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ORIGINAL PAPER

The urban heat island and its impact on heat waves and human health in Shanghai

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Abstract With global warming forecast to continue into the foreseeable future, heat waves are very likely to increase in both frequency and intensity. In urban regions, these future heat waves will be exacerbated by the urban heat island effect, and will have the potential to negatively influence the health and welfare of urban residents. In order to investigate the health effects of the urban heat island (UHI) in Shanghai, China, 30 years of meteorological records (1975–2004) were examined for 11 first- and second-order weather stations in and around Shanghai. Additionally, automatic weather observation data recorded in recent years as well as daily all-cause summer mortality counts in 11 urban, suburban, and exurban regions (1998–2004) in Shanghai have been used. The results show that different sites (city center or surroundings) have experienced different degrees of warming as a result of increasing urbanization. In turn, this has resulted in a more extensive urban heat island effect, causing additional hot days and heat waves in urban regions compared to rural locales. An examination of summer mortality rates in and around Shanghai yields heightened heat-related mortality in urban regions, and we conclude that the UHI is directly responsible, acting to worsen the adverse health effects from exposure to extreme thermal conditions.

Keywords Global warming · Urban heat island · Heat wave · Human health

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Introduction

In recent years, the impact of weather on human health has become an issue of increased significance, especially considering the potential impacts of global warming and an increased urban heat island effect due to urbanization (Kunst et al. 1993; Kalkstein and Greene 1997; Guest et al. 1999; Smoyer et al. 2000). Warming of the climate system is unequivocal. The IPCC Fourth Assessment Report (AR4) clearly indicates that the updated 100-year linear trend (1906–2005) of global surface temperature is 0.74 K. The warming trend over the last 50 years has averaged 0.13 K per decade and 11 of the last 12 years (1995–2006) rank among the 12 warmest years since 1850 (IPCC 2007). A warming climate will likely result in an increase in the frequency and intensity of heat waves (McMichael et al. 1996; Meehl et al. 2001; Patz and Khaliq 2002).

The urban heat island (UHI) has become one of the largest problems associated with the urbanization and industrialization of human civilization, as the increased temperatures associated with the UHI tend to exacerbate the threats to human health posed by thermal stress. As a result, the UHI has been a central theme among climatologists, and it is well documented in many metropolitan areas around the world (Oke 1973; Katsoulis and Theoharatos 1985; Balling and Cerveny 1987; Lee 1992; Saitoh et al. 1996; Yamashita 1996; Böhm 1998; Figuerola and Mazzeo 1998; Klysik and Fortuniak 1999; Kim and Baik 2002; Wilby 2003). The UHI experienced by many cities is larger at night than during the day, more pronounced in winter than in summer, and is most apparent when winds are weak. For example, in Beijing, the difference in mean air temperature between the city center and surrounding fields can be as much as 4.6 K (Zhang et al. 2002; Song and Zhang 2003). This results in additional hot days in urban locales, which can directly influence the health and welfare of city residents.

As UHIs are characterized by increased temperature, they can potentially increase the magnitude and duration of heat waves within cities. Scientists have also discovered that the impacts of heat waves on humans vary among different regions within a city. As early as 1972, Buechley et al. (1972) investigated the relationship between the heat island and "death island" and found that the mortality rate during a heat wave increases exponentially with the maximum temperature, an effect that is enhanced by the UHI. Clarke (1972) revealed that the nighttime effect of UHIs can be particularly harmful during a heat wave, as it deprives urban residents of the cool relief found in rural areas during the night. Thus, during heat waves, death rates are often much higher in cities than in outlying environs (Henschel et al. 1969; Buechley et al. 1972; Clarke 1972; Jones et al. 1982; Smoyer 1998). An epidemiologic study of mortality during the summer 2003 heat wave in Italy also illustrated that those living in urban regions have an elevated risk of death compared to those living in suburban or rural areas as a result of heightened urban temperatures (Conti et al. 2005).

Unlike purely tropical regions that remain warm all year round, Shanghai experiences a subtropical climate with cold, dry winters and wet, hot summers, as well as a pronounced UHI (Ding et al. 2002; Zhou et al. 2002). Shanghai has been found to be prone to heat-related mortality (Tan et al. 2004, 2007), although few studies have quantitatively or qualitatively examined the impact of the UHI on the frequency or the intensity of heat waves along with its corresponding impact on heat-related mortality among the urban and suburban populations. Thus, the goal of this paper is to determine the influence of the Shanghai UHI on heat waves and human health within both urban and rural locales.

Materials and methods

The study was carried out over the region of Shanghai, China, which encompasses approximately 6,300 km^2, and contains a population listed as slightly over 18 million in 2006. In order to capture the effects of urban areas on local climate, 30 years (1975–2004) of daily maximum temperature were compiled covering only the summer months, defined here as May through October. These data were examined for 11 first- and second-order weather stations (Fig. 1) and were obtained from the Shanghai Meteorological Bureau. The specific sites in this study are: the urban site (XuHui-58367), suburban sites (MingHang-58361, BaoShan-58362, PuDong-58470, JiaDing-58365), and exurban sites (ChongMing-58366, NanHui-58369, JinShan-58460, QinPu-58461, SongJiang-58462, FengXian-58463). For each year throughout the 30-year research period, we first examined the yearly extreme maximum temperature (the single hottest day in each year), the mean daily maximum temperature in mid-summer (defined as July through August), and the number of hot days (defined as days exceeding 35°C in T_{max}) for each of the 11 stations. Simple linear regression was used to discern overall trends in the data, and the statistical significance of these trends was assessed (Table 1). The number of hot days, as well as heat wave duration at urban, suburban, and exurban sites, are listed in Table 2.

The UHI intensity is typically defined as the temperature difference (ΔT) between the urban (u), suburban (s), and exurban (e) locations. This is described in terms of the difference in daily maximum temperature between the urban center and suburban sites ($\Delta T_{u\text{-}s}$), and that between urban center and the exurban stations ($\Delta T_{u\text{-}e}$). The observed values of urban, suburban, and exurban sites were represented by the temperature from the urban site (XuHui station), the average of four suburban stations (MinHang, BaoShan, PuDong, JiaDing), and the average temperature from the exurban stations (ChongMing, NanHui, JinShan, QingPu, SongJiang and FengXian), respectively. The UHI intensity of each site (ΔT_i) is calculated by the temperature difference between the urban site (XuHui station) and each suburban or exurban site as follows:

$$\Delta T_i = Tmax_0 - Tmax_i$$

While $Tmax_0$ is the daily maximum temperature at the urban site, $Tmax_i$ is the daily maximum temperature at the suburban or exurban site. In order to investigate the diurnal

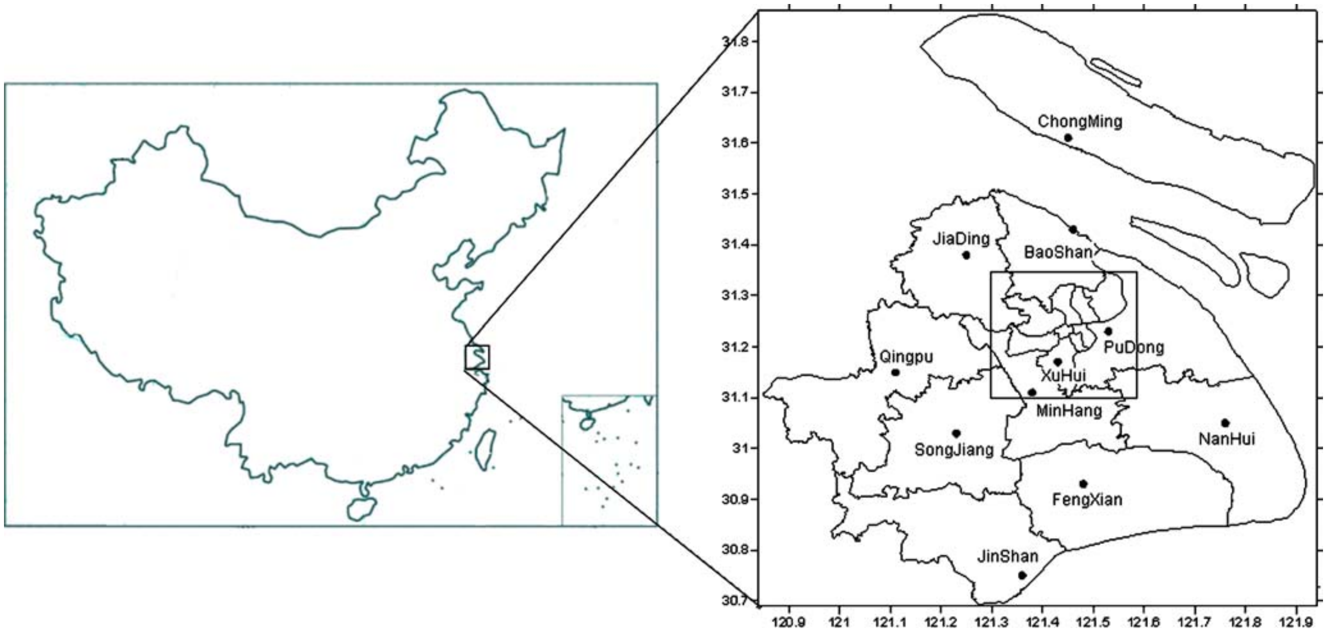


Fig. 1 Shanghai within China and the spatial distribution of 11 weather stations across Shanghai

variation of the UHI intensity, the temperature difference between the urban (XuHui), suburban (JiaDing), and exurban (ChongMing, FengXian, JinShan, SongJiang) sites are calculated from automatic weather stations from June through August, 2005–2007. The observed variations in the urban heat island effect have been plotted in Figs. 2, 3, and 4.

Here, a "hot day" is defined as a day with a daily maximum temperature exceeding 35°C in at least 1 of the 11 sites in Shanghai. Days below this threshold were categorized as "non-heat days." Additionally, a heat wave is defined as a period with at least three consecutive hot days. Although this definition is somewhat arbitrary, it was chosen to correspond with the Chinese Meteorological Administration heat warnings, which are issued when maximum temperatures are forecast to exceed 35°C. Furthermore, with the assumption that each meteorological

Table 1 The rates of increase and linear regression results by year for annual extreme maximum temperature, mean maximum temperature in mid-summer (Jul–Aug), and hot days at urban, suburban, and exurban sites

Sites		Yearly extreme maximum temperature			Mean maximum temperature in mid-summer (Jul–Aug)			Hot days		
		Rate of increase (K / year)	R^2	p	Rate of increase (K / year)	R^2	p	Rate of increase (days / year)	R^2	p
Urban	XuHui	**0.085**	**0.389**	**0.0001**	**0.073**	**0.240**	**0.0044**	**0.64**	**0.388**	**0.0001**
Suburban	MinHang	**0.049**	**0.172**	**0.0181**	**0.051**	**0.150**	**0.0282**	**0.29**	**0.168**	**0.0197**
	BaoShan	**0.066**	**0.271**	**0.0022**	**0.054**	**0.136**	**0.0376**	**0.40**	**0.278**	**0.0019**
	PuDong	**0.067**	**0.204**	**0.0095**	**0.054**	**0.158**	**0.0240**	**0.34**	**0.279**	**0.0018**
	JiaDing	**0.062**	**0.241**	**0.0043**	**0.049**	**0.128**	**0.0448**	**0.41**	**0.272**	**0.0021**
Exurban	QingPu	**0.051**	**0.158**	**0.0244**	0.045	0.112	0.0609	**0.28**	**0.161**	**0.0229**
	ChongMing	0.035	0.090	0.0918	0.038	0.082	0.1138	0.10	0.070	0.1427
	NanHui	0.029	0.053	0.2053	0.028	0.064	0.1623	0.09	0.074	0.1305
	JinShan	0.013	0.013	0.5409	0.024	0.042	0.2603	0.07	0.026	0.3817
	SongJiang	0.034	0.076	0.1276	0.034	0.070	0.1442	0.20	0.090	0.0952
	FengXian	0.009	0.004	0.7196	0.020	0.030	0.3408	0.08	0.036	0.2950

Statistically significant slopes at 95% confidence level ($p \leq 0.05$) are in bold

Table 2 The average number of hot days and the occurrence of different heat wave durations at urban, suburban, and exurban sites in Shanghai (1975–2004)

Sites		Hot days (days / year)	Heat wave duration			
			≥3 days	≥5 days	≥7 days	>10 days
Urban	XuHui	11.2	39	18	9	5
Suburban	MinHang	7.4	25	12	4	1
	BaoShan	7.5	22	11	8	1
	PuDong	5.2	18	8	1	0
	JiaDing	7.6	27	9	5	1
Exurban	QingPu	7.7	26	9	4	0
	ChongMing	3.1	9	5	2	0
	NanHui	2.7	7	2	1	0
	JinShan	5.2	14	6	3	0
	SongJiang	6.4	21	8	4	0
	FengXian	3.7	8	2	2	0

observation site represents its entire area or district, we classify days in which more than eight of the sites experienced maximum temperatures above 35°C as “large-scale hot days”, thus covering 59.6–82.6% of the total area of Shanghai. The consistency of hot day occurrence among the 11 sites has been plotted in Fig. 5.

All deaths recorded between 1998 and 2004 for all regions of Shanghai were obtained from the Shanghai Municipal Center for Disease Control and Prevention. These data consist of the daily mortality totals of each district for all causes of death and cover the summer study period.

Excess deaths are calculated by subtracting a baseline death rate from the observed daily mortality value. Numerous methods have been identified in the literature for calculating the baseline mortality (Gosling et al. 2009), and here, we adopt a 30-day moving average for the same year (Rooney et al. 1998; Dessai 2002, 2003; Gosling et al. 2007).

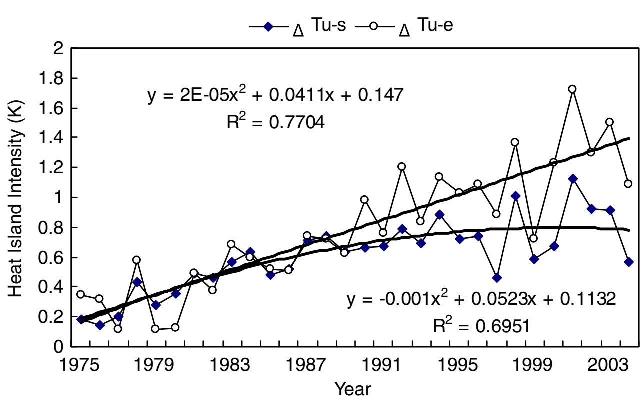


Fig. 2 The variation of urban heat island intensity [in terms of the difference of daily maximum temperature between the urban center and suburban sites ($\Delta T_{u\text{-}s}$), and that between urban and exurban ($\Delta T_{u\text{-}e}$) sites] from 1975 to 2004

Results

Warming trends at the urban, suburban and exurban sites

As demonstrated in Table 1, there are different linear warming trends in the different areas (city center, suburban, and exurban areas) of Shanghai over the last 30 years (1975–2004), covering the yearly extreme maximum temperature, the average maximum temperature from July through August, and the number of hot days during the

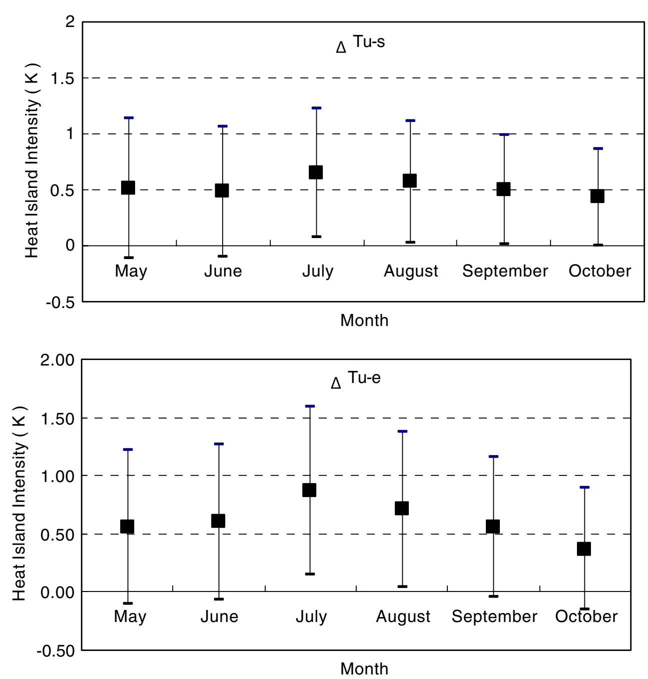


Fig. 3 The mean heat island intensity [in terms of the difference of daily maximum temperature between the urban center and suburban sites ($\Delta T_{u\text{-}s}$), and that between urban and exurban stations ($\Delta T_{u\text{-}e}$)] by month from 1975 through 2004. *Error bars* indicate ±1 SD

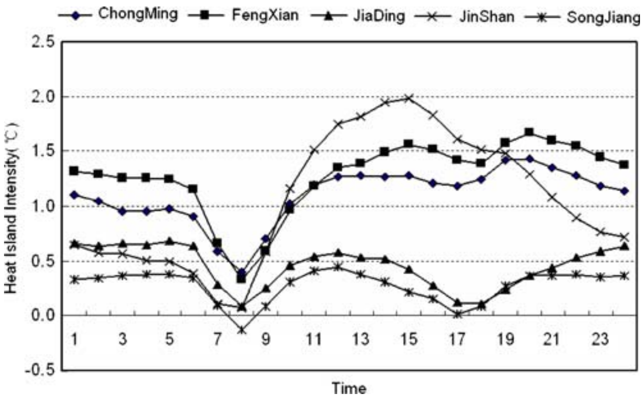


Fig. 4 The diurnal variation of the temperature difference between the city center (XuHui) and suburban(JiaDing), and various exurban sites (ChongMing, FengXian, JinShan, SongJiang) over 24 h in summer (June–August, 2005–2007)

summer. Significant trends, using a 95% confidence level ($p<0.05$), are observed at the city center, all suburban sites, and one exurban location (QingPu).

The average mid-summer (July and August) maximum temperature in the urban center is rising at a rate of 0.073 K per year ($p=0.0044$), with a 0.085 K per year ($p=0.0001$) increase in yearly extreme maximum temperature. Similarly, in the city center, the number of hot days is increasing by a rate of 0.64 days per year ($p=0.0001$), while more modest increases varying from 0.29 ($p=0.0197$) to 0.41 ($p=0.0021$) days per year are observed at the suburban sites. There are no significant upward trends in exurban areas, with one single exception (QingPu). Clearly, urban regions in Shanghai are warming at a faster rate than those in the surrounding areas.

Variations in the characteristics of the urban heat island effect

The intensity of the urban heat island is measured in terms of the difference in daily maximum temperature between the urban center and the suburban sites ($\Delta T_{u\text{-}s}$), and that between the urban center and the exurban sites ($\Delta T_{u\text{-}e}$) (Fig. 2). From the 1970s to the mid-1980s, the UHI was much less pronounced, with an average difference in daily maximum summer temperature of 0.2–0.4 K between the city center and its surroundings. However, these temperature differences increased during the period of study, particularly between the city center and the exurban locations. In fact, beginning in the mid-1980s, there is a distinct deviation between the UHI intensities of the exurban and the suburban sites. While the temperature difference of urban-exurban areas rose further to 1.6 K, differences between the urban and suburban sites remained at approximately 0.8 K. This disparity is likely due to the rapid expansion of Shanghai into the suburban regions beginning in the mid-1980s.

The UHI intensity was strongest in July during the summer months, where the average UHI intensity reached 0.9 K between urban and exurban areas ($\Delta T_{u\text{-}e}$), and 0.6 K between urban and suburban areas ($\Delta T_{u\text{-}s}$) (Fig. 3). Furthermore, the diurnal variation of the heat island intensity derived from the six automatic weather stations located in the urban (XuHui), suburban (JiaDing), and exurban sites (ChongMing, FengXian, JinShan, SongJiang) in summer (June through August), 2005–2007, shows that the heat island intensity is more pronounced in the daytime than that in the night (Fig. 4). The highest value in the region of 0.5–2.0 K occurs at noon or in the afternoon, corresponding approximately to the time in which the daily maximum temperature is reached.

The urban heat island and heat waves

As a result of increased temperatures within the urban locales, the UHI may affect the number of hot days as well as the duration of heat waves, potentially increasing the risk of mortality from heat stress. The yearly average number of hot days and the total number of heat waves with different durations over the research period (1975–2004) at different locations in Shanghai are listed in Table 2. Not surprisingly, the largest average value of annual hot days is 11.2 days per year in the urban site (XuHui), while fewer hot days occur in the exurban sites such as ChongMing, NanHui, or FengXian. Similarly, heat wave duration is also impacted by the UHI, so that the longest duration heat waves (for example, a heat wave with at least 10 consecutive hot days) usually occurred in the urban area. There were five such events at the urban location (XuHui) with only one event recorded at the suburban stations (MinXing, BaoShan, JiaDing).

In order to discern whether increasing numbers of hot days are attributable to a regional climate warming or to an expanding UHI, we examined the five hottest years (1978, 1983, 1988, 1998, and 2003) and analyzed the consistency of hot day occurrence among the 11 sites. This was done to

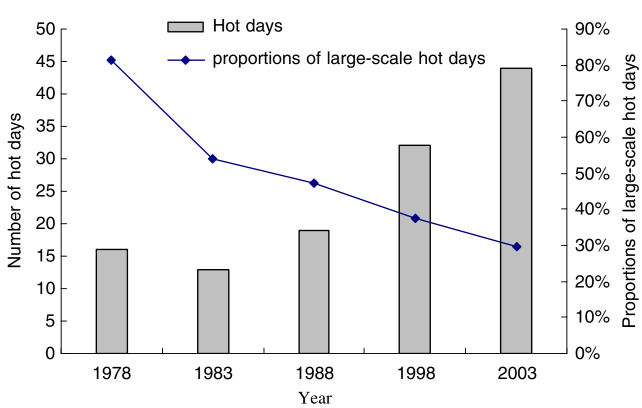


Fig. 5 The number of hot days (>35°C) and the proportion of large-scale hot days (>35°C at eight or more stations) during the five hottest years on record

determine the frequency of "large-scale hot days" in the investigation area during these years. Figure 5 illustrates a decreasing trend of the proportion of the large-scale hot days corresponding with an increasing number of hot days. For example, at least 1 of the 11 stations in Shanghai reported a hot day 16 times in 1983, and among these there were 13 large-scale hot days, accounting for 81.3%. In 2003, however, there were 45 hot days reported but only 29.5% of these were large-scale hot days. Thus, it seems that the growing UHI increases the number of hot days around the city center, but large-scale hot days are not increasing. This provides strong evidence that the warming is local in nature, caused almost entirely by the UHI, and not as a result of a larger, regional warming pattern.

The urban heat island and excess death

The relationships between heat and human health are summarized in Table 3, which illustrates the excess mortality rate, the number of heat waves, and the average maximum temperature for each heat wave from 1998 to 2004 in each region. Population-adjusted excess mortality in each region, along with UHI intensity, has been plotted for each year in Fig. 6. The excess deaths in the central urban region are higher than those in the suburban and exurban sites, which coincide well with heat island intensity, especially in the two severe heat waves in 1998 and 2003 (Tan et al. 2004, 2007). For example, with the 1998 heat wave, the excess mortality rate in the urban area is about 27.3/100,000, compared to only 7/100,000 in the exurban districts.

Furthermore, a comparison between excess deaths and the spatial coverage of the two heat waves in 1998 and 2003 (Fig. 7) shows that the extent of high temperatures played an important role in the number of excess deaths. In general, the more stations that reported hot days, the higher the number of excess deaths. In 1998, Shanghai experienced long duration, large-scale hot days with more than nine districts experiencing temperatures above 35°C for nine consecutive days from August 8 to 16. As a result, excess deaths increased sharply with a maximum value of 453 deaths observed on August 16. On the other hand, in 2003, there were frequent hot days, often with a large number of consecutive days, but these heat waves were not often experienced by a large number of stations. Thus, the spatial coverage of the 2003 event was much smaller than that observed in 1998, resulting in fewer deaths.

Discussion

The urban heat island effect is among the most well-documented impacts of human activity on local climate. As large-scale climate change continues, the UHI is very likely to exacerbate the warming, resulting in more frequent and more intense heat waves (Wilby 2003). Research on the UHI has typically focused on tropical or mid-latitude cities for the dual purposes of understanding the dynamics of the energy balance in the urban boundary layer and its application to issues related to urban pollution, energy conservation, and the prevention of heat-related health problems or deaths (Buechley et al. 1972; Smoyer 1998).

Here, the comparison between meteorological monitoring stations both inside and around the city of Shanghai revealed the large impact of the urban heat island effect on temperature, heat waves, and human health. The results demonstrate that the meteorological sites (city center and its surroundings) have experienced different degrees of warming over the period of record as a direct result of increasing urbanization and a more pronounced heat island. Additionally, we find that the hottest days (above 35°C), as well as prolonged heat waves, are more likely to occur in urban locales.

The UHI is often referred to as a nighttime phenomenon with the highest values of the UHI intensity occurring between midnight and early morning, especially in winter. This has been documented in the United States, Italy, and beyond (Basu and Samet 2002; de'Donato et al. 2008), highlighting that the major differences between urban and rural areas were measured during the night. However, for Shanghai, our results show that the heat island is often more pronounced in the daytime during the summer, with the highest urban–rural differences ranging from 0.5 to 2.0 K at noon or in the afternoon, coinciding with the timing of maximum daily temperature.

The increased thermal loads found in urban areas may be a direct factor for heightened levels of human mortality (Clarke and Bach 1971; Jones et al. 1982; Conti et al. 2005). Additionally, previous studies note that virtually all causes of mortality increase during extreme heat waves, including respiratory failure and circulatory system failure from heart attack or stroke. The results of this study demonstrate that heat-related mortality (all-cause deaths above the baseline) is often much higher in the inner city than in outlying environs during heat waves, coinciding with heat island intensity. Inhabitants of urban areas may experience sustained thermal stress both day and night as city surfaces often heat up quickly during the day but are slow to cool at night (Sheridan and Dolney 2003). There is emerging evidence that the urban population shows greater sensitivity to heat compared to those in rural regions. For example, analyses of the 1995 Chicago heat wave have shown that the relative risk for a heat-related hospital admission in the city was nearly two times higher compared to the suburbs (Rydman et al. 1999). Similar results were found in 2003, where heat wave mortality was greater in

Table 3 Summary statistics of excess mortality rate and mean maximum temperature in heat waves, broken down by region and year

Year	Item	Urban	MinHang	BaoShan	PuDong	JiaDing	ChongMing	NanHui	JinShan	QingPu	SongJiang	FengXian
1998	Heat waves	3	2	2	1	1	1	2	1	2	1	2
	Longest duration	7/8–17/8	8/8–17/8	7/8–15/8	8/8–16/8	8/8–16/8	8/8–15/8	10/8–16/8	8/8–17/8	7/8–16/8	8/8–17/8	9/8–16/8
	Tmax(°C)	36.8	36.9	36.4	37	36.4	35.9	36.2	36.3	36.5	36.4	35.8
	Excess mortality rate (1/100,000)	27.30	18.20	18.99	15.82	13.08	9.21	12.81	8.01	12.51	18.15	7.00
1999	Heat waves	0	0	1	0	0	0	0	0	0	0	0
	Longest duration			9/9– 11/9								
	Tmax(°C)			35.3								
	Excess mortality rate (1/100,000)			0.40								
2000	Heat waves	2	2	1	2	1	0	0	1	1	1	0
	Longest duration	20/7–24/7	20/7–24/7	20/7–23/7	20/7–24/7	20/7–23/7			21/7–24/7	21/7–23/7	21/7–24/7	
	Tmax(°C)	36.1	35.3	36.8	35.7	36			35.4	35.9	35.8	
	Excess mortality rate (1/100,000)	−2.51	2.29	−0.25	0.91	0.41			0.94	1.09	0.20	
2001	Heat waves	2	3	1	2	3	0	0	1	2	1	0
	Longest duration	19/7–31/7	25/7–29/7	28/6–2/7	28/6–2/7	28/6–2/7			29/6–2/7	28/6–3/7	29/6–1/7	
	Tmax(°C)	36.5	35.7	36.1	36.1	36.2			36.1	36.4	36.1	
	Excess mortality rate (1/100,000)	0.93	−0.89	2.29	0.95	4.82			1.89	2.85	3.82	
2002	Heat waves	4	0	0	1	0	0	0	0	0	0	0
	Longest duration	22/8–26/8			14/7–16/7							
	Tmax(°C)	36.1			36.4							
	Excess mortality rate (1/100,000)	2.57			0.41							
2003	Heat waves	4	4	2	4	4	1	0	2	4	3	1
	Longest duration	19/7–6/8	28/7–3/8	21/7–29/7	19/7–25/7	19/7–4/8	25/7–29/7		28/7–30/7	28/7–3/8	28/7–4/8	27/8–30/8
	Tmax(°C)	36.6	36.1	36.9	36	36.3	35.7		36.2	36.6	36.2	35.9
	Excess mortality rate (1/100,000)	4.32	6.39	5.85	1.64	17.39	1.42		3.41	5.89	3.16	0.00
2004	Heat waves	2	2	3	3	3	2	0	0	2	2	1
	Longest duration	16/7–31/7	19/7–31/7	17/7–7/30	20/7–25/7	17/7–1/8	20/7–25/7			17/7–31/7	17/7–31/7	23/7–25/7
	Tmax(°C)	36.2	36	35.8	35.9	36.2	35.8			36	36.2	36.5
	Excess mortality rate (1/100,000)	3.33	5.60	−0.23	1.00	2.89	−0.57			0.22	1.56	−0.39

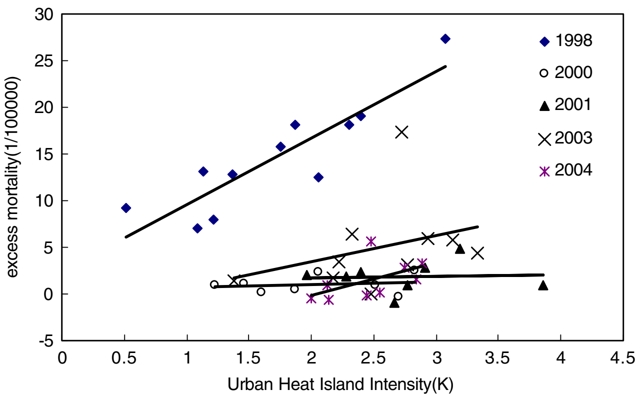


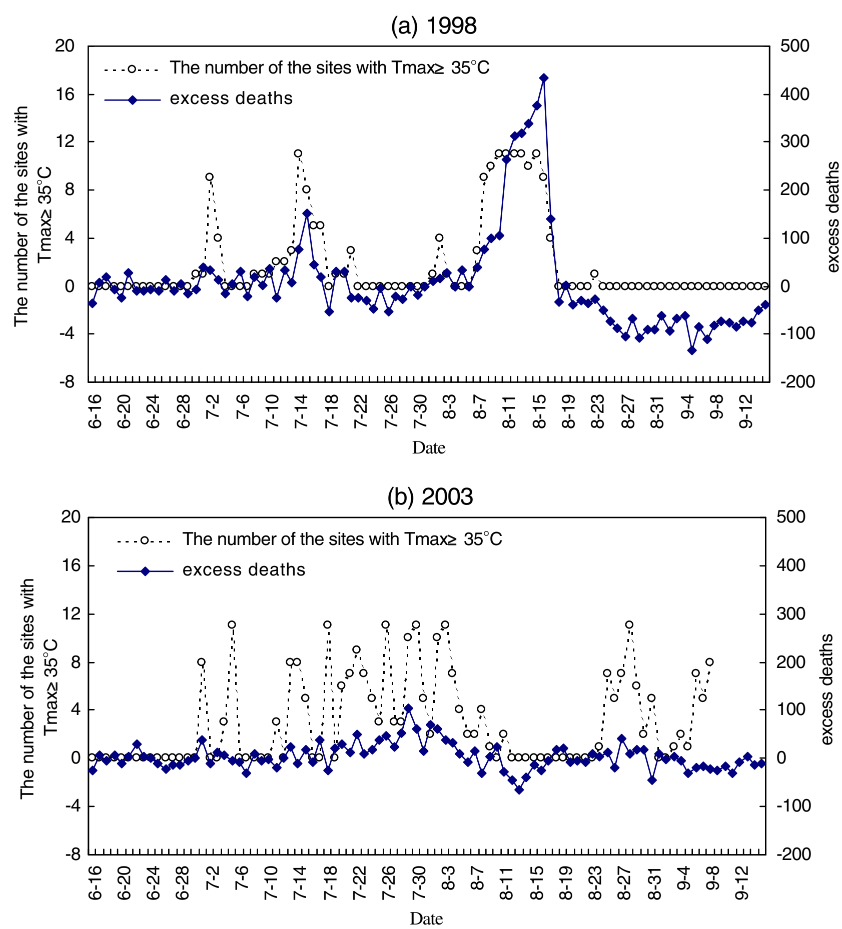
Fig. 6 The excess mortality rate and the heat island intensity for heat waves in Shanghai

urban regions compared to suburban areas in Switzerland (Grize et al. 2005).

Our previous investigation revealed that observed differences in heat-related mortality between two severe heat waves in 1998 and 2003 could be traced to the longevity of the heat; prolonged exposure to heat is more stressful to human health than isolated hot days (Tan et al. 2007). Here, we confirm that the UHI serves to enhance the prolonged exposure to heat in the city center, resulting in elevated levels of heat-related mortality in urban regions.

This study was subject to several limitations. First, many approaches such as absolute threshold temperature (Huynen et al. 2001), relative threshold temperature (Hajat et al. 2002), and synoptic climatological approaches (Sheridan 2002; Sheridan and Kalkstein 2004) can also be used to define heat waves. Although our definition is somewhat arbitrary, it was chosen to correspond with the Chinese Meteorological Administration's heat warnings, which are issued when maximum temperatures are forecast to exceed 35°C. Thus, Chinese residents are more familiar with the definition used here. Second, the effects of the UHI on heat-related mortality are multifaceted, and we did not examine data measuring air pollution, other meteorological factors such as cloud cover or humidity, or the potential impacts of socioeconomic status or other social variables. Therefore, no confounding effects were evaluated. Previous research indicates that human mortality is impacted by both ambient meteorological conditions and atmospheric pollutant levels. The stagnant atmospheric conditions common during heat waves can trap pollutants in urban areas, exacerbating the negative impacts of the heat wave

Fig. 7 The number of excess deaths versus the number of stations reporting hot days during the summers of 1998 (**a**) and 2003 (**b**)



(Anderson et al. 1996; Piver et al. 1999; Johnson et al. 2005). Air pollution such as ozone and PM10 compound the heat–mortality relationship, and previous research suggests that between 21 and 38% of the excess deaths observed during the summer 2003 European heat wave were attributable to these pollutants (Stedman 2004). However, it remains difficult to separate the impacts of heat and pollution on human health, and it is possible that some of the heightened urban mortality totals in this study were partially a result of elevated concentrations of airborne pollutants found in the city center.

Conclusion

There is no doubt that the urban heat island (UHI) has a profound impact on human health. The UHI serves to enhance the intensity of heat waves, which in turn adversely affects human health due to an increased exposure to extreme thermal conditions. As a result, heat-related mortality is found to be higher in the city center compared to suburban locales. This research provides evidence that Shanghai local officials should be cognizant of the increased thermal loads experienced in urban regions and take appropriate action to help reduce the impact of heat on the population.

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