other pairs of extremes.

In particular, from 1960 to 1985, Guangzhou and Shenzhen did not experience serious heat waves. The first peak of heat threat in these two cities appeared in 1989–1990, when 31 and 30 extreme heat days were identified in Guangzhou, and 19 and 28 extreme heat days were also identified in Shenzhen. Then in 2000, Shenzhen experienced a second heat wave with 27 extreme heat days. Nevertheless, with 15 extreme heat days, Guangzhou was not very hot at that time. In 2004, Shenzhen suffered the last heat wave, lasting 25 days, while in Guangzhou there was also a peak of 36 days. However, when the heat wave threat in Shenzhen was below the mean value, Guangzhou suffered the longest heat wave of 49 days in 2007. When the threats were weighted by magnitude indices, the stages of the threats were more apparent. The sub-peak in 1963 was weaker, and so was the sub-peak in 1995–1996.

In 1990, there were zero heavy rain days in Guangzhou, and in Shenzhen there were three. This minimum heavy rain threat corresponded exactly to the peak heat wave. In 2001, both Shenzhen and Guangzhou reached peak heavy rain threat, when the heat wave threats were relatively at a minimum. The inconsistent period was mainly in 1960–1970. In particular, in 1965, Guangzhou suffered a peak of 9 days of heavy rain, while the threat in Shenzhen was lower than the mean value. In 2008, there was also an apparent inconsistency, where Shenzhen reached peak of threat but the threat is concealed for Guangzhou. When weighted by the magnitude index, this inconsistency in 2008 was more distinct. In other words, the three peaks of heavy rain in Shenzhen were better identified using unscaled magnitudes, indicating that the peak of heavy rain threat in 2001 was not unique in Fig. 2d compared with Fig. 2c.

Compared with temperature and precipitation, changes in wind represent more local, microclimatic characteristics. Thus, the variation curves for strong wind threats for these two cities are significantly different. In Guangzhou, high threat of strong wind occurred mainly before 1985, while in Shenzhen the high stress period was 1985–1995. It should be accepted that variations in strong wind threat are more difficult to interpret than the other two threats. However, it is still clear that the period of low wind threat in 1995–2005 corresponded to the period of high heat wave threat. Therefore, although wind speed can vary significantly depending on the location of the climate station, the basic rule that higher wind speeds result in lower temperatures still holds.

## 3.2 Variation of UTCI heat stress

Facing the obvious increase in heat wave hazard, it is necessary to further examine the thermal comfort for citizens. The departures from the mean values of UTCI heat stress shown in Fig. 3 suggest that the stresses in these two cities have not increased significantly. After using unscaled magnitudes to weight the index in order to weaken the sub-peaks, three main peaks of UTCI heat stress in Shenzhen and four in Guangzhou were identified.

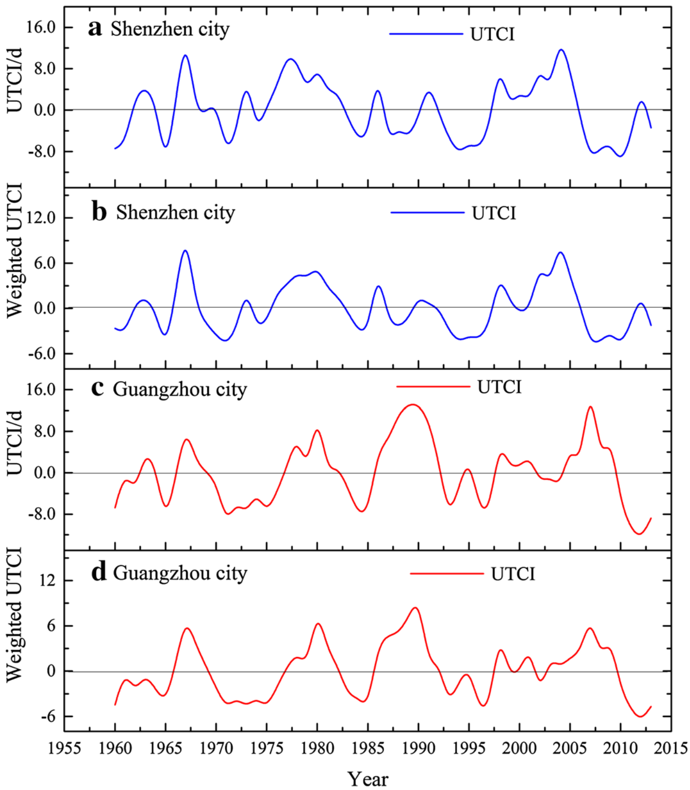


**Fig. 3** Departure from the mean value of extremes in UTCI heat stress, in comparisons with two indices for Shenzhen and Guangzhou, 1960–2013

Specifically, the first peak of UTCI heat stress appeared in 1967, when there were 28 extreme days in Guangzhou and 23 in Shenzhen. The second peak appeared in 1980, when there were 26 extreme days in Guangzhou and 21 in Shenzhen. In 1990, Guangzhou experienced the third peak, whereas the stress in Shenzhen was close to the mean value. A similar phenomenon occurred in 2004, when Shenzhen experienced the third peak, but the stress in Guangzhou was near the mean value. Finally, Guangzhou experienced the fourth peak in 2007, while Shenzhen was in the wave trough of UTCI heat stress. It is apparent that the year 2000 was a tipping point, as the curves before 2000 mostly matched.

It was found that through the decades, the UTCI heat stress has not increased, unlike the situation with heat waves. Some of the long heat waves corresponded to high UTCI heat stress, such as for Guangzhou in 1990 and 2007, although the UTCI depended on the daily mean temperature rather than the maximum temperature in heat wave extraction. In some other years, the UTCI heat stresses were significantly different from the heat waves, especially in Shenzhen, where long heat waves did not trigger high UTCI heat stresses. Because the calculation of the UTCI included consideration of wind speed and humidity, the maximum temperature might not directly threaten people's comfort along the coast. In addition, as the daily mean wind speed used in the UTCI is usually very different from the maximum wind speed, the UTCI heat stress does not match the strong wind stress.

## 3.3 Trends and correlations between climate extremes

In order to examine the variation of the climatic extremes, linear regression was used to find the yearly change rate of the indices (Table 1). The trend of heat waves increased faster for Guangzhou than for Shenzhen, both in terms of day units and the weighted index. The rates of increase were 0.793 and 0.707 day/year, respectively. For heavy rain, the difference was distinct, increasing much faster in Guangzhou than in Shenzhen in day units. The weighted index of heavy rain decreased in Shenzhen, indicating that the threat of heavy rain might be weaker. For strong wind, the trend in Guangzhou decreased sharply, while Shenzhen only experienced a very weak decrease. For UTCI stress, the two cities had opposite trends. The stress increased 0.128 day/year in Guangzhou, but decreased 0.217 day/year in Shenzhen. It is notable that although the heat wave threat in the metropolises has increased in recent years, the thermal comfort for citizens has not deteriorated. With the more apparent urban heat islands and warmer urban climate due to urbanization, whether there is an increase in thermal stress to people is still no clear. At least, the UTCI results show that the higher temperatures do not necessarily indicate a worse thermal environment. Therefore, the most evident climatic extreme which related to climatic hazard should be heat wave because of its trend of rapid growth.

By quantifying the correlations between the climate extremes, it was found that most of the climate extremes were uncorrelated with one another, and the extremes between the adjacent cities may also not be in accordance (Table 2). Nevertheless, some relationships

**Table 1** Variation trends of the extreme indices in 1960–2013

| | Guangzhou day/year | Guangzhou weighted index/year | Shenzhen day/year | Shenzhen weighted index/year |
|---|---|---|---|---|
| Heat wave | 0.793 | 1.634 | 0.707 | 1.357 |
| Heavy rain | 1.028 | 0.854 | 0.127 | −0.110 |
| Strong wind | −1.554 | −2.305 | −0.087 | −0.084 |
| UTCI stress | 0.128 | 0.350 | −0.217 | −0.154 |

**Table 2** Correlations between climate extremes, in day/weighted index units

| | Climate extremes in Guangzhou | | | | Climate extremes in Shenzhen | | | |
|---|---|---|---|---|---|---|---|---|
| | Heat wave | Heavy rain | Strong wind | UTCI stress | Heat wave | Heavy rain | Strong wind | UTCI stress |
| Climate extremes in Shenzhen | 0.445**/0.433** | 0.301*/0.187 | 0.107/−0.031 | 0.243/0.371** | – | – | – | – |
| Heavy rain | −0.154/−0.050 | 1 | – | – | −0.014/−0.077 | 1 | – | – |
| Strong wind | −0.176/−0.138 | −0.204/−0.189 | 1 | – | −0.531**/−0.492** | −0.058/0.060 | 1 | – |
| UTCI stress | 0.466**/0.430** | −0.291*/−0.129 | −0.192/−0.176 | 1 | 0.241/0.286* | 0.045/0.022 | −0.498**/−0.390** | 1 |

** Significant at $p = 0.01$; * significant at $p = 0.05$

are still apparent. The heat wave threat in Guangzhou and Shenzhen were significantly correlated, namely 0.445 in day unit and 0.433 in weighted index unit. Significant correlation also existed for heavy rain threat when counted as days, and for UTCI stress when counted by weighted index. Therefore, the heat extremes of the two cities were somewhat related. In Guangzhou, the correlation between heat wave threat and UTCI stress was significant, namely 0.466 in day unit and 0.430 in weighted index unit, whereas the correlation was much weakened in Shenzhen. The negative correlation between heavy rain threat and UTCI in Guangzhou was not found in Shenzhen. However, the strong wind threat had significant negative correlations with both heat wave threat and UTCI stress in Shenzhen, which was not obvious in Guangzhou. Therefore, the relationships between trends in interannual climatic extremes depend on the specific characteristic of the metropolis. The heat threat may be similar in adjacent regions, but the pervasive relationship for all metropolises remains unclear.

## 4 Discussion

### 4.1 The daily consistency of the extremes between the two cities

Compare the extreme days between the two cities, different kinds of indices showed various relationships. As the former result showed, there were more heat wave and UTCI stress days in Guangzhou, which simultaneously meant more heavy rain and strong wind in Shenzhen. For Shenzhen, the 466 heat wave days had 255 dates accorded with the heat wave days in Guangzhou, which accounted for more than 50 %. However, the 672 UTCI stress days only showed 283 dates appeared in the extraction of Guangzhou. This phenomenon reflected although heat waves may happen in the both cities at the same time, the stress of temperature on the citizens may be less similar. For Guangzhou, only 92 coincident heavy rain dates were found in the 300 heavy rain days, and the coincident strong wind dates were even only 58 in the 245 extracted days. This low accordance may attribute to the indices of extreme precipitation and maximum wind speed often acted as local variables and influenced by surface conditions. Nevertheless, there still existed some related extreme events, and thus the top three longest intersected durations for temperature indices and highest intensity day for extreme precipitation/maximum wind were extracted (Table 3).

In 1992, a 10-day heat wave in both cities was identified from the intersected durations. In this heat wave, the average maximum temperature in Shenzhen was 35.1 °C, and in Guangzhou the value was 35.5 °C. The second longest intersected duration of heat wave happened in 1990, when both of the cities reached the peak temperature of 37.0 and 37.7 °C at 8/17/1990. In 1998, accompanied with the famous flood disaster of Yangtze River in South China, an interconnected event appeared that Pearl River, which to the

**Table 3** Dates in the top three longest intersected durations for each index

| | Heat wave | Heavy rain | Strong wind | UTCI stress |
|---|---|---|---|---|
| 1st | 8/27/1992–9/5/1992 | 8/23/1999 | 7/22/1971 | 6/11/1980–6/21/1980 |
| 2nd | 8/11/1990–8/19/1990 | 9/27/1993 | 9/6/1980 | 8/8/1966–8/13/1966 |
| 3rd | 7/27/1998–8/4/1998 | 6/17/1983 | 7/22/1980 | 6/28/2004–7/2/2004 |

south of Yangtze River, suffered a long heat wave. The average maximum temperatures in Shenzhen station and Guangzhou station were both at 35.6 °C in that duration. In 8/23/1999, the heavy rain triggered by a powerful rainstorm of No.8 typhoon poured 298.3 mm in Shenzhen and 239.0 mm in Guangzhou. Similarly, the strong wind in 22/7/1971 was triggered by the No.21 typhoon named "Nadine," and led to 18.0 m/s maximum wind speed in Shenzhen as well as 16.8 m/s in Guangzhou. In addition, the UTCI stress was mainly triggered by heat wave. In the 11 days of intersected duration in 1980, the daily maximum temperature was ranged from 32.7 to 35.3 °C in Shenzhen and from 33.4 to 34.3 °C in Guangzhou. To sum up, although many of the extreme dates did not show close relationship between the two adjacent cities, some extreme events happened simultaneously in historical records, which may lead to regional hazards events.

### 4.2 The comparison of extremes with hazards events

Depending on the disaster statistics of Guangdong province, the numbers of people dead/injured or suffered from hazard events can be qualified. Thus, the damage of hazard event can be backdated to the climate extremes. It was clearly the serious disasters often in relation to high values of climate records and weighted index (Table 4). In May 24, 1998, a destructive flood was triggered by rainstorm in Shenzhen. The precipitation was 135.5 mm/day, which corresponded with weighted index of 0.862. This high weighed index revealed the extreme was stronger than 86.2 % of the total extremes. In the effect of this flood, 10 people were dead and 11 people were injured. In a similar case, the 99.0 mm/day precipitation with weighted index of 0.807 caused 6000 people migration in Guangzhou. The strong wind was a direct extreme event in typhoon hazard. In 9/2/2003, the No.19 typhoon named "Dujuan" resulted in the death of 22 people and injury in 99 people in Shenzhen, which corresponded with the maximum wind speed of 12.2 m/s and weighted index of 0.908. But there also existed some strong wind extremes not in relation to typhoon. In July 17, a grade 8 gale in Guangzhou showed 11.0 m/s maximum wind speed in climate records. This extreme with weighted index of 0.874 caused injury in three people and 9000 $hm^2$ crops were damaged. In contrast with heavy rain and strong wind, heat waves seldom people injuries. However, the high maximum temperature of 35.9 and 36.1 °C with UTCI stress of 32.2 and 32.9 °C during July 24–25, 2006 resulted in injury in 167 people in Shenzhen, which was a serious damage. In addition, it should be note that the definition of heat wave is often in a time span of 3 days, but hazards events may happen in a shorter timescale. Thus, the introduction of UTCI, which identified this heat event with weighted index of 0.734 and 0.895, was useful to determine the hazards.

**Table 4** Relation of extremes with people dead/injured (suffered) from hazards events on date scale

| City | Dates | Climate extremes | Climate records | weighted index | People injures |
|---|---|---|---|---|---|
| Shenzhen | 5/24/1998 | Heavy rain | 135.5 mm | 0.862 | 10/11 |
| Guangzhou | 6/27/1997 | Heavy rain | 99.0 mm | 0.807 | (6000) |
| Shenzhen | 9/2/2003 | Strong wind | 12.2 m/s | 0.908 | 22/99 |
| Guangzhou | 7/11/1989 | Strong wind | 11.0 m/s | 0.874 | 0/3 |
| Shenzhen | 7/24/2006–7/25/2006 | UTCI stress | 32.2–32.9 °C | 0.734–0.895 | 0/167 |

### 4.3 Uncertainties and limits

Uncertainties can be generated both by the climate records and by the process of selecting extreme days. Although different algorithms have different sensitivities in selecting the extremes, the most extreme events could still be held from different extraction processes. Besides addressing aspects of the statistical methods used, such as replacing the 90th percentile with the 95th as the threshold, or extending the time series, we should also focus on the limits of the raw climate record. The relevant issues are as follows. First, the records are incomplete; for example, daily maximum wind speeds were not observed before 1970 in Shenzhen. Second, the quality of the observation instruments is gradually improving. The high maximum wind speeds in Guangzhou in the 1960s were difficult to calibrate, resulting in part of the uncertainties. Third, with urbanization, meteorological stations were often migrated. For example, the Guangzhou meteorological station has been moved twice, in 1988 and 1996. Although the curves of climatic extreme indices were smooth and similar to those of Shenzhen during this period, a slight uncertainty remained.

Nevertheless, these two adjacent metropolises had long climatic records, which are relatively unique in China, and a comparison could be made within the same climate type and urbanization stage. Although the records were not perfect, the results were effective enough to provide answers to our former questions, as most of the records were of good quality without consecutive missing days, especially after 1980. In addition, using historical records of humidity and mean wind speed, the UTCI curve could be drawn from 1960. This long index time series could be effectively compared with the heat wave data, enriching the measurement of heat threats. Therefore, the limitations of the data could not overturn the conclusion, and a better-designed experiment is still being explored.

## 5 Conclusions

In the study of integrated climate hazard, the temporal trends of various climate extremes should be identified in an integrated way using effective indices. This study focused on heat waves, heavy rain, strong wind, and UTCI stress in Guangzhou and Shenzhen in 1960–2013. For daily records in the 90th percentile threshold, a kernel density function was adopted to weight the indices. From the results, clear conclusions were reached.

First, Guangzhou and Shenzhen both experienced an increase in heat wave threat and a decrease in strong wind threat. The change amplitudes for Guangzhou were greater than for Shenzhen. The heavy rain threat and UTCI were was both increased in Guangzhou, whereas the heavy rain threat fluctuated, and the UTCI stress decreased in Shenzhen. Second, the correlation of heat wave threat between Guangzhou and Shenzhen was significant. For heavy rain threat and UTCI stress, some significant correlations existed, but they depended on the definition of the extreme indices. There was no correlation between the strong wind stresses in the two cities. Third, the relationships among the different indices were mostly weak, and depended on the cities' characteristics. The heat wave threat was correlated with UTCI stress in Guangzhou, while both heat wave threat and UTCI stress were correlated with strong wind threat in Shenzhen. Fourth, the variation of UTCI stress indicated that although the heat wave threat has increased, thermal bioclimate conditions for human habitats have not deteriorated, especially in Shenzhen. Finally, the daily-level results showed the heat waves had close relationship between the two adjacent cities, and people suffered from hazard events were usually in high weighted indices of extremes. In future studies, better-designed experiment is still in need to predict the climatic disaster risk.

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