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ORIGINAL ARTICLE

Heat wave impacts on mortality in Shanghai, 1998 and 2003

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Abstract A variety of research has linked extreme heat to heightened levels of daily mortality and, not surprisingly, heat waves both in 1998 and in 2003 all led to elevated mortality in Shanghai, China. While the heat waves in the two years were similar in meteorological character, elevated mortality was much more pronounced during the 1998 event, but it remains unclear why the human response was so varied. In order to explain the differences in human mortality between the two years' heat waves, and to better understand how heat impacts human health, we examine a wide range of meteorological, pollution, and social variables in Shanghai during the summers (15 June to 15 September) of 1998 and 2003. Thus, the goal of this study is to determine what was responsible for the varying human health response during the two heat events. A multivariate analysis is used to investigate the relationships between mortality and heat wave intensity, duration, and timing within the summer season, along with levels of air pollution. It was found that for heat waves in both summers, mortality was strongly associated with the duration of the heat wave. In addition, while slightly higher than average, the air pollution levels for the two heat waves were similar and cannot fully explain the observed differences in human mortality. Finally, since the meteorological conditions and pollution levels for the two heat waves were alike, we conclude that improvements in living conditions in Shanghai, such as increased use of air conditioning, larger living areas, and increased urban green space, along with higher levels of heat awareness and the implementation of a heat warning system, were responsible for the lower levels of human mortality in 2003 compared to 1998.

Keywords Heat wave · Heat-related mortality · Maximum temperature · Air pollution · Living conditions · Air conditioner · Shanghai

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Introduction

Previous research suggests that extreme heat waves are associated with heightened levels of human morbidity and mortality (Kunst et al. 1993; Hajat et al. 2002). Furthermore, there is mounting evidence that increasing levels of atmospheric carbon dioxide are at least partially responsible for an observed warming trend across the globe, particularly in the high latitudes (Karl and Trenberth 2003). Many scientists believe that a warmer climate will result in elevated summer temperatures and more frequent and intense heat waves (Gaffen and Ross 1998; Meehl and Tebaldi 2004). Thus, according to some predictions, heat-related mortality is expected to increase considerably as global temperatures continue to rise (Kalkstein 1993; Kalkstein and Greene 1997; McGeehin and Mirabelli 2001). To better gauge the future impacts of heat on human health, numerous studies have examined the relationships between heat waves and human mortality for cities around the world, including in the United States, Canada, The Netherlands, Italy, China, and others. Although the exact impacts of heat vary in different regions, most scientists agree that overall mortality rates rise during extreme heat waves (Giles and Balafoutis 1990; Semenza et al. 1996, 1999; Rooney et al. 1998; Nakai et al. 1999; Smoyer et al. 2000; Braga et al. 2001; Tan et al. 2004).

In July and August 2003, an extended heat wave resulted in above-average temperatures throughout Europe, Scandinavia, and western Russia, and monthly mean temperatures for this event exceeded the 90th percentile in each region. As a result of the extreme conditions, the 2003 heat wave in Europe resulted in a significant increase in human morbidity and mortality with estimates ranging from 22,000 to 50,000 excess deaths (Schär et al. 2004; WHO 2004; Brucker 2005).

The summer of 2003 was also unusually hot across much of Asia, and Shanghai recorded the hottest summer in over 50 years. Research has shown that Shanghai is particularly prone to extreme heat, and previous heat waves have coincided with elevated levels of human mortality. For example, an intense heat wave in 1998 resulted in numerous deaths; on several days, the daily number of deaths in the city was over three times the daily summer average (Tan et al. 2004). Surprisingly, despite its record-breaking temperatures, the 2003 heat wave in Shanghai resulted in far fewer deaths compared to the 1998 event. Several hypotheses have been presented to help explain the different human response to the two heat waves. For example, did Shanghai residents adjust after 1998, changing their awareness or behavior, and how many lives were saved as a result of the implementation of a heat warning system in 2002?

Scientists have also discovered that the impacts of heat waves on humans vary among different regions within a city. Mortality rates were found to be higher within the inner city region, possibly due to the urban heat island effect, elevated pollution levels, and the age distribution of the population (Buechley et al. 1972; Schuman 1972; Jones et al. 1982). Since heat waves have different impacts on various locations within a city, investigators have begun to look at factors that that might be responsible for these observed differences. First, it is well documented that urbanization alters the local climate, resulting in elevated temperatures (Oke 1973; Bohm 1998), particularly at night. Second, air pollution is also higher within urban areas, and extreme heat might enhance this effect since previous research suggests that elevated pollution levels often accompany heat waves (Piver et al. 1999). The elevated levels of pollution associated with heat waves can be particularly dangerous since heightened levels of ozone, fine particulates, and nitrogen dioxide have all been associated with increased daily mortality (Anderson et al. 1996). Finally, population differences within a city, such as age, income, and access to air conditioning, can also be important factors in assessing the effect of heat waves on daily mortality (Keatinge 2003). Thus, the goals of this investigation are to: (1) compare the weather conditions in Shanghai during the heat waves of 1998 and 2003 to see if differing meteorological variables such as maximum or heat wave duration might have resulted in the lower death toll in 2003; (2) determine if heightened levels of air pollution might have exacerbated the human-health impact of either of the heat waves; and (3) examine whether varying socio-economic factors within Shanghai such as access to air conditioning and living conditions can explain some of the differences in daily mortality for the heat waves of 1998 and 2003.

Materials and methods

Daily mortality data for Shanghai were obtained from the Shanghai Municipal Center for Disease Control and Prevention. These data consist of daily mortality totals for all causes of death and cover the summers (15 June to 15 September) of 1998 and 2003. The meteorological data consist of daily maximum and minimum temperatures and were provided by the Shanghai Meteorological Bureau. Similar to the mortality data, the daily temperatures were examined over the summers of 1998 and 2003.

Many methods exist for characterizing the definition of a heat wave (Kalkstein and Valimont 1986). Usually, cut-off points are used, above which human health is expected to deteriorate. For example, depending on the definition, a heat wave might begin if maximum temperatures reach 30°C for a given day, or if there are a specified number of hours or days above a specific temperature. Here, for the period 15 June–15 September for the 1998 and 2003 summers, a “heat day” is defined as a day with a daily maximum temperature exceeding 35°C. Days below this threshold were categorized as “non-heat days.” Using this criterion, a heat wave is defined as a period with at least three consecutive heat 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. To evaluate the excess human mortality within the two years, we found the average daily mortality in Shanghai on non-heat days and then compared mortality on heat days to this value. Finally, in addition to daily temperature, we examined the duration of the heat wave (the number of consecutive days with maximum temperature ≥35°C, Duration) and the timing within the summer season (Time). These data, along with the daily mortality totals, were then used in the analysis to investigate the association between mortality and the heat waves of 1998 and 2003. The daily number of deaths, daily maximum temperature, and heat wave duration are plotted for 15 May to 15 September, 1998 and 2003 (Figs. 1 and 2).

To estimate the impact of air pollution on mortality during the 1998 and 2003 heat waves, we obtained daily mean concentrations of the following air pollutants: fine particulates (PM_{10}, particulate matter with aerodynamic diameter ≤10 microns), SO_2, and NO_2. These data covered the same summer time span and were provided by the Shanghai Environmental Monitoring Center (SEMC).

Pearson’s correlation analyses were conducted between the daily number of deaths and some weather and air pollutant parameters over the study periods in 1998 and in 2003, with a lagged effect of 0–10 days. The daily number of deaths was correlated with the weather variables and air pollutant concentration on the same day, 1 day prior, 2 days prior, etc., until 10 days prior.

Two stepwise linear regression models were developed using maximum temperature, heat wave duration, time of season, and air pollution level. Furthermore, we obtained data on air conditioning use, living space, and the coverage rate of urban green areas from the Shanghai Municipality of Statistic Bureau to explain the impact of changing living condition on Shanghai residents’ vulnerably to heat waves.

Results

The summer of 2003 had slightly higher temperatures, more days with daily maximum temperatures exceeding 35°C, and longer-lasting heat waves compared to the summer of 1998. Some descriptive statistics for the two summers are illustrated in Table 1 and, clearly, while the meteorological conditions were somewhat similar, the human mortality response varied considerably between 1998 and 2003. In 1998, there were 27 heat days, 3 heat waves (30 June–3 July, 11–21 July, and 7–17 August), and the highest daily maximum temperature recorded reached to 39.4°C on 15 August. Throughout the summer of 1998, mortality peaked on 16 August, which coincided with the 10th day of the third heat wave of the summer (Fig. 1). This mortality maximum occurred during the longest heat wave of the summer. Similar to 1998, 2003 experienced 3 heat wave periods (12–14 July, 17 July–6 August, and 23 August–7 September), although 2003 contained 13 more heat days. In 2003, the largest increase in human mortality occurred on 30 July during the second heat wave of the summer, the season’s longest (Fig. 2). Surprisingly, the number of deaths did not increase as sharply during this prolonged July heat wave compared to the 1998 event. For

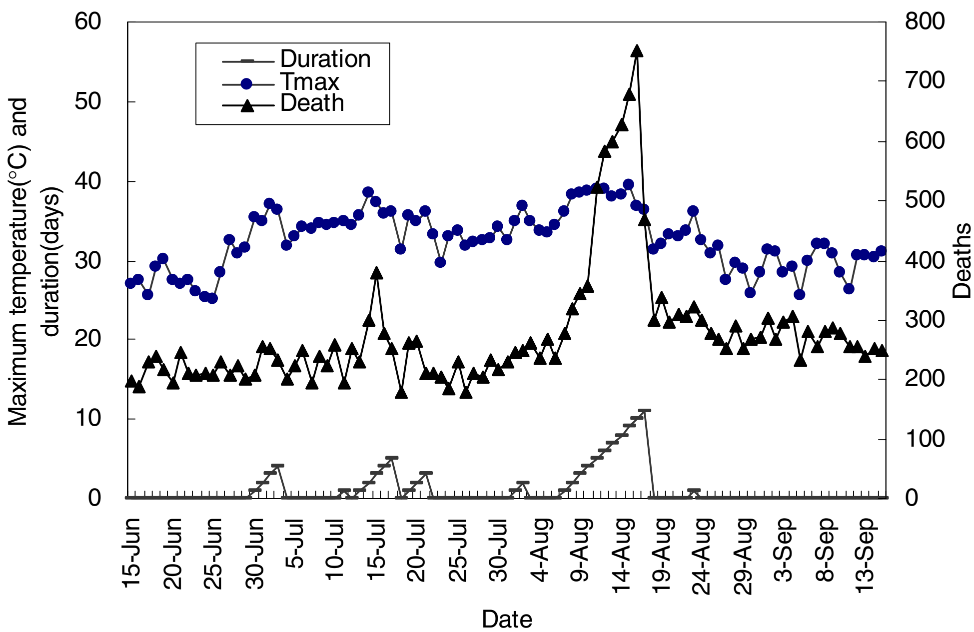

Fig. 1 Daily maximum temperature (Tmax), heat wave duration (Duration), and daily total number of deaths in 15 June–15 September 1998, Shanghai

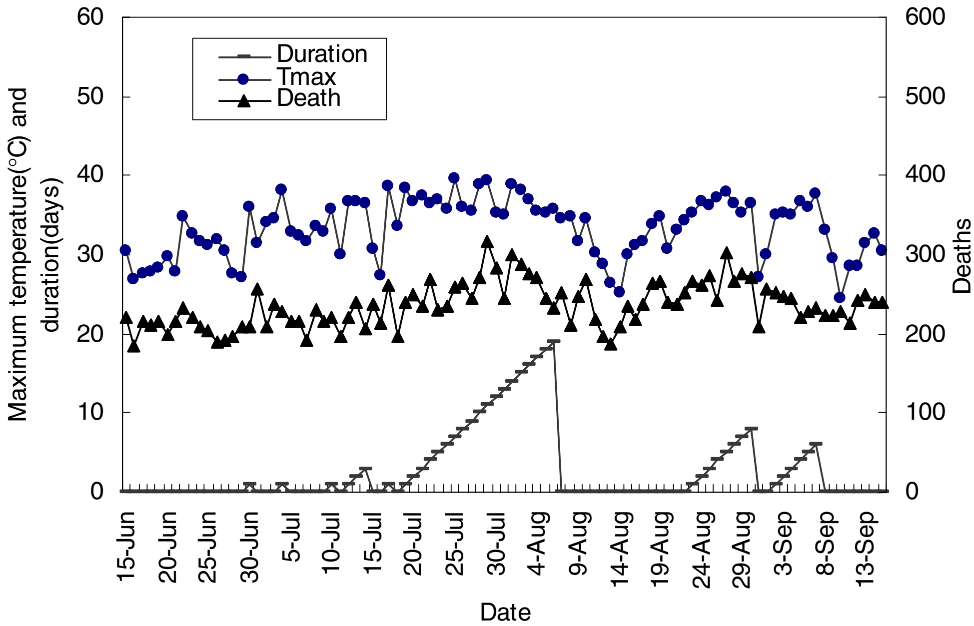

Fig. 2 Daily maximum temperature (Tmax), heat wave duration (Duration), and daily total number of deaths in 15 June–15 September 2003, Shanghai

Table 1 Descriptive statistics of weather, air pollution and some relation variables during summer in 1998 and 2003 in Shanghai

Item	1998	2003
Weather parameters		
Extreme maximum temperature and date	39.4°C on 15 August	39.6°C on 25 July
Number of heat days	27	40
Longest heat wave duration (days)	11	19
Average maximum temperature in 2nd half June	28.5°C	30.2°C
Average maximum temperature in July	34.2°C	35.1°C
Average maximum temperature in August	34.2°C	33.7°C
Average maximum temperature in 1st half September	29.8°C	32.3°C
Number in population (millions)		
Total	13.066	13.418
65~69 years	0.602	0.595
70~74 years	0.469	0.593
75~80 years	0.301	0.423
80+ years	0.247	0.374
Age-specific average number of deaths		
65~69 years	29 (9)	22 (5)
70~74 years	42 (16)	34 (6)
75~80 years	51 (21)	44 (9)
80+ years	93 (24)	93 (10)
Average number of deaths		
All days	277 (105)	236 (28)
In non-heat days	244 (37)	223 (21)
In heat days	358 (162)	253 (26)
Average air pollutant concentrations (mg/m^3) in summer		
SO_2	0.0386 (0.0146)	0.0377 (0.0113)
NO_2	0.0629 (0.0211)	0.0423 (0.0153)
PM_{10}	0.0992 (0.0285)	0.0852 (0.0362)
Socio-economic factors		
Number of air conditioners per 100 households	68.6	135.8
Living space per capita (m^2)	9.7	13.8

Standard deviation in parentheses.

example, during the 1998 heat wave, 752 deaths were reported on 16 August, nearly three times the non-heat day average. Conversely, the maximum number of daily deaths during the 2003 heat wave was 317 on 29 July, 42% above the non-heat day average. It is possible that 1998 reduced vulnerable population to the extent that it was smaller in 2003 and so not as large a pool at risk, but the comparison of numbers of elderly in the categories 65–69, 70–74, and 75+ years of age, and the age-specific mortality between the two periods show that it is not a cause (Table 1).

The average concentrations of three main air pollutants (PM_{10}, SO_2, NO_2) during heat days and non-heat days in 1998 and 2003 summer are listed in Table 2. Although the pollution levels slightly decreased in 2003 compared to 1998, it is above the WHO Air quality guidelines (WHO 2005). The concentrations of PM_{10} were elevated during heat days (p=0.0000) and there are no difference of SO_2 and NO_2 level between heat days and no-heat days in 1998, while in 2003, the levels of SO_2 were slightly elevated during heat days (p=0.0761) and there are no difference of NO_2 and PM_{10} level between heat days and non-heat days.

It is possible that both heat and heightened levels of air pollution played a role in the elevated daily mortality levels. In order to discern which parameters are most closely linked to daily mortality, Pearson's correlation and stepwise linear regression analysis were conducted. First, Pearson's correlation analyses were conducted between daily number of deaths and some weather and air pollutant parameters over the study periods in 1998 and 2003 (Table 3). Table 3 shows that there are positive correlations between the daily number of deaths and maximum temperature (Tmax), the number of consecutive heat days (Duration) and timing in the summer season (Time) in both years, and positive correlations with PM_{10} in 1998 and with SO_2 in 2003. Second, two stepwise linear regressions were run for 1998 and 2003 summers on the following variables: daily maximum temperature, mean temperature, and minimum temperature, for both the present and previous days, daily mean air pollution concentrations of PM_{10}, SO_2, and NO_2 for the present and previous days, timing in the summer season (Time), and the number of consecutive heat days (Duration). The time in the summer season and consecutive day variables were included since previous research has linked these two variables with elevated mortality during heat waves. The two algorithms for 1998 and 2003 are listed in Table 4 and clearly show that elevated mortality is not solely based upon the temperature itself. For example, the number of consecutive heat days is associated with elevated mortality, especially in 1998, supporting previous research that suggests extended heat waves are particularly detrimental to human health. Surprisingly, time of year is positively correlated with mortality, suggesting that the population is more prone to heat-related mortality in August than in July. This runs contrary to previous research and is likely caused by a sample size of only two years and the fact that the two most severe heat waves throughout the period of study occurred particularly late in the summer season. Finally, although air pollution levels were slightly higher during the heat waves, none of the pollutants was found to significantly affect mortality, and thus we conclude that the slight increase in pollution was not responsible for the heightened levels of mortality during the two summers.

In addition to temperature and pollution, we evaluated several socio-economic variables to help explain the differences in mortality between the 1998 and 2003 heat waves (Fig. 3). First, air conditioning use in Shanghai increased dramatically over the period of study. In 1998, there were 68.6 air conditioners reported per 100 households; this number jumped to 135.8 air conditioners per 100 households by 2003. Next, we examined average per capita living space

Table 3 Correlation coefficients of daily number of deaths and some weather and air pollutant parameters in 1998 and 2000. Numbers in parenthese were lagged days

Year	Time	Duration	Tmax	PM_{10}	SO_2	NO_2
1998	0.34	0.83	0.51	0.45 (5)		
2003	0.41	0.56	0.62		0.36 (8)	

*Significance was determined using α=0.05 level.

Table 2 Comparison the daily 24-h mean concentrations of air pollutant (mg/m^3) between heat days and non-heat days in 1998 and 2003

Year	Item	Heat day	Non-heat day	T-value	p-value
1998	n	27	66		
	SO_2	0.0393 (0.0066)	0.0384 (0.0169)	0.37	0.7128
	NO_2	0.0651 (0.0102)	0.0620 (0.0149)	1.15	0.2525
	PM_{10}	0.1150 (0.0169)	0.0927 (0.0298)	4.55	0.0000
2003	n	40	53		
	SO_2	0.0401 (0.0119)	0.0359 (0.0106)	1.79	0.0761
	NO_2	0.0407 (0.0162)	0.0435 (0.0146)	0.87	0.3847
	PM_{10}	0.0846 (0.0334)	0.0856 (0.0334)	0.14	0.8866

WHO Air quality guidelines (WHO 2005: SO_2:0.020 mg/m^3 (24-h mean); NO_2:0.200 mg/m^3 (1-h mean); PM_{10}:0.050 mg/m^3 (24-h mean)
Standard deviation in parentheses.

Table 4 Result of regression analysis between mortality and various dependent variables

Model	Variable	Parameter estimate	Standard error	T-value	Prob. >F[a]	Model prob. >F	R^{2b}
1998 model (*n*=93)	Intercept	182.99	10.87	16.83	0.0000		
	Time	1.15	0.20	5.79	0.0000		
	Duration	36.63	2.29	15.99	0.0000		
	Total model					0.0000	0.7696
2003 model (*n*=93)	Intercept	104.84	20.54	5.10	0.0000		
	Time	0.33	0.07	4.55	0.0000		
	Duration	1.62	0.49	3.32	0.0013		
	Tmax	3.33	0.63	5.27	0.0000		
	Total model					0.0000	0.5603

[a] Only variables in the model that are statistically significant at the 0.05 level are used.
[b] This value represents an adjusted R^2 ,which has been adjusted for degrees of freedom in the model.

within Shanghai, and this value also increased over time from 9.7 m^2 to 13.8 m^2 in 1998 and 2003, respectively. Finally, Shanghai Municipal Government had paid more attention to landscaping construction since 1994 and adopted a strategic decision, that is, taking landscaping construction as a prior consideration in construction of urban modernization, so that the coverage of urban green area increased in extent from 19.1% to 35.2% over the same time period. This improvement of the urban green area led to a decrease in the heat island effect in Shanghai (Ding et al. 2002; Zhou et al. 2002). It is likely that these improving conditions were at least partially responsible for the decline in heat-related mortality during the 2003 heat wave.

Discussion

We have examined the relationships between mortality, weather, and air pollution in Shanghai during the summers of 1998 and 2003. For both summers, daily mortality in Shanghai was highly correlated with the time of summer season and the duration of heat wave. We believe this study further supports research suggesting that the duration of a heat wave plays an important impact in human mortality. These findings indicate that prolonged exposure to heat is more stressful to human health than isolated hot days since there is a cumulative effect on the body's ability to regulate temperature, thus straining the thermoregulatory system (Semenza et al. 1996; Braga et al. 2001). However, despite its statistical significance in this study, we believe that our finding suggesting that late-season heat waves are more deadly is improbable. Coincidently, the most severe heat in both 1998 and 2003 occurred late in the season, and considering our sample size is of only two years, we feel this is what caused the time of season variable to be statistically significant (Kalkstein and Greene 1997; Smoyer et al. 2000; Braga et al. 2001; Tan et al. 2004).

Previous research indicates that human mortality throughout a heat wave can be affected by both meteorological conditions as well as atmospheric pollution levels. The stagnant atmospheric conditions common during heat waves can trap pollutants in urban areas, exacerbating the negative

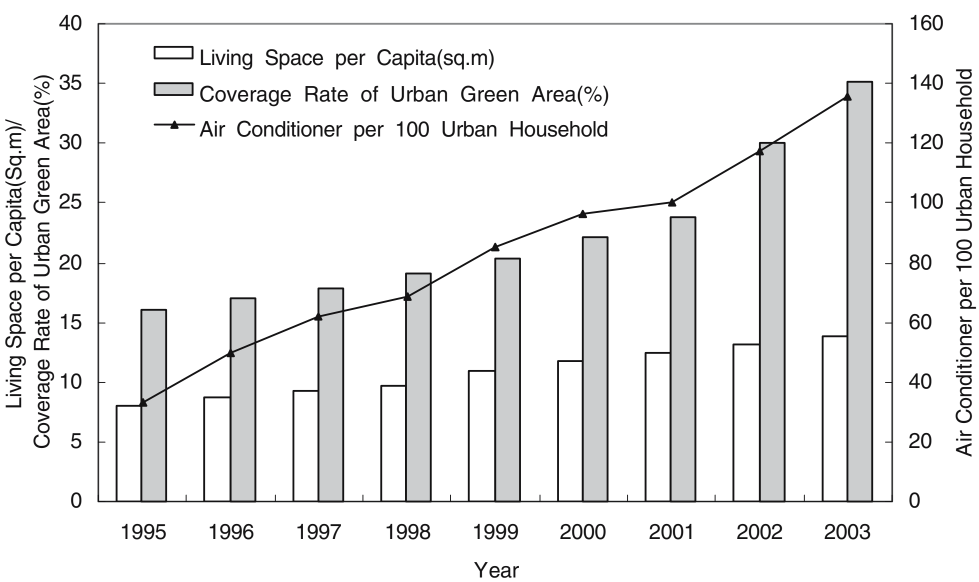

Fig. 3 The increase of living space, household air conditioners, and coverage of the urban green area in recent years in Shanghai

impacts of the heat wave. However, it remains unclear how the combination of pollution and excessive heat impacts human health (Anderson et al. 1996; Piver et al. 1999). Here, the relationships between temperature and mortality seem to be stronger than those between mortality and atmospheric pollution for both the 1998 and 2003 heat waves in Shanghai. Furthermore, although the 2003 heat wave was slightly warmer and more prolonged compared to 1998, there were no significant differences in air pollution levels between the two events. Thus, it is unlikely that air pollution was the primary cause of elevated mortality, especially in 1998. However, it remains difficult to segregate the specific impacts of both pollution and weather and to identify how both might work together to impact human health.

Since weather and pollution cannot fully explain the differences in mortality between the summers, perhaps changing population sensitivity is responsible. For example, to reduce the negative health impacts often associated with extreme heat, there are numerous mitigating actions that both individuals and the city can undertake, such as: use air conditioning, utilize shaded dwellings, develop light-colored building materials and road surfaces, and employ well-placed vegetated areas that provide ongoing and passive (i.e., not requiring immediate action from at-risk individuals during heat events) heat stress risk reduction. Between 1998 and 2003, there was an increase in air-conditioning use, larger living spaces, and a higher coverage of urban green space. These are all important changes in Shanghai, especially considering previous research has suggested that widespread use of air-conditioning reduces the effects of heat waves (Keatinge 2003). Air conditioning can allow people to continue to work effectively in hot weather and undoubtedly lessens heat stress, thus protecting susceptible portions of the population throughout a heat wave. Furthermore, larger living areas can result in better ventilation throughout a home, creating a more comfortable indoor environment. Finally, soil and grass have a lower heat conductivity and storage capacity compared to bricks and concrete surfaces and, thus, the increase in coverage of green areas across Shanghai could be another factor that might explain the differing human responses to the two heat waves.

Findings in the USA during the 1995 heat wave in Chicago identified several portions of the population that are particularly prone to heat-related mortality, including those who are bedridden or people who live in poorly ventilated or non-air conditioned homes (Semenza et al. 1996). Studies such as these, along with the high mortality rate during the 1998 heat wave in Shanghai, may be partially responsible for increasing the public awareness about the potential dangers of the heat. Thus, another possible explanation of the lower mortality levels in 2003 is that awareness and prevention efforts have both improved over the study period. In addition, with the help of the WMO and WHO, in 2002, a heat/health watch warning system was established in Shanghai, resulting in increased education to the public about the dangers that heat can pose to the population (Tan et al. 2004). The system is based on the identification of an "oppressive air mass", moist tropical plus (MT+), which historically has been associated with elevated mortality in Shanghai. In addition, an algorithm was developed, based on weather/mortality relationships during MT+ incursions, that estimates the number of heat-related deaths in the city. When an MT+ air mass is present, and deaths are forecast, the system issues a warning of various levels (based on the estimated number of deaths), and this information is transmitted by the press to the population and numerous stakeholders (Shanghai Municipal Center for Disease Control & Prevention, for example). The system was evaluated by the Shanghai Urban Environmental Meteorology Research Center, and was shown to be a good predictor of heat-related deaths in Shanghai. The validation strongly suggested that, "the system can be used to save lives and lessen the negative (health) impact of heat waves" (Tan et al. 2004). It is likely that the institution of the system was at least partially responsible for the lower mortality levels observed during the dangerous heat wave of 2003 in Shanghai.

Conclusion

This study confirms that increased levels of daily mortality are often associated with very hot weather in Shanghai, especially during the heat waves of 1998 and, to a lesser extent, 2003. While air pollution might account for some of the excess mortality, the relationship between temperature and mortality is stronger than that between atmospheric pollution and mortality. The improvement of living conditions within Shanghai, the wider availability of air-conditioning, and the adoption of a heat warning system have likely decreased the populations' vulnerability to extreme heat, and this could explain why the heat wave of 2003 resulted in fewer deaths than the 1998 event.

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