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ORIGINAL PAPER

Added effect of heat wave on mortality in Seoul, Korea

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Abstract A heat wave could increase mortality owing to high temperature. However, little is known about the added (duration) effect of heat wave from the prolonged period of high temperature on mortality and different effect sizes depending on the definition of heat waves and models. A distributed lag non-linear model with a quasi-Poisson distribution was used to evaluate the added effect of heat wave on mortality after adjusting for long-term and intra-seasonal trends and apparent temperature. We evaluated the cumulative relative risk of the added wave effect on mortality on lag days 0–30. The models were constructed using nine definitions of heat wave and two relationships (cubic spline and linear threshold model) between temperature and mortality to leave out the high temperature effect. Further, we performed sensitivity analysis to evaluate the changes in the effect of heat wave on mortality according to the different degrees of freedom for time trend and cubic spline of temperature. We found that heat wave had the added effect from the prolonged period of high temperature on mortality and it was considerable in the aspect of cumulative risk because of the lagged influence. When heat wave was defined with a threshold of 98th percentile temperature and ≥2, 3, and 4 consecutive days, mortality increased by 14.8 % (7.5–22.6, 95 % confidence interval (CI)), 18.1 % (10.8–26.0, 95 % CI), 18.1 % (10.7–25.9, 95 % CI), respectively, in cubic spline model. When it came to the definitions of 90th and 95th percentile, the risk increase in mortality declined to 3.7–5.8 % and 8.6–11.3 %, respectively. This effect was robust to the flexibility of the model for temperature and time trend, while the definitions of a heat wave were critical in estimating its relationship with mortality. This finding could help deepen our understanding and quantifying of the relationship between heat wave and mortality and select an appropriate definition of heat wave and temperature model in the future studies.

Keywords Heat wave · Mortality · Temperature · Weather

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Introduction

The impact of heat waves on health has been an issue because warming trends have accelerated in recent decades and heat extremes, as manifested by heat waves, have been increasing in intensity, duration, and frequency (Li et al. 2013; Meehl and Tebaldi 2004). Moreover, heat waves may also be responsible for high mortality rates in the future (Peng et al. 2011). In addition to a positive association between high temperature and mortality (Basu et al. 2008), a few studies have recently suggested that heat waves could have an added effect on mortality because of prolonged periods of high temperature (Anderson and Bell 2009; Hajat et al. 2006; Rocklov et al. 2012). In contrast, others suggested that the added effect was negligibly small and therefore did not substantially affect the mortality rate (Gasparrini and Armstrong 2011; Barnett et al. 2012). Therefore, existence and size of the added effect from the prolonged period of heat is still inconclusive and more researches are needed to understand the influence of heat wave on health.

There is no standard definition of a heat wave, and therefore, diverse metrics of temperature and duration are used to define heat waves. Some researchers suggest that the definition of a heat wave could affect its influence on mortality (Hajat et al. 2006; Kent et al. 2014; Tong et al. 2010). However, previous studies in Asia that used a relatively short study period with a few definitions of heat wave (Son et al. 2012; Chen et al. 2015) showed the risk that the influence of heat waves on mortality was limited to particular years with extreme episodes. Therefore, further research is needed to determine the effect of heat waves on mortality by using various definitions of heat wave and data for a long duration and to understand the influence of heat waves in order to choose a proper definition for its application in intervention strategy.

The aim of this study was to evaluate the added effect of heat waves on mortality and changes in its effect depending on the definitions of heat waves and models.

Materials and methods

Seoul is the largest metropolitan area in Korea and has a registered population of 10,195,318 as per the data of 2012. Seoul is located at 37° 34′ N and 126° 58′ E and has a temperate climate with four distinct seasons. The daily mean temperature of Seoul ranges from −15.7 to 33.0 °C during 1992–2012.

Data

Mortality and meteorological data were collected from January 1992 to December 2012 for this study. Meteorological data were provided by the weather database of the Korea Meteorological Administration. Hourly atmospheric temperatures and dew point temperature values were collected every 3 h in Jongno-Gu, which is located in the middle of the city, and were summarized as daily mean value (Korea Meteorological Administration). Apparent temperatures (AT, °C) were calculated by the formula (O'Neill et al. 2003): Apparent temperature $= -2.653 + 0.994$ (atmospheric temperature) $+ 0.0153$(dew point temperature) ^{2}.

Daily death counts were obtained from the mortality records of the Korea National Statistical Office (Korea National Statistical Office). Total (non-accidental) deaths are defined as A00-R99 in the International Classification of Diseases revision 10 (ICD-10) excluding external causes and suicides; cardiovascular diseases, as I00-I99; and respiratory diseases, as J30-J98 (World Health Organization). We restricted the study period to the warm season (from May to September), which included the known durations for heat waves and excluded the influence of cold temperature.

Heat wave definitions

Previous studies have suggested various definitions for heat waves by using different thresholds and durations. In this study, we defined a heat wave on the basis of city-specific threshold values of daily apparent temperature. Nine definitions were used in the metric system consisting of three temperature thresholds (90th, 95th, and 98th percentiles) and three cutoff of minimum duration days (2, 3, and 4 days): (1) temperature ≥90th percentile and prolonged for ≥2 consecutive days, (2) ≥90th percentile and ≥3 consecutive days, (3) ≥90th percentile and ≥4 consecutive days, (4) ≥95th percentile and ≥2 consecutive days, (5) ≥95th percentile and ≥3 consecutive days, (6) ≥95th percentile and ≥4 consecutive days,(7) ≥98th percentile and ≥2 consecutive days, (8) ≥98th percentile and ≥3 consecutive days, and (9) ≥98th percentile and ≥4 consecutive days (Anderson and Bell 2011; Son et al. 2012; Tian et al. 2013). The days during study period was categorized into heat wave or non-heat wave days according to the definitions of heat wave. The higher thresholds of 99th percentiles were excluded in this study because only a small number of heat waves were observed during particular years. For instance, heat waves with thresholds above the 99th percentile of mean temperature and duration ≥2 days occurred in only 2 years—1994 and 2012—in the study period (1992–2012).

Two approach to the temperature effect on mortality

It is needed to leave out the influence of high temperature on mortality when evaluating the additional heat wave effect. We had two approaches to the relationship between apparent temperature and non-accidental mortality. The first approach is using stepwise linear regression model. We visualized the relationship between mean apparent temperature and mortality with a generalized additive model (GAM) (Supplementary Material, Fig. S1). After visualization of non-linear relationship, piecewise linear regression model was used to estimate the threshold where the effect of apparent temperature would change abruptly. It was obtained from the following piecewise linear regression formula (Lim et al. 2014):

$$\begin{aligned}\mathrm{Ln}[\mathrm{E(Y)}] = {} & \beta_0 + \beta_1(\text{apparent temperature}) \\ & + \beta_2(\text{apparent temperature}-\xi)_+ + \beta_3\mathrm{DOW} \\ & + ns(\text{time})\end{aligned}$$

Where threshold (ξ) is a threshold point for apparent temperature and $(\text{apparent temperature}-\xi, 0)_+$ refers to the maximal value of {apparent temperature$-\xi$,0} This model was fitted as the best when it was with the threshold of 32.6 °C.

The second is to construct a natural cubic spline model for the relationship between temperature and mortality with the two equally spaced knots in log scale and 3 degrees of freedom (df), which was frequently adopted in the previous studies (Petkova et al. 2014; Chen et al. 2015). Temperature has the lagged effect on mortality and therefore, its change depending on time ought to be considered. The delayed effect of temperature was estimated by natural cubic spline of maximum lag day up to 30 days with the two equally spaced knots and 4 df (Petkova et al. 2014; Chen et al. 2015). We supposed that both of the models (piecewise linear regression model, natural cubic spline model) had the same lag structure, and then compared the effect sizes of heat wave between the cubic spline and the piecewise linear model for the relationship between apparent temperature and mortality. The fitting of the model was determined by the Quasi-Poisson Akaike's Information Criterion (Q-AIC).

Model structure for the estimation of the added heat wave effect on mortality

We used a distributed lag non-linear model (DLNM) with a quasi-Poisson distribution to evaluate the main (temperature) and the added effect of heat waves on mortality (Gasparrini and Armstrong 2011). The covariates including long-term and intra-seasonal trends, day of week (DOW), and daily mean apparent temperature were controlled for in the model. The model structure is as follows:

$$\mathrm{Ln}[\mathrm{E}(\mathrm{Y_t})] = a + \beta \mathrm{Cb.HW}_{t,l} + \gamma \mathrm{Cb.temp}_l + \delta \mathrm{DOW}_t + \mathrm{ns(time)}$$

Where $E(Y_t)$ is the expected number of deaths on day t with over-dispersed Poisson distribution; α is the model intercept; HW_t has binary values, which is 1 for heat wave day and 0 for non-heat wave day; temp_t stands for apparent temperature on day t; $\mathrm{Cb.HW}_{t,l}$ and$\mathrm{Cb.temp}_l$ is a matrix of relationship and lag for heat wave day and apparent temperature, which has a maximum lag day of l; DOW represents the categorical variables for the day of the week; ns represents a non-linear relationship between the covariate and dependent variable using the natural spline; ns(time) is for the adjustment of long-term and intra-seasonal trend with 3 degrees of freedom (df) per warm season; and β, γ, and δ are the coefficients for HW, apparent temperature, and DOW. Population size for each year was additionally adjusted for as an option of offset term in the log form.

Similar to the main (temperature) effect, the added effect of heat wave on mortality could be prolonged. Therefore, the delayed response to the added effect of heat wave on mortality was also evaluated by the above-mentioned way of the lag structure. The additional effect of heat wave, which came from the consecutive days of high temperature, were tested using lag structure up to 30 lag days of cubic spline with the two equally spaced knots and 4 df. Additionally, the risk increases in mortality from the added wave effect were calculated on lag day 0 for the comparison with the previous research. All statistical analysis was performed using SAS version 9.3 (SAS Inc., Cary, NC, USA) and R 3.1.2 (R Foundation for Statistical Computing, Vienna, Austria) with the *mgcv* and *dlnm* packages.

Results

Table 1 shows the definitions of heat wave used in this study and the occurrence of heat waves from 1992 to 2012 as per the definitions. For the threshold value of the 90th percentile of mean temperature, the average number of heat wave days ranged from 10.0 to 13.6 per year, depending on the duration. This value reduced to 2.2 when we defined heat wave with a threshold value of 98th percentile and duration of four consecutive days. The maximum number of heat wave days was up to 43 per year, while there were no heat waves in certain years (1993 and 1998) when the threshold temperature for heat wave was set as the 90th percentile and ≥2 consecutive days. Furthermore, heat waves started as early as July 3 and as late as August 30 during the warm season.

Summary statistics of mortality and meteorological data are shown in Table 2. The daily average temperature was 22.6 °C (range, 10.8 to 33.0 °C) during the warm season in 1992–2012. The mean dew point and apparent temperature was 16.1 °C (min., −3.9 °C; max., 26.9 °C) and 24.2 °C (min., 9.0 °C; max., 39.6 °C), respectively. The influence of temperature on mortality according to lag days was shown in the supplementary material (Supplementary Material, Fig. S2). Daily average counts of all-cause and total (non-accidental) death were 101.3 and 88.2 in Seoul, respectively, of which average of 23.3 and 3.5 people died daily from cardiovascular and respiratory disease during the warm season in 1992–2012, respectively.

The added effects of heat wave on mortality by various lag days and definitions of heat waves were plotted in Fig. 1. We observed positive effect size of heat wave from lag 0 to around 10 days when we defined heat wave using the cutoff of 95th and 98th percentile temperature. However, the added effect defined with 90th percentile of threshold was relatively small but similar patterns of delayed effects compared to 95th and 98th percentiles.

Table 3 shows the added effect of heat waves on total mortality depending on different definitions and models. The effect was estimated as the cumulative relative risk from lag

Table 1 Definition of heat waves and heat wave days in Seoul, 1992–2012

Heat wave	Definitions			Heat wave day per year		
	Temperature	Duration	*N*	Mean	Range	Start date (earliest, latest)
HW1	≥90th percentile	≥2 consecutive days	286	13.6	0.0–43.0	July 3, Aug 30
HW2	≥90th percentile	≥3 consecutive days	256	12.2	0.0–41.0	July 3, Aug 30
HW3	≥90th percentile	≥4 consecutive days	211	10.0	0.0–41.0	July 3, Aug 19
HW4	≥95th percentile	≥2 consecutive days	132	6.3	0.0–35.0	July 12, Aug 17
HW5	≥95th percentile	≥3 consecutive days	104	5.0	0.0–35.0	July 12, Aug 13
HW6	≥95th percentile	≥4 consecutive days	92	4.4	0.0–35.0	July 12, Aug 13
HW7	≥98th percentile	≥2 consecutive days	55	2.6	0.0–33.0	July 12, Aug 13
HW8	≥98th percentile	≥3 consecutive days	49	2.3	0.0–33.0	July 12, Aug 13
HW9	≥98th percentile	≥4 consecutive days	26	2.2	0.0–33.0	July 12, Aug 12

days 0–30. We observed that heat waves added the additional impact to the effect of high temperature and caused higher mortality rate as the temperature threshold of its definitions became stricter. For example, when heat wave was defined with a threshold value of the 90th percentile, the influence of heat wave on the mortality was minimal and negligible (3.7–5.8 %). However, with a definition with a threshold value of the 95th percentile, heat wave was associated with increasing mortality by 8.6–11.3 %. Furthermore, with a definition with 98th percentile, the increase in mortality reached up to 14.8–18.1 %. When we applied piecewise linear regression for temperature in the model (model 2 in Table 3), the effect sizes of heat wave were smaller than those in the model with cubic spline for temperature except a model with definition with 98th percentile and longer than three consecutive days. Regardless of models for temperature, heat wave had the greatest impact on mortality when it was defined as ≥98th percentile and ≥3 consecutive days.

The estimated risk increases in mortality on lag day 0 were 1.95 % [0.94–2.97, 95 % confidence interval (CI)], 1.95 % (0.96–2.95, 95 % CI), and 2.43 % (1.41–3.47, 95 % CI), respectively, when heat waves were defined as ≥95th percentile combined with three cutoff of duration (≥2, ≥3, ≥4 consecutive days). When it came to 98th percentile, they were 3.49 % (2.04–4.96, 95 % CI), 3.74 % (2.26–5.23, 95 % CI), and 4.03 % (2.51–5.57, 95 % CI) on lag day 0 (data not shown).

Although magnitude of heat wave effect on cardiovascular and respiratory mortalities were greater than total mortality, the greatest effect was similarly observed when we define heat wave days as ≥98th percentile and ≥3 consecutive days. For instance, cardiovascular and respiratory mortalities increased

Table 2 Summaries of the mortalities and meteorological data during warm seasons in Seoul, 1992–2012

	Mean	SD	Range
Population	10,345,767	236,178	10,173,162–10,935,230
Mortality (count)[a]			
All-cause	101.3	12.2	64.0–270.0
Accidental	13.1	5.5	2.0–193.0
Non-accidental	88.2	11.0	55.0–168.0
Cardiovascular	23.3	5.8	8.0–60.0
Respiratory	3.5	1.9	0.0–13.0
Temperature (°C)			
Mean	22.6	3.7	10.8–33.0
Min.	19.0	4.1	6.0–28.9
Max.	26.6	3.9	12.0–38.3
Dew point temperature (°C)	16.1	5.3	-3.9–26.9
Apparent temperature (°C)	24.2	5.8	9.0–39.6
Relative humidity (%)	69.1	13.2	21.1–97.4

[a] Daily mean frequency of mortality from 1992 to 2012

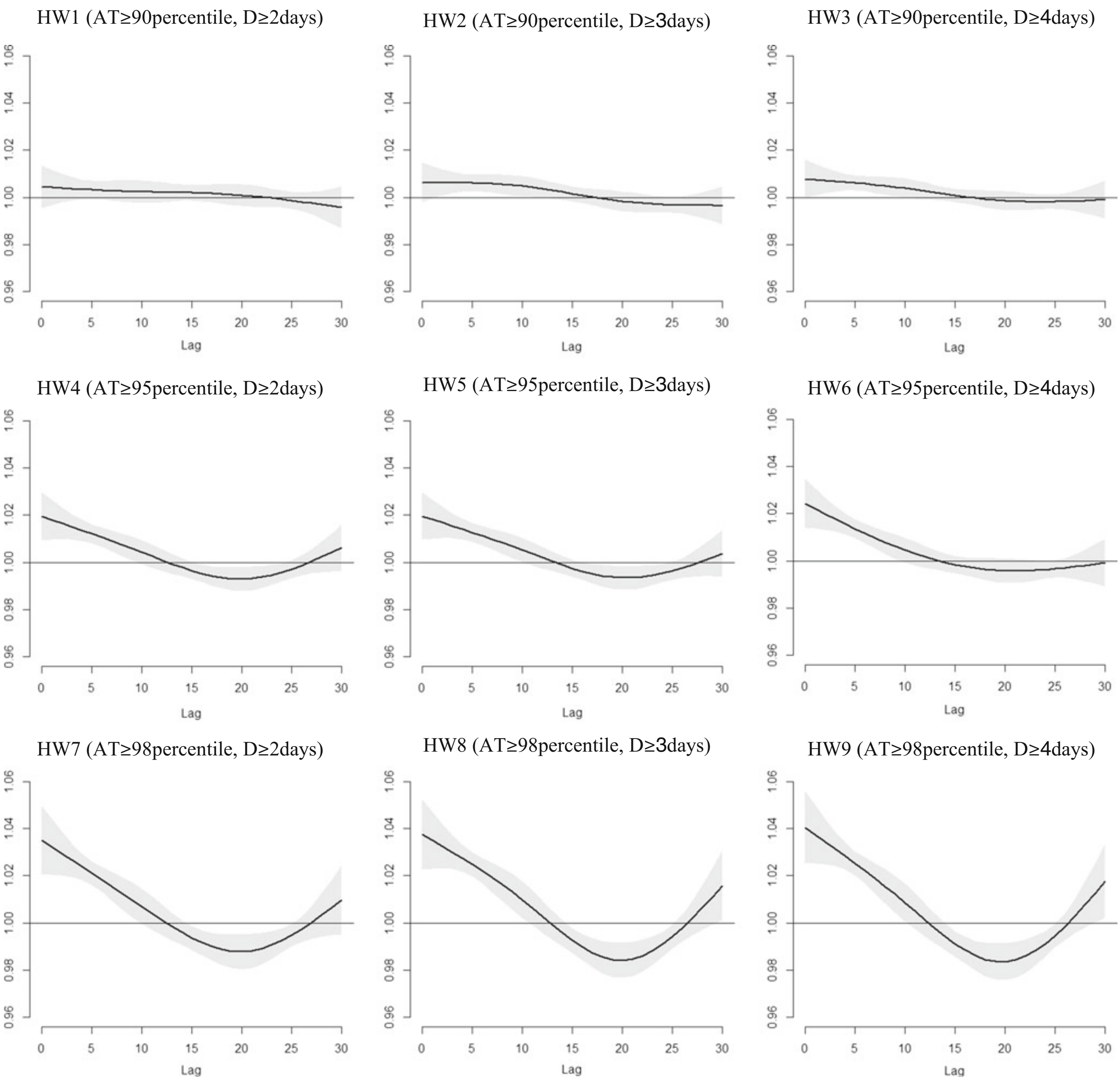

Fig. 1 Plot for changes in relative risk of the added wave effect on daily mortality depending on the lag days and the various definitions for heat wave. Heat wave (HW) 1–9 was defined by the threshold of apparent temperature (AT) and duration (D). HW 1, 2, and 3 were defined as more than 2, 3, and 4 consecutive days, respectively, of daily apparent temperatures above the 90th percentile. HW 4, 5, and 6 were defined as more than 2, 3, and 4 consecutive days, respectively, of daily apparent temperature above the 95th percentile. HW 7–9 corresponded with the 98th percentile of apparent temperature

by 31.2 and 19.6 % on heat wave day, respectively, compared to on non-heat wave day. These figures were higher than 18.1 % increase in total mortality on heat wave day of the same definition and also higher than any other risk increases in cardiovascular and respiratory mortality from other heat wave definitions.

Sensitivity analysis showed that the influences of heat wave were robust to changes of the degrees of freedom for time trend during warm season (Supplementary Material, Fig. S3) as well as df for the cubic spline of apparent temperature (Supplementary Material, Fig. S4).

Discussion

This study displayed cumulative added heat wave effect on mortality independently from high temperature effects in Seoul, Korea. Moreover, the added effect lasted around

Table 3 Cumulative relative risk of the mortality due to the added wave effect in Seoul compared with non-heat wave days, 1992–2012

	Heat wave			Model 1 (cubic spline)			Model 2 (piecewise linear)		
	Temperature	Duration	*N*	RR	LCI	UCI	RR	LCI	UCI
Total	≥90th	≥2	286	1.037	0.972	1.106	0.973	0.935	1.012
	≥90th	≥3	256	1.047	0.985	1.114	0.978	0.937	1.021
	≥90th	≥4	211	1.058	1.002	1.118	0.970	0.924	1.019
	≥95th	≥2	132	1.086	1.016	1.162	0.929	0.842	1.025
	≥95th	≥3	104	1.092	1.026	1.162	0.935	0.829	1.055
	≥95th	≥4	92	1.113	1.048	1.183	1.028	0.903	1.170
	≥98th	≥2	55	1.148	1.075	1.226	1.093	0.881	1.355
	≥98th	≥3	49	1.181	1.108	1.260	1.289	1.071	1.552
	≥98th	≥4	26	1.181	1.107	1.259	1.246	1.059	1.467
Cardiovascular	≥90th	≥2	286	1.069	0.945	1.209	0.869	0.806	0.937
	≥90th	≥3	256	1.125	1.003	1.263	0.888	0.819	0.963
	≥90th	≥4	211	1.147	1.035	1.270	0.891	0.812	0.978
	≥95th	≥2	132	1.231	1.087	1.395	0.841	0.701	1.009
	≥95th	≥3	104	1.215	1.082	1.364	0.858	0.683	1.076
	≥95th	≥4	92	1.229	1.099	1.374	0.993	0.778	1.267
	≥98th	≥2	55	1.281	1.138	1.443	1.491	1.002	2.220
	≥98th	≥3	49	1.312	1.166	1.475	1.741	1.235	2.456
	≥98th	≥4	26	1.306	1.164	1.466	1.592	1.179	2.150
Respiratory	≥90th	≥2	286	1.057	0.778	1.436	0.874	0.723	1.057
	≥90th	≥3	256	1.080	0.806	1.448	0.896	0.731	1.099
	≥90th	≥4	211	1.129	0.871	1.464	0.953	0.754	1.203
	≥95th	≥2	132	1.078	0.781	1.487	0.787	0.490	1.263
	≥95th	≥3	104	1.137	0.842	1.534	1.018	0.574	1.805
	≥95th	≥4	92	1.192	0.892	1.592	1.375	0.748	2.530
	≥98th	≥2	55	1.170	0.851	1.610	2.386	0.851	6.688
	≥98th	≥3	49	1.196	0.872	1.642	2.602	1.071	6.319
	≥98th	≥4	26	1.182	0.865	1.614	2.215	1.013	4.841

RR relative risk, *LCI* 95 % lower confidence interval, *UCI* 95 % upper confidence interval

10 days and tended to increase as the threshold of temperature or duration for the heat wave became stricter. We also observed a variation in the effect size depending on the model for the temperature effect; however, the effect sizes were robust to degrees of freedom for time trend.

We found that there was a significant added effect of heat wave to high temperature, and it became greater as the threshold or duration increased. Several previous studies also showed similar patterns (Anderson and Bell 2009, 2011; Gasparrini and Armstrong 2011; Hajat et al. 2006; Tian et al. 2013). In previous studies, the effect of heat wave effect on mortality tended to increase as the definition of heat wave became stricter. Recently, another research evaluated the consistent outcomes changed significantly with a change in the definitions of heat wave (Chen et al. 2015). We also found similar influence of various thresholds for the definition on the added wave effect.

Although effect of heat wave on mortality using various definitions showed similar patterns with previous studies, effect size of heat wave was different depending on studies. Two previous studies showed a much smaller effect of heat waves (Gasparrini and Armstrong 2011; Barnett et al. 2012) as compared to that in our study. Barnett et al. (2012) showed that excess risk mortality were 0.0 % (−0.2 to 0.2 %) and 0.5 % (0.2 to 0.8 %) due to the heat wave, when it was defined as ≥95 and >98th percentile of temperature on more than two consecutive days. Other researchers also showed a smaller and insignificant effect of heat wave as 0.4 % (−0.5 to 1.4 %, 95 % CI) and 1.3 % (−0.3 to 2.9 %, 95 % CI), respectively, when it was defined as ≥2 and ≥4 days and ≥98th percentile of temperature (Gasparrini and Armstrong 2011). Both of the above-mentioned studies showed a smaller increase in the mortality than our study, compared to the effect sizes from the same threshold for the definitions of heat wave. In contrast, other researchers showed a larger effect of heat wave on mortality (Huang et al. 2010; Tian et al. 2013; Tong et al. 2010) than our study. Of these studies, one study conducted in Beijing showed that heat waves, defined as the threshold temperature of the 95th percentile and ≥2 consecutive days, caused a 20.7 % (9.5 %–32.0 %) increase in cardiovascular mortality (Tian et al. 2013). Moreover, Tong et al. (2010) reported that the mortality increased by 11 % (4.0–19 %) and 15 % (6.0–25 %) due to the heat wave with thresholds ≥95th percentile for temperature and ≥3 and ≥4 continuous days (Tong et al. 2010).

Different modeling for the exclusion of high temperature effect was one of the reasons why there was heterogeneity in the added effect of heat waves on mortality in terms of effect size. It has been reported that the effect of heat waves increased substantially when the linearity between temperature and mortality was assumed (Hajat et al. 2006). Thus, the added effect could be inflated because a simple model cannot reflect the effect of extreme temperature or delayed effect of high temperature. This is in line with the finding that the added effect of heat waves decreased substantially when either flexible splines for temperature or flexible lag structure was assumed in the model (Gasparrini and Armstrong 2011). However, the added heat wave effect was not solely explained by the incomplete exclusion of high temperature effect from heat wave. Some research showed that there was still a significant added heat wave effect on mortality in the model of flexible spline and lag structures (Anderson and Bell 2011; Tian et al. 2013; Rocklov et al. 2012). We also found that substantial risk increase in mortality from the consecutive days of high temperature in both of the cubic spline model and the linear threshold model. Furthermore, the added effect became considerable in the aspect of cumulative risk increase because it also had the lagged influence. The added heat wave effect from consecutive days of high temperature could be responsible for a high mortality rate owing to the accumulated stress because of no cooling down period (Hajat et al. 2006).

The added heat wave effect varied depending on the region. Of the aforementioned studies, two studies conducted in the USA showed a smaller effect of heat wave on mortality (Anderson and Bell 2009, 2011; Gasparrini and Armstrong 2011) than that reported in the current study. On the other hand, studies from Australia and China reported a larger influence of heat wave on mortality (Tong et al. 2010; Tian et al. 2013) as compared to our study. Furthermore, there was considerable difference in the effect of heat wave on mortality in three European cities (London, Budapest, and Milan) and between northeast, midwest, and south cities in the USA (Hajat et al. 2006; Anderson and Bell 2011). Thus, the relationship between heat wave and mortality could vary owing to the housing environment, urbanization, public transportation, and acclimatization (Anderson and Bell 2009). Especially, some researchers suggested that air conditioning and heat island effect could contribute to different response of mortality to heat (Petkova et al. 2014; Ostro et al. 2010). Heat-related mortality has decreased in New York as air conditioning ownership had increased in the twentieth century (Petkova et al. 2014). Moreover, ownership and use of air conditioners was suggested to reduce hospitalization for cardiovascular disease, stroke, respiratory disease, and heat stroke in California (Ostro et al. 2010). Therefore, different usage of air conditioners could be an important factor to explain the regional variation in high temperature effect on mortality. Additionally, a few evidences have been suggested that heat island effects can modify the effect of temperature on mortality (Gabriel and Endlicher 2011; Vandentorren et al. 2006). Low wind speed and high surface temperature, which was the characteristics of heat island, came from the thermal capacity of urban environment covered by building and roadways and it could make a metropolitan area susceptible to heat stress. For example, a 1 °C increase in Hong Kong increased the risks of mortality in areas with high or low urban heat island indices by 4.1 and 0.7 %, respectively (Goggins et al. 2012). Another study performed in Montreal reported that mortality on summer days is higher in areas with high surface temperatures (Smargiassi et al. 2009). Therefore, external environment including air conditioning and heat island could affect the relationship between high temperature and mortality. However, we can only allude to the possibility of effect modification in terms of the additional wave effect because the above-mentioned literatures focused on the temperature effect.

Moreover, individual factors including gender, age, and socioeconomic position could be modifiers of the effect (Son et al. 2012). The susceptible group for heat wave was known to be the elderly, the deprived, and females (Anderson and Bell 2009; Goggins et al. 2012; Son et al. 2012). Therefore, evaluation of their relationship between heat waves and mortality in the regions is necessary to select a proper definition in order to set up regional heat wave warning systems considering the population and environment.

Despite our important findings, our study had a few limitations that need to be addressed. First, the study location was limited to a single city, thereby limiting the generalizability of our findings. Second, air pollutants, which could be modifiers, were not considered in our analysis. However, since air pollutants are known to cause very little change in the effect of heat wave on mortality (Tian et al. 2013), it is likely that they had very little effect on our findings. Third, direct measurements of indoor temperatures and exposure times to outdoor temperatures were not available from the data source.

In summary, we evaluated the relationship between the added effect of heat wave and mortality using a long period of study and lag structure. We found that heat wave had the additional wave effect from the prolonged period on mortality and it was considerable in the aspect of cumulative risk increase because of the lagged influence. This effect was robust to the flexibility of the model for temperature and time trend, while the definitions of a heat wave were critical in estimating its relationship with mortality. This finding could help deepen our understanding and quantifying of the relationship between heat wave and mortality and suggest the need to select an appropriate definition.

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References

Anderson BG, Bell ML (2009) Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiology 20(2):205–213. doi:10.1097/EDE.0b013e318190ee08

Anderson BG, Bell ML (2011) Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. Environ Health Perspect 119(2): 210–218. doi:10.1289/ehp.1002313

Barnett AG, Hajat S, Gasparrini A, Rocklov J (2012) Cold and heat waves in the United States. Environ Res 112:218–224. doi:10.1016/j.envres.2011.12.010

Basu R, Feng WY, Ostro BD (2008) Characterizing temperature and mortality in nine California counties. Epidemiology 19(1):138–145. doi:10.1097/EDE.0b013e31815c1da7

Chen K, Bi J, Chen J, Chen X, Huang L, Zhou L (2015) Influence of heat wave definitions to the added effect of heat waves on daily mortality in Nanjing, China. Sci Total Environ 506–507:18–25. doi:10.1016/j.scitotenv.2014.10.092

Gabriel K, Endlicher W (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ Pollut 159:2044–2050

Gasparrini A, Armstrong B (2011) The impact of heat waves on mortality. Epidemiology 22(1):68–73. doi:10.1097/EDE.0b013e3181fdcd99

Goggins WB, Chan EY, Ng E, Ren C, Chen L (2012) Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong. PLoS One 7:e38551

Hajat S, Armstrong B, Baccini M, Biggeri A, Bisanti L, Russo A, Paldy A, Menne B, Kosatsky T (2006) Impact of high temperatures on mortality: is there an added heat wave effect? Epidemiology 17(6): 632–638. doi:10.1097/01.ede.0000239688.70829.63

Huang W, Kan H, Kovats S (2010) The impact of the 2003 heat wave on mortality in Shanghai, China. Sci Total Environ 408(11):2418–2420. doi:10.1016/j.scitotenv.2010.02.009

Kent ST, McClure LA, Zaitchik BF, Smith TT, Gohlke JM (2014) Heat waves and health outcomes in Alabama (USA): the importance of heat wave definition. Environ Health Perspect 122(2):151–158. doi:10.1289/ehp.1307262

Li T, Horton RM, Kinney P (2013) Future projections of seasonal patterns in temperature-related deaths for Manhattan. Nat Clim Chang 3: 717–721. doi:10.1038/nclimate1902

Lim YH, Park Y, Kim H, Hong YC (2014) Effects of cold and hot temperature on dehydration: a mechanism of cardiovascular burden

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305(5686):994–997

O'Neill MS, Zanobetti A, Schwartz J (2003) Modifiers of the temperature and mortality association in seven US cities. Am J Epidemiol 157(12):1074–1085

Ostro B, Rauch S, Green R, Malig B, Basu R (2010) The effects of temperature and use of air conditioning on hospitalizations. Am J Epidemiol 172(9):1053–1061. doi:10.1093/aje/kwq231

Peng RD, Bobb JF, Tebaldi C, McDaniel L, Bell ML, Dominici F (2011) Toward a quantitative estimate of future heat wave mortality under global climate change. Environ Health Perspect 119(5):701–706. doi:10.1289/ehp.1002430

Petkova EP, Gasparrini A, Kinney PL (2014) Heat and mortality in New York City since the beginning of the 20th century. Epidemiology 25(4):554–560. doi:10.1097/EDE.0000000000000123

Rocklov J, Barnett AG, Woodward A (2012) On the estimation of heat-intensity and heat-duration effects in time series models of temperature-related mortality in Stockholm, Sweden. Environ Heal 11:23

Smargiassi A, Goldberg MS, Plante G, Fournier M, Baudouin Y, Kosatsky T (2009) Variation of daily warm season mortality as a function of micro-urban heat islands. J Epidemiol Community Health 63(8):659–664

Son JY, Lee JT, Anderson GB, Bell ML (2012) The impact of heat waves on mortality in seven major cities in Korea. Environ Health Perspect 120(4):566–571. doi:10.1289/ehp.1103759

Tian Z, Li S, Zhang J, Guo Y (2013) The characteristic of heat wave effects on coronary heart disease mortality in Beijing, China: a time series study. PLoS One 8(9):e77321. doi:10.1371/journal.pone.0077321

Tong S, Wang XY, Barnett AG (2010) Assessment of heat-related health impacts in Brisbane, Australia: comparison of different heatwave definitions. PLoS One 5(8):e12155. doi:10.1371/journal.pone.0012155

Vandentorren S, Bretin P, Zeghnoun A, Mandereau-Bruno L, Croisier A, Cochet C, Riberon J, Siberan I, Declerq B, Ledrans M (2006) 2003 heat wave in France: risk factors for death of elderly people living at home. Eur J Pub Health 16(6):583–591