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ORIGINAL PAPER

Temporal changes in extreme high temperature, heat waves and relevant disasters in Nanjing metropolitan region, China

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Abstract The urban heat environment in Nanjing metropolitan region is significantly affected by human activities. The days of high temperature and heat waves became increasingly obvious. Therefore, this paper aimed to reveal the temporal changes in high temperature and heat waves and analyze the relevant disasters. The results showed that the duration and average high temperature were both increasing during 1951–2013. Days of heat waves were mainly concentrated in August. The longest duration of extreme heat was in 2013 lasting 9 days. The major issues caused by high temperature and heat waves were energy consumption, power shortage, human health and human habitat deterioration. Land

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use change driven by human activities altered the underlying surface and accelerated urban heat island effect. These views provide scientific evidence for assisting urban planning and industrial restructuring in the future.

Keywords Extreme high temperature · Heat waves · Potential disaster · Land use · Nanjing metropolitan region

1 Introduction

Climate change is the core topic of global change science. Due to economic development, the response of anthropogenic activities to climate change is increasingly important and reported widely (IPCC 2007). The most direct appearance of climate change is global warming, which is also affected by rapid urbanization and industrialization (United Union 2014). High temperature and heat waves in the urban area brought numerous disasters such as human health and mortality (Gong et al. 2012), water quality and human habitat deterioration (Grimm et al. 2008), power shortages (Zhang et al. 2010). Numerous researches about the effect of high temperature on human health have been widely concerned and implemented (Anderson and Bell 2011; Dessai 2002). In these studies, scholars mainly focused on three aspects: analyzing the relationship between the main epidemiologic and specific heat waves, modeling the general temperature-mortality shape between a climatic event and its impact on mortality (Fouillet et al. 2007), and cause-specific and age-stratified mortality caused by persistent extreme temperatures (Rocklöv et al. 2011). Meanwhile, two typical cases about human mortality caused by heat waves in the world were reported. In 1995, Chicago heat wave resulted in 939 resident's deaths (Whitman et al. 1997). It is estimated that as many as 70, 000 Europeans died as a result of the roughly 2-week period of unusually high temperatures in August 2013 (Robine et al. 2007). High temperature has become a major public health problem (Kovats and Hajat 2008).

In addition, the relationship between high temperature and urban planning has been concerned by scholars (Zhang et al. 2011; Zhou et al. 2014). Surface temperature is a key parameter for analysis of urban thermal environment and climate, and it is also an important component of the surface energy balance process (Voogt and Oke 2003). The rapid urbanization driven by human activities caused the increase in artificial impervious surfaces, which altered underlying surface of urban. Then, the altered urban thermal environment led to heat accumulation higher than the suburbs range (Arnfield 2003). In the urban area, changes in the underlying surface and heat environment resulted and accelerated in urban heat island effects. Air temperature, building materials, impervious surface and surface temperature are all affecting the heat distribution in the city. This resulted in a series of disasters for citizens, such as human health and mortality (Pengelly et al. 2007; Smoyer-Tomic et al. 2003).

Many scholars analyzed urban heat island effect and the relationship between high-temperature changes and specific disasters (Rinner and Hussain 2011; Liu and Zhang 2011; Shi et al. 2012; Chen et al. 2006). However, related researches regarding changes in high temperature, heat waves and their disasters were relatively rare. Thus, this paper analyzed spatial and temporal analysis of high temperature and various disasters to provide scientific evidence for human health protection and urban planning. Meanwhile, this paper also resolved insufficient analysis of related disasters caused by high temperature in previous studies. As one of developed cities and famous furnaces in China, Nanjing is a typical study area for analyzing changes in high temperature and the relevant disasters. What is changing trend of high temperature? What are disasters caused by high temperature? To address these questions, two specific objectives of this research are to (1) analyze the temporal changes in high temperature in Nanjing from 1951 to 2013; (2) reveal the potential disasters brought by high temperature.

2 Data and method

2.1 Study area

As the capital of Jiangsu Province, Nanjing is located in the southwest of Jiangsu Province (Fig. 1). Nanjing metropolitan region includes *Jiangning, Pukou, Liuhe* District and *Jiangnan Eight Districts* (including *Jianye*, *Gulou*, *Baixia*, *Xuanwu*, *Xiaguan*, *Qinhuai*, *Yuhuatai and Qixia*). Nanjing holds 7.4 million permanent residents and administrates an area of 6,515 km^2 (Ouyang et al. 2012). Nanjing has a humid subtropical climate and

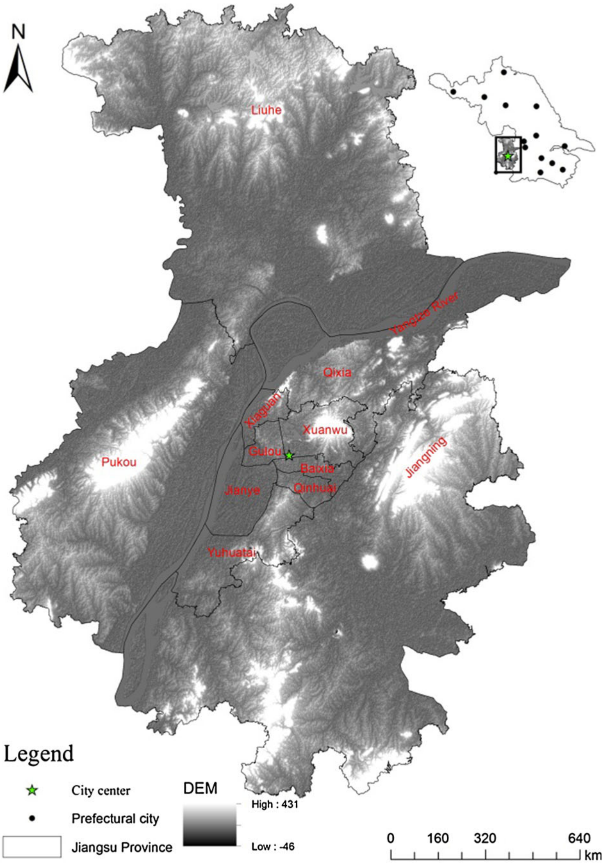

Fig. 1 Map of Nanjing metropolitan region and its location in Jiangsu Province

influenced by the East Asia Monsoon (Shi et al. 2012). The mean annual temperature is 15.7 °C, and the average precipitation is 1,106.5 mm (Xu et al. 2010).

2.2 Data source

Landsat 5 Thematic Mapper (TM) remotely sensed imageries were acquired from US Geological Survey in 2010. According to cloud coverage, noise of remotely sensed imageries and crop planting calendar, the optimum Landsat data with orbit (120/37 and 120/38) were selected (Table 1). Land cover samples were obtained using handheld GPS for land cover classification accuracy assessment.

The ground control points from field work were used to rectify Landsat remote sensing imageries in 2010, and error of geometric registration was less than 0.5 pixels. Then, the radiometric calibration was used to transform digital number values into apparent reflectance (Markham and Barker 1987; Price 1987; Moran et al. 1992). The remote sensing imageries were mosaicked and extracted using the administrative boundary with vector format. The land use data in 1980s were obtained from Data Sharing Infrastructure of Earth System Science in China (http://www.geodata.cn/Portal/index.jsp). Daily climate observation data from 1951 to 2010 in Nanjing were obtained from National Principal Station of China Meteorological Administration.

2.3 Methodology

The flowchart illustrates the procedures for explaining temporal changes in high temperatures and their disasters during 1951–2013 (Fig. 2). Firstly, four high-temperature types were identified based on their definitions and temperature data from 1951 to 2013. Then, the temporal changes in high temperatures were analyzed. Secondly, the response of disasters to high temperatures was analyzed based on numerous related reports and literature. Finally, land surface temperature was derived from thermal band of Landsat 5 TM remotely sensed image in 2010. These data resolve the limitation of spatial distribution of temperature. Meanwhile, the urban expansion was extracted based on land use map in 1980s and 2010 derived from remotely sensed imageries. After that, the relationship between urban expansion and high temperatures was analyzed to provide scientific evidence for urban planning and industrial restructuring in Nanjing. Thus, three methods about high-temperature extraction, urban expansion and land surface temperature extraction were analyzed, respectively.

2.3.1 Extreme high-temperature information extraction

The definitions of high temperatures and heat waves varied among different countries and regions (Mazon et al. 2014). In this paper, the temperature greater than or equal to 35 °C is considered as a high temperature (Zhang et al. 2005). A heat wave is defined as a period of at least three consecutive days with the daily maximum temperature at or above 35 °C. A

Table 1 Path/row and acquiring date of remotely sensed images

Satellite	Sensor	Path/row	Resolution (m)	Acquisition date
Landsat 5	TM	120/37,120/38	30	2010_08_19

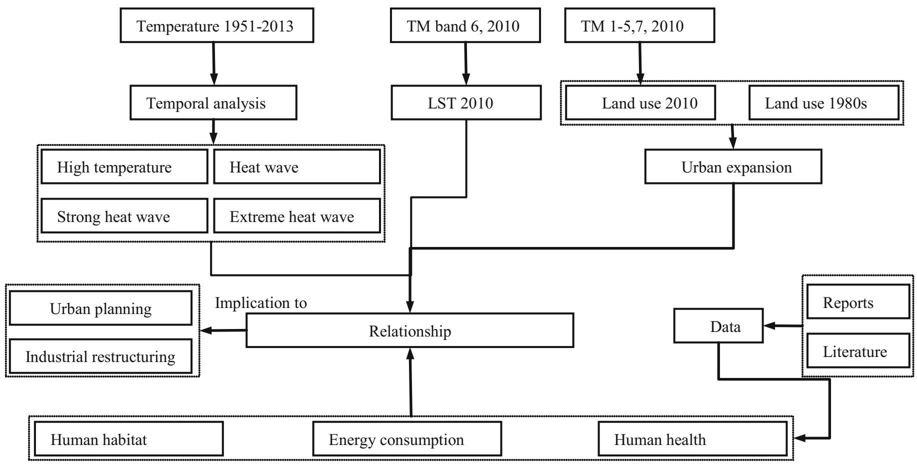

Fig. 2 Flowchart of this paper

strong heat wave is defined as at least five consecutive days with the daily maximum temperature greater than or equal to 35 °C. An extreme heat wave is defined as at least three consecutive days with the daily maximum temperature at or above 38 °C.

2.3.2 Land use classification and urban expansion

According to the classification criteria of State Bureau of Land Administration and Chinese Academy of Sciences, the land use types were divided into seven categories, including cropland, woodland, grassland, water body, wetland, built-up land and unused land (Liu et al. 2005, 2014). Then, the maximum likelihood classification (MLC) method derived from ENVI 4.7 software was employed to obtain the land use classification in 2010. In order to obtain higher accuracy, a visual interpretation method was also employed for the post-classification. The total accuracy of classification and Kappa coefficients were 89 % and 0.85, respectively. Then, urban expansion was analyzed based on land use maps.

2.3.3 Surface temperature inversion

The spectral radiance of Landsat 5 TM thermal band was converted into brightness temperature (Weng et al. 2004). The formula is as follows:

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (1)$$

where T represents pixel brightness temperature in K; $K_1 = 60.776$ W/(m^2 sr μm), $K_2 = 1{,}260.56$ K for Landsat 5 TM images.

In this paper, an inversion algorithm was employed to retrieve surface temperature (Artis and Carnahan 1982). The formula is as follows:

$$S_t = \frac{T_B}{1 + (\lambda \times T_B/\rho)\ln\varepsilon} \quad (2)$$

where S_t is the surface temperature (K); T_B is brightness temperature; λ is wavelength of thermal infrared, the value of 11.5 μm; $\rho = 0.01438$ m K; ε is emissivity. The emissivity is an important parameter, which is correlated with and calculated using vegetation cover (Markham and Barker 1985; Snyder et al. 1998).

3 Results and analysis

3.1 Changes in high temperature in various months

According to meteorological data during 1951–2013, high temperature in Nanjing mainly occurred in July–August (Fig. 3). Days of high temperature were relatively less in June and September compared with July–August. The curve of changes in frequencies of high temperature showed the trend of "increasing–decreasing" from June to September. The number of days with high temperature in June was 72, and then, it increased to 491 in July while reduced to 364 in August and 35 in September, which showing an inverted V trend.

3.2 Inter-annual variability of the high temperature

The days of high temperature were greater than 35 °C, and the annual average high temperature during 1951–2013 was calculated and mapped using a 5-year moving average method (Fig. 4a). The days and average high temperature were both employed to illustrate duration of high temperature and inter-annual variations in high temperature. According to Fig. 4a, there was a total of 962 days of high temperature in the summer during 1951–2010, with an average of 16 days per year. In 2013, duration of high temperature was the longest with 46 days. Meanwhile, the average high temperature was the largest with 37.01 °C. However, the smallest number of days of high temperature occurred in 1982 with nil. The number of high-temperature days in 1960s, 1970s, 1990s and 2000s was relatively more, especially in 2000s. Since 2000, the days of high temperature have been increasingly dense. The average high temperature was also keeping a higher level. The

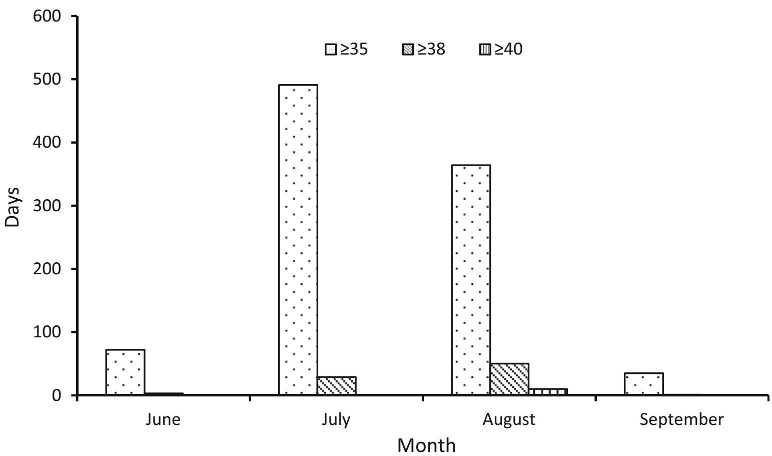

Fig. 3 Days of high temperature in Nanjing metropolitan region, 1951–2013

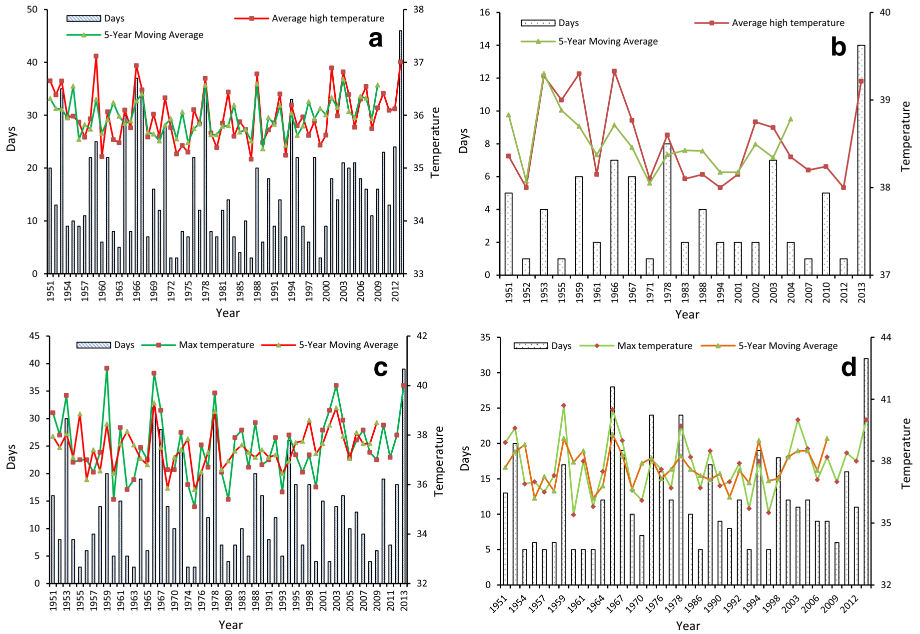

Fig. 4 **a** Days of high temperature (≥35 °C); **b** days of high temperature (≥38 °C); **c** days of heat wave (≥35 °C and ≥3 days); **d** days of strong heat wave (≥35 °C and ≥5 days)

changing trend of high-temperature days correlates with the changes in average high temperature.

According to Fig. 4b, there was only a total of 83 days of harmfully high temperature in the summer during 1951–2010, with an average of 4 days per year. In 2013, duration of high temperature was the longest with 14 days. The highest temperature occurred in 1966 with 39.33 °C, followed by 39.21 °C in 2013.

According to Table 2, there was only a total of 10 days of extremely high temperature in the summer during 1951–2010. The days of extremely high temperature were mainly concentrated in August, 2013. The extremely high temperature continued 6 days from 6 to 13 August, which caused an extreme heat disaster for citizens in Nanjing. In addition, the days of extremely high temperature also occurred in 1959 and 1966, with the maximum temperature of 40.7 and 40.5 °C. The changing trend of extremely high temperature showed an increase of extremely high temperature in Nanjing.

3.3 Temporal analysis of the heat waves

The number of heat waves days was 684, and it was 39 days in 2013 (Fig. 4c). The number of strong heat waves days was 475, and it was 32 days in 2013 (Fig. 4d). The difference between heat waves and strong waves showed that most days in 2013 were strong heat waves days. The duration of heat waves and strong heat waves became larger from 2000 to 2013.

The duration of extreme heat waves in 2013 was the largest with 9 days (Table 3). The duration of extreme heat waves increased from three in 1951 to nine in 2013. The extreme

Table 2 Days of high temperature (≥40 °C) in Nanjing, 1951–2013

Date	1959.8.22	1966.8.7	2013.8.2	2013.8.6	2013.8.8	2013.8.9	2013.8.10	2013.8.11	2013.8.12	2013.8.13
Max. temperature	40.7	40.5	40	40	40	40	40	40	40	40

Table 3 Process of extreme heat waves (≥38 °C, 3 days) in Nanjing, 1951–2013

	Duration (month/day)	Days	Average temperature	Max. temperature	Min. temperature
1951	8/6–8/8	3	38.57	38.9	38.2
1953	8/23–8/26	4	39.28	39.6	38.9
1959	8/19–8/24	6	39.3	40.7	38.3
1966	8/5–8/10	6	39.48	40.5	38.9
1967	8/26–8/27	3	38.9	39	38.8
1978	7/4–7/10	7	38.67	39.7	38.2
1988	7/17–7/19	3	38.2	38.5	38
2003	7/28–8/2	6	38.8	40	38.1
2010	8/12–8/14	3	38.3	38.4	38.2
2013	8/6–8/14	9	39.78	40	39

heat waves usually occurred in August, which revealed that August is the hottest month in Nanjing.

4 Discussion

4.1 Potential disaster of extreme high temperature to urban environment

4.1.1 Effect of extreme high temperature on human habitat

High-temperature hazard is a phenomenon, which resulted in discomfort of human beings, animals and plants due to high temperatures. With the acceleration of urbanization and increasing global warming, urban heat island effect became more serious. Meanwhile, green space has been reduced, making high-temperature phenomena increasingly prominent in Nanjing metropolitan region. Such heat disasters affect the human habitat and threaten the health of urban residents. Sustained high temperatures also increase water and power demands in the city. Photochemical pollution in the city was also exacerbated, seriously affecting the human habitat of residents. The loss of infrastructure, such as roads, in the city can be also affected by high temperature. High temperatures increase road accidents by causing tire blowout and fatigue driving. It appears likely to cause public disorder, accidents and indirect effects such as poisoning and fires.

4.1.2 Effect of extreme high temperature on energy consumption

A questionnaire in 2013 showed that residents used air-conditioning all days caused by high temperature in the summer (CCTV 2013). The electricity consumption was 1,557° in July–August 2012, while it increased to 2,702.42° in 2013 for a citizen's family in the questionnaire. The maximum electricity load increased by 10 % when the average temperature in summer rose three degrees.

The correlation coefficient between daily peak load of power and the maximum temperature was 0.91 (Jiang 2003). It indicates that increase in daily temperature increase power consumption. Electricity increased by 81.18 % from 2006 to 2012 (Fig. 5). Although electricity in Nanjing increased gradually, the deficit of electricity was still existed and was an increasing trend. Power supply situation in Jiangning District remained stressed due to rapid urban expansion. Power shortages were mainly caused by the continued hot weather. The electricity load of air-conditioning accounted for approximately 1/3 of the electrical demand.

Shortage of electricity in Nanjing caused by sustained high temperatures can result in increase in power accidents, which have a significant impact on hospitals, universities, army, people's lives and social stability in Nanjing. Increased use of refrigeration equipment caused overload of electric power grid. During the heat waves, water consumption of city soared, which caused difficulty in supplying water. The sustained high temperatures exacerbated surface evaporation to make rapid decline in groundwater level and reservoir storage significantly. The exacerbated drought caused by high temperature not only affected the growth and yield of grain (Yun 2013a), but also resulted in wilt of the ecological forest in the city (Yun 2013b).

4.1.3 *Effect of extreme high temperature on human health*

Physiological equivalent temperature (PET) is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under the actual complex outdoor conditions to be assessed (Gulyás and Matzarakis 2007).German scientists considered the PET greater than 41 °C as high-temperature heat warning criteria (Höppe 1999). The effect of heat wave and high temperature on the mortality of cardiovascular diseases was significant (Rey et al. 2007). The mortality was increased with the rise of maximum temperature (Wu et al. 2013). High temperature and humidity both prevent evaporative cooling in Nanjing, which is more uncomfortable than mere heat and considered as typical weather causing heat stroke and heat-related illness (Li et al. 2005). Muggy weather with high temperature in Nanjing leads to heatstroke easily. Additionally, heat waves tend to make people feel uneasy, even the phenomenon of consciousness disorder. In the summer, hot and muggy weather results in heat cold, heatstroke, diarrhea and skin allergies. The continuous high temperatures also seriously affect children's emotional well-being. Heat stroke, emotional distress, heat cramps, gastrointestinal diseases, fever are major acute and chronic diseases caused by high temperature.

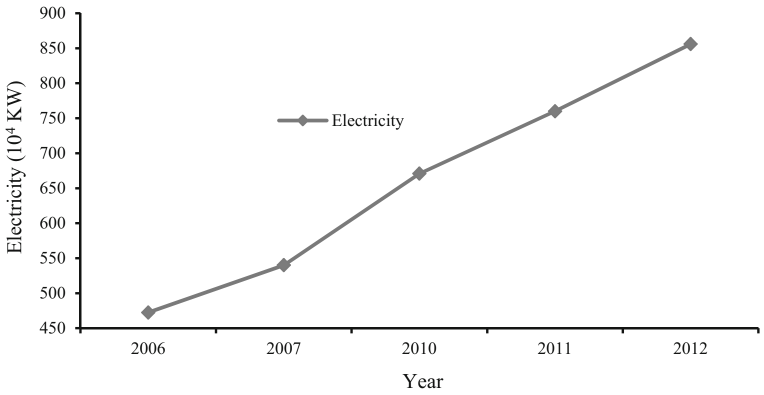

Fig. 5 Changing trend of electricity in Nanjing metropolitan region

The solar dermatitis is one of major diseases caused by high temperature and strong sunshine. In 2013, the outpatients of solar dermatitis accounted for nearly half of the whole dermatology outpatients in the Nanjing Tongren Hospital (Xu and Yang 2013). In the summer of 2013, Nanjing experienced an extreme high temperature. The outpatients of the many hospitals in Nanjing increase by 20–30 % than 2012. The average of daily outpatients in Nanjing Children's Hospital was approximately 5,500, peaking at 6,500 (Yang 2013). According to cases in all hospitals, it is summarized that the largest crowd harmed by the high temperature were young children, the elderly and young people working outdoors. This result was also consistent with the results from Xu et al. (2011). Ability to regulate the body temperature of the elderly is reduced, and the temperature threshold for sweating also increases (Kenney and Hodgson 1987). Thus, the elderly are one of major victims caused by high temperature.

In Nanjing Children's Hospital, a total of 765 children were treated but only 265 sickbeds on July 10, 2013 (Chen 2013). On July 30, 2013, a heatstroke patient died in Nanjing (Huang 2013). On August 6, 2013, more than 100 cases of cold and fever patients and 500–600 patients for emergency were admitted by Nanjing Gulou Hospital, including one patient suffering by severe heat stroke (Wang 2013). On July 30, 2013, six elderly died from high temperature in Nanjing, while Jiangsu Provincial Hospital received three patients with severe heat stroke and more than 200, 250 patients were received by Nanjing Military Hospital and First Hospital of Yangtze River (Yi et al. 2013). From July 21, 2013, to July 29, 2013, there were about 100 cases of heat stroke where one person died (Zhang and Lu 2013). In 2010, the outpatients in Nanjing Gulou Hospital increased from 400 to 600 in the summer and patient population increased by approximate 50 % in the First Hospital of Nanjing (Zhou et al. 2013).

4.2 Implication to water quality

High air temperatures cause the increase in water temperatures, especially for rivers (Webb et al. 2003). The increased water temperatures also affect circulation patterns in lakes and rivers, as well as the rate of biogeochemical and ecological processes that determine water quality (Solheim et al. 2010). Rising temperatures favor the growth of cyanobacteria (Paerl and Huisman 2008). The excessive growth of cyanobacteria forms blooms, which depleting the dissolved oxygen in water and producing toxic and hazardous substances (Whitehead et al. 2009). The dead cyanobacteria release large amounts of organic matter and emit stench, which stimulating breeding of heterotrophic bacteria and resulting in deterioration of water quality.

In addition, numerous reports on water quality caused by high temperatures provide sufficient evidence to prove this argument. In 2013, water quality of some rivers in Nanjing was deteriorated with unpleasant odor caused by sustained high temperatures (Zhou 2013). Meanwhile, sustained high temperatures resulted in aquatic plants soaring in multiple lakes, severely affecting water quality (Lv 2013). Sustained high temperatures also contributed to the deterioration of water quality in the Xuanwu Lake, the largest lake in Nanjing metropolitan region (Yu 2013).

4.3 The response of extreme high temperature to land use change

Underlying surface is critical for urban heat environment. As an important underlying surface, impervious surface seriously exacerbates heat island effects in the urban areas. However, urban green space and water can alleviate the urban heat island effect, which was called "cool island effect." In addition, green building identifications in the urban areas, such as special building materials, can mitigate the urban heat island effect. Thus, land use changes can quantitatively express changes in underlying surface. Then, the response of land use changes to temperature can be used to express the relationship between land use changes and temperature.

The variations in building materials, density, height and urban green space between new and old city areas have caused a difference in surface temperature. According to land use data in 1980 and 2010, the urban expansion information was extracted. Then, the land surface temperature of urban expansion was obtained based on GIS spatial analysis. Four samples with rectangle shape in old and new city areas were selected to compare the variations in temperature (Fig. 6a). The results showed that the surface temperature in the new city areas was higher than old town selections (Fig. 6b).

4.4 Implication to urban planning

With urbanization, the urban heat island phenomenon has become increasingly evident. Thus, how to plan urban layout and collocate reasonably cold–hot patches is essential to alleviate the urban heat island phenomenon. The number, area and spatial distribution of cold patches create local microclimate and mitigate urban heat island effects. Additionally, urban construction materials, such as glass, have an impact on the urban heat island. Therefore, increases in built-up area and application of new materials lead to changes in surface thermal environment. Therefore, the application of green building materials and cold patches (water and green vegetation) should be considered in the urban planning to mitigate the urban heat island effect.

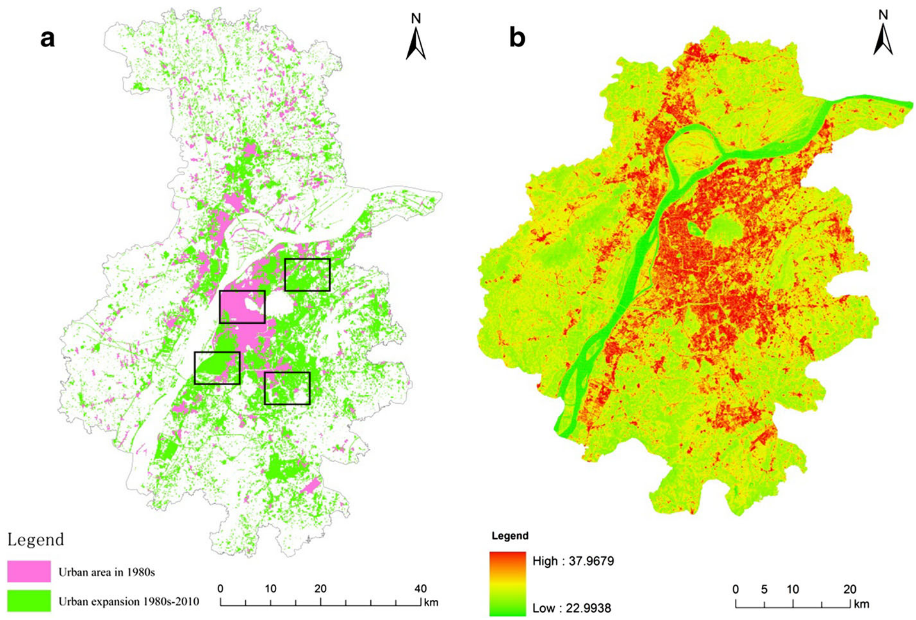

Fig. 6 Urban expansion from 1980s to 2010 (**a**) and land surface temperature in 2010 (**b**)

4.5 Implication to industrial restructuring

The tertiary industry is relatively developed in Nanjing, and commercial electricity load is relatively large. Meanwhile, the percentage of heavy industry has exceeded 80 %, especially cement, smelting, iron and steel industry. The high usage of electricity and high temperature in summer causes the shortage of electricity. Thus, upgrading the industrial structure and energy saving are implemented to ease the stress of using electricity. It is difficult to avoid power shortage due to high temperature. However, electricity savings via the industrial restructuring add more supply to residents to ease heat disaster.

4.6 Relationship among land use change, economic development path and human health

The process of urbanization was accelerated driven by rapid economic development. Numerous economic development zones, industrial parks, newly developed areas have appeared under explicit urban functional zoning and economic development paths. Thus, the area of impervious surfaces increased correspondingly to result in severe island heat effect. Additionally, the distance between the place of residences and commercial areas increased due to urban expansion. However, part of the dilapidated buses is still without air-conditioning. These factors associated with traffic congestion increased the period of exposure to high temperatures for citizens. The high temperatures and fatigue on the way to work and back make citizens more susceptible to heat stroke, which is consistent with the results from Xu et al. (2011). Due to the process of urbanization and the 2014 Youth Olympic Games, numerous outdoor construction projects brought health risks caused by high temperature for these employees.

4.7 Limitations

Lack of sufficient data about mortality and hospitalization caused by high temperature and heat waves, and quantitative analysis about the response of human health to high-temperature events were not fully illustrated. It is a major limitation in this article although there have been numerous discussions about the relationship between high-temperature events and human health using reports and related literature. In addition, the sparse spatial resolution of temperature data resulted in limitations in discussing the spatial variations of high temperatures in Nanjing metropolitan region.

Thus, further research will refer to these aspects, especially the relationship between human health and high-temperature events. The integrating quantitative analysis on the response of disasters caused by high temperature with land use change, industrial restructuring could put this case study in a broader context and make the implications more explicit particularly to policy makers.

5 Conclusions

This paper analyzed the temporal changes in high temperature and heat waves in Nanjing metropolitan area and the potential disasters. With rapid urbanization, the days of high temperature increased with longer duration. Increases in impervious surface areas altered the underlying surface and accelerated urban heat island effects. The surface temperature in the urban expansion area was relatively high due to application of high reflectance building materials and rare vegetation cover. Shortages of power, mortality, human habitat deterioration and energy consumption were all major disasters brought by high temperature in the city. The research provided implications on urban planning and industrial restructuring in the future. The results in this paper were also robust, and the methods can be also applied in the related researches in the other regions.

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