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ORIGINAL PAPER

Changes in the association between summer temperature and mortality in Seoul, South Korea

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Abstract The health impact of climate change depends on various conditions at any given time and place, as well as on the person. Temporal variations in the relationship between high temperature and mortality need to be explored in depth to explain how changes in the level of exposure and public health interventions modify the temperature–mortality relationship. We examined changes in the relationship between human mortality and temperature in Seoul, which has the highest population in South Korea, considering the change in population structure from 1993–2009. Poisson regression models were used to estimate short-term temperature-related mortality impacts. Temperature-related risks were divided into two "time periods" of approximately equal length (1993 and 1995–2000, and 2001–2009), and were also examined according to early summer and late summer. Temperature-related mortality in summer over the past 17 years has declined. These decreasing patterns were stronger for cardiovascular disease-related mortality than for all non-accidental deaths. The novel finding is that declines in temperature-related mortality were particularly noteworthy in late summer. Our results indicate that temperature-related mortality is decreasing in Seoul, particularly during late summer and, to a lesser extent, during early summer. This information would be useful for detailed public health preparedness for hot weather.

Keywords High temperature · Mortality · South Korea · Weather

Introduction

Elevated temperatures during summer months have been reported to be associated with increased daily morbidity and mortality since the early twentieth century (Basu and Samet 2002; Gover 1938; Schickele 1947; Stallones et al. 1957). More intense and frequent extreme weather events are expected as a consequence of predicted climate change (IPCC 2007; Meehl et al. 2000) and have become important considerations in public health agendas in recent years.

Mortality rates rise due to high temperatures during and immediately after a heat wave (Son et al. 2012; Ye et al. 2011). However, the magnitude of these health effects is difficult to predict due to a variety of factors. In fact, the relationship between human health and high temperature is a complex issue that is related to exposure, sensitivity, and adaptive capacity (IPCC 2001). Exposure and sensitivity are the two factors that determine the "potential impact" from climate change. Adaptive capacity determines whether the "potential impact" is translated into the "actual impact". Finally, the health impact of climate change depends upon the extent of the three components and their aggregation (Chestnut et al. 1998; Donaldson et al. 2003; Kalkstein and Greene 1997; Keatinge et al. 2000; McGeehin and Mirabelli 2001; Seretakis et al. 1997). Davis et al. (2003a, b) reported that a decline in summer mortality in 28 US cities from 1964 to 1998 was attributable mainly to changes in adaptation strategies. Studies in North Carolina (United States), southern Finland, and southeast England also described declines in heat-related mortality from 1971 to 1997, with the most

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striking decline in the hottest region, North Carolina (Donaldson et al. 2003). However, the health impact of climate change (e.g., temperature-related deaths) depends on various conditions at any given time, place, and person.

We previously reported that mortality increases with temperatures above city-specific thresholds during the hot season in six major cities in South Korea (Kim et al. 2006). However, indications of a change with time in the health impact of high temperature have been inconclusive. Temporal variations in the relationship between high temperature and mortality must be explored in more depth to explain how changes in the level of exposure and public health interventions modify the temperature-mortality relationship. If historical temperature mortality relationships have changed (i.e., if the mortality response differs significantly for the same climate conditions over time), then public health strategies to protect against the adverse health impacts of a heat wave could be adjusted.

The goal of this analysis was to examine changes in the relationships between human mortality and temperature in Seoul, which has the largest population in South Korea, after considering the population structure from 1993–2009.

Materials and methods

Study scope

This study examined Seoul, which is the capital of the Republic of Korea and has the highest population density of all cities in Korea. In previous studies, we observed clear associations between high temperature and mortality in Seoul (Ha et al. 2011; Kim et al. 2006). For the purposes of this study, we set 1 June–31 August as summer and used the summers from 1993–2009, excluding the summer of 1994 as an extremely rare event, because of unusually hot weather (mean daily temperature of 26.3 °C in summer of 1994, and of 24.4 °C in summer of the entire study period) and high mortality (mean daily death counts of 91.9 in summer of 1994, and of 86.1 in summer of the entire study period) (see Table 1). We examined deaths that occurred at all ages and also separately in those aged 65 years or more. We considered all-cause mortality (*International Classification of Diseases,10th Revision* [International Classification of Diseases (ICD)-10], codes A00–U99)] and cardiovascular disease (CVD)-related mortality (ICD-10 codes I00–I99).

Weather and mortality data

Measurements of relative humidity and ambient temperature taken every 3 h were obtained from the Korea Meteorological Administration for 1993–2009. Daily mean temperature and humidity were calculated as the average of every 3-h measurement from one representative meteorological station in Seoul. No notable changes in station location occurred during the study period, and the station recorded a complete data series for 1993–2009. On the basis of previous work (Ha et al. 2011; Kim et al. 2006), we used the moving average of daily mean temperature during the same day and the previous day (referred to hereafter as a lag of 0–1 days) throughout this study to represent our exposure variable.

Data on every death of a Seoul resident for 1993–2009 were obtained from the Korean National Statistical Office (KNSO). These data excluded individuals who died in the study area but were not residents, as well as accidental deaths (ICD-10 codes V00–Y99). Over time, changes in the age structure of Seoul's population could significantly influence the daily mortality rate, thereby potentially biasing temporal comparisons. Daily death counts according to age and cause of death were included after standardizing age (5-year grouping; i.e., 0–4, 5–9, 10–14, etc.). The population on 31 December 2009, was set as an index population for standardization. This direct standardization method (Anderson and Rosenberg 1998) is a common epidemiological technique and was performed using yearly resident registration information from the KNSO and the population of linearly interpolated intervening days. Age-standardized daily mortality served as the basis for all subsequent analyses.

Statistical analysis

In general, high temperature has an adverse effect on health, which suggests a potential nonlinearity. So, a Poisson regression model with a natural cubic spline (NCS) function was used to assess the temperature–mortality relationship in our study. Moreover, all models included the NCS function with three degrees of freedom (df) for summer dates (i.e., from days 1–91 of the summer season) to control for intra-summer seasonal patterns. Long-term temporal trends were accounted for by modeling indicator terms for each year (15 terms for 16 years). Indicator terms were also used to control for day-of-week and holiday effects (three terms for holidays including Sunday, the day after a holiday or holidays, Saturday, and other days). Average daily humidity on the current and previous day (0–1 day lag) was modeled using the NCS (with 3 df). For quantitative effects, we estimated the temperature effect on mortality above the threshold at which the risk of mortality begins to increase with increasing temperature. Appropriate temperature

Table 1 Average daily temperature and number of deaths in summer (June–August) in Seoul for 1993–2009

Year	Temperature (°C)[a]			Deaths							
	All summer (1 June–31 August)	Early summer (1 June–15 July)	Late summer (16 July–31 August)	Non-standardization				Standardization			
				All[b]		CVD[c] related		All[b]		CVD[c] related	
				All ages	≥65 years	All ages	≥65 years	All ages	≥65 years	All ages	≥65 years
1993	22.6	22.2	23.0	81.8	46.2	25.3	16.6	146.4	96.3	47.4	34.6
1994[d]	26.3	23.9	28.6	91.9	54.3	28.4	19.6	163.5	110.8	53.2	40.0
1995	24.1	22.3	25.8	82.8	47.9	22.8	15.1	144.1	96.3	41.4	30.3
1996	24.2	22.6	25.8	84.3	50.1	23.8	16.3	144.9	98.6	42.6	32.0
1997	25.5	23.5	27.3	85.0	51.6	20.4	13.5	142.4	98.4	35.5	25.9
1998	24.0	22.8	25.1	84.6	51.2	21.9	14.7	136.9	93.8	36.4	26.9
1999	25.0	23.8	26.1	84.8	50.3	20.7	13.5	130.8	88.6	32.9	23.7
2000	25.6	24.8	26.3	87.6	52.7	21.5	14.6	130.6	89.0	33.2	24.5
2001	25.0	23.4	26.5	88.5	54.9	22.9	16.2	128.3	88.8	34.4	26.2
2002	23.9	23.1	24.7	87.3	53.9	24.0	17.0	121.9	83.5	34.7	26.3
2003	23.2	22.3	24.0	84.3	52.8	23.0	16.4	113.4	77.8	31.8	24.2
2004	24.7	23.0	26.3	86.8	57.3	24.4	17.9	112.8	79.9	32.3	25.0
2005	24.4	23.0	25.7	85.6	55.8	24.0	18.0	106.0	73.5	30.3	23.7
2006	24.0	22.5	25.5	88.8	60.1	24.9	19.1	105.4	74.8	30.1	23.8
2007	24.6	23.3	25.9	87.1	59.8	23.3	17.9	98.6	69.8	26.6	20.9
2008	24.0	22.8	25.1	86.2	59.6	21.9	17.5	92.9	65.4	23.8	19.2
2009	24.2	22.7	25.5	86.3	60.4	19.4	15.2	88.3	62.1	19.9	15.7
Total	24.4	23.1	25.7	86.1	54.0	23.1	16.4	123.9	85.1	34.5	26.1

[a] Mean daily temperature (0 day lag)

[b] All non-accidental deaths

[c] Cardiovascular disease

[d] The 1994 data were not used in any other analyses

thresholds were also selected based on model fit (Kovats et al. 2004).

We used three different models to assess the trend of the temperature effect on mortality during the past 17-year period. The first modeled temperature (0–1 day lag) used NCS (with 4 df) with an adjustment for day-of-week and holiday, calendar year, summer date, and humidity (as described above) to assess the functional form of the temperature–mortality relationship (model 1):

$$\begin{aligned} Log[E(Y)] = \beta_0 &+ \alpha_{\mathrm{i}}(\textit{day-of-week and holiday}) \\ &+\gamma_{\mathrm{j}}(\textit{calendar year}) \\ &+\mathrm{NCS}(\textit{summer date}, \mathrm{df}=3) \\ &+\mathrm{NCS}(\textit{humidity}, \mathrm{df}=3) \\ &+\mathrm{NCS}(\textit{temperature}, \mathrm{df}=4), \end{aligned} \quad (1)$$

where E(Y) denotes the expected daily death counts; the subscript i refers to 1, 2, 3 for days-of-week and holiday; the subscript j refers to 1, 2, …, 15 for calendar years.

To quantify the temperature effect on mortality during all summer seasons, temperature was modeled as a log-linear term that assumed no association below the specific threshold values and a linear increase in mortality above the threshold (model 2):

$$\begin{aligned} Log[E(Y)] = \beta_0 &+ \alpha_{\mathrm{i}}(\textit{day-of-week and holiday}) \\ &+\gamma_{\mathrm{j}}(\textit{calendar year}) \\ &+\mathrm{NCS}(\textit{summer date}, \mathrm{df}=3) \\ &+\mathrm{NCS}(\textit{humidity}, \mathrm{df}=3) \\ &+\beta_1(\textit{temperature}) \\ &+\beta_2(\textit{temperature}-\delta)_+, \end{aligned} \quad (2)$$

where ($temperature-\delta)_+$ refers to max{$temperature-\delta$, 0} (i.e., 0 if the temperature was less than the specific threshold value). Threshold values used in this model were determined based on the best fitting model (as determined by Akaike's information criterion (AIC); Akaike 1973) among models that used different threshold values (in 0.1 °C increments of potential threshold values based on inspection of the graph).

A third model was used to estimate the effect of change on the association between temperature and mortality during the summer months (model 3):

$$\begin{aligned}Log[E(Y)] = \beta_0 &+ \alpha_{\mathrm{i}}(day\text{-}of\text{-}week\ and\ holiday)\\ &+\gamma_{\mathrm{j}}(calendar\ year)\\ &+\mathrm{NCS}(summerdate, \mathrm{df}=3)\\ &+\mathrm{NCS}(humidity, \mathrm{df}=3)\\ &+\beta_1(temperature)\\ &+\beta_2(temperature-\delta)_+\\ &+\beta_3\left[(temperature-\delta)_+ \times PERIOD\right],\end{aligned} \tag{3}$$

where *PERIOD* refers to summers during the study period. To examine temporal changes in temperature-related mortality, we divided the time series into two "time periods" of approximately equal length (1993 and 1995–2000, and 2001–2009). Data from 1994 were not used for this study because average temperatures in summer 1994 were exceptionally high compared to all other years (Table 1). Summers in the 1990s were classified as the 1990s summers (*PERIOD*=0), and those in the 2000s were classified as the 2000s summers (*PERIOD*=1). Summer temperature (0–1 day lag) was modeled as a log-linear term, assuming a common threshold temperature value during the study period. An interaction term for study period (*PERIOD*=0, 1) and summer temperature (0–1 day lag) above the common threshold value was used to determine whether *PERIOD* modified the association between summer temperature and mortality.

Previous studies of high temperature and mortality proposed that the effect of single days on temperature was larger earlier in the summer in seven US (Kalkstein and Smoyer 1993) and European cities (Baccini et al. 2008; Hajat et al. 2002). Unstable weather patterns (e.g., a significant drop/increase in temperature) are also more likely to occur in the coming decades (Guo et al. 2011; Plavcova and Kyselý 2010). As one factor (i.e., exposure) that determines the "potential impact" in the relationship between mortality and high temperature, sudden temperature changes (calculated as current day's average temperature − previous day's average temperature) could be considered. We conducted further analyses to investigate the effect of this rule on the relationship between temperature and mortality in early summer and in late summer. Early summer and late summer were defined as 1 June–15 July and 16 July–31 August, respectively.

All analyses were performed using R software version 2.2.0 (The R Foundation for Statistical Computing, version 2.2.0, 2004, http://cran.r-project.org). The convergence tolerances of the regression models were set to 10^{-9}, with a limit of 1,000 iterations to avoid biased regression coefficients and standard error estimates (Dominici et al. 2002; Pattenden et al. 2003).

Results

Description

Figure 1 shows the time series of daily death counts with and without direct standardization. South Korea is facing a significant ageing of the population, and 21 % of the population is expected to be 65 years and over in 2026 (KNSO 2005). After direct standardization of the five age categories, daily death counts decreased significantly with peaks in winter and dips in summer. These results suggest that the raw mortality rates cannot be compared directly over time because of inherent demographic differences.

Table 1 shows the average daily temperature and number of deaths in summer (June–August) in Seoul from 1993–2009. On average, 124 persons in Seoul died from natural causes each day during the summer from 1993–2009; of these, 35 died from CVD-related causes. For the 17-year study period, a gradual downward trend was observed for the average number of deaths (146.4 and 47.4 in 1993 to 88.3 and 19.9 in 2009 for all causes of death and CVD-related deaths, respectively) and was statistically significant (i.e., regression coefficients of −4.14 ($P<0.001$) and −1.50 ($P<0.001$) for all causes of death and CVD-related deaths, respectively). Average daily mean temperatures over the entire study period were 24.4, 23.1, and 25.7 °C for summer, early summer, and late summer, respectively. During the 17-year study period, no increasing or decreasing trends in daily mean temperature were found. However, average temperatures in summer 1994 were exceptionally high compared to those in all other years (Table 1).

We plotted the exposure–response relationship between the moving average (lag 0–1) of daily mean summer temperatures and daily death counts for all summers, early summers, and late summers with and without partitioning them into the 1990s and the 2000s (Fig. 2). All plots showed a rapidly increasing pattern of relative risk on daily death counts as temperature increased above the specific threshold value. For all summers combined, the associations with higher temperatures appeared stronger for the 65+ years age group than for all other ages combined and for CVD-related mortality than for all-cause-related mortality (all ages combined). For CVD-related mortality, associations with higher summer temperatures were stronger in the 1990s than in the 2000s. Moreover, these declining trends in the association between high temperature and mortality were quite obvious in late summer for CVD-related mortality and all-cause-related mortality.

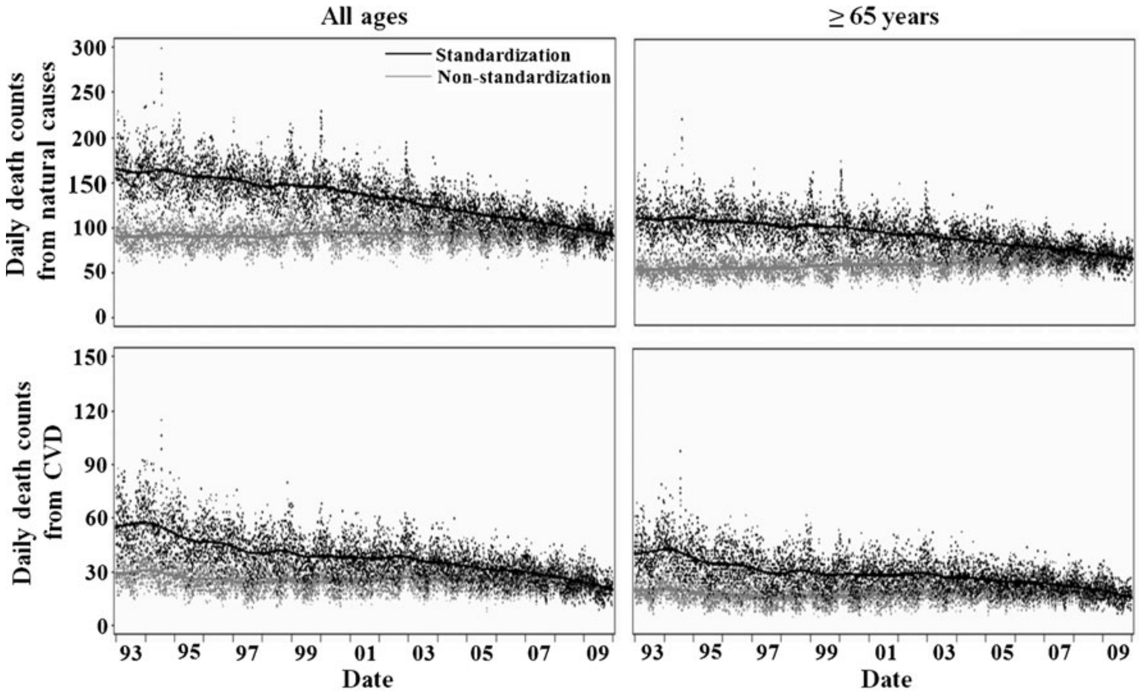

Fig. 1 Daily death counts for all ages and the ≥65 year age group with and without direct standardization (the population on 31 December 2009, was used as an index population) in Seoul from 1993–2009

Quantification of effects

From model 2, the summer temperature thresholds (0–1 day lag) for all non-accidental causes of death were 27.2, 22.8, and 27.9 °C for the entire summer, early summer, and late summer, respectively (Table 2). According to model 2 estimates, a 1 °C increase in summer temperatures (0–1 day lag) above the threshold was associated with increases in mortality for all ages and for those 65 years and older of 5.36 % [95 % confidence interval (CI), 4.14–6.60 %] and 7.31 % (95 % CI, 5.83–8.81 %) for the entire summer, 2.25 % (95 % CI, 1.49–3.02 %) and 2.46 % (95 % CI, 1.53–3.39 %) for early summer, and 8.73 % (95 % CI, 6.52–10.98 %) and 11.98 % (95 % CI, 9.30–14.72 %) for late summer, respectively (Table 2). For CVD-related mortality, a 1 °C increase in summer temperatures above a threshold was associated with increases in mortality of 7.06 % (95 % CI, 4.70–9.49 %) and 8.91 % (95 % CI, 6.17–11.72 %) for the entire summer, 4.73 % (95 % CI, 3.24–6.24 %) and 5.11 % (95 % CI, 3.39–6.86 %) for early summer, and 10.43 % (95 % CI, 6.18–14.86 %) and 13.86 % (95 % CI, 8.89–19.05 %) for late summer in all ages and in those aged 65 years and older, respectively (Table 2). All effect estimates were statistically significant at an alpha level of 0.05.

When we separated summers into two groups (summers of the 1990s and those of the 2000s), the association between high temperature and mortality in the 2000s increased relative to that in the 1990s for all non-accidental causes of death but declined relative to the 1990s for CVD-related deaths (percentage increases in all non-accidental deaths of 4.73 % and 6.78 % in the 1990s and 6.05 % and 7.89 % in the 2000s; and in CVD-related deaths of 8.69 % and 10.47 % in the 1990s and 5.27 % and 7.29 % in the 2000s in all ages and in the 65 years and over population, respectively). The same trends were observed for early summer (percentage increases in all non-accidental deaths of 2.14 % and 2.25 % in the 1990s and 2.38 % and 2.69 % in the 2000s; and in CVD-related deaths of 5.45 % and 6.50 % in the 1990s and 3.98 % and 3.69 % in the 2000s for all ages and the 65 years and over population, respectively). However, the association between high temperature and mortality in late summer in the 2000s declined relative to that in the 1990s for all non-accidental causes of death and for CVD-related deaths (percentage increases in all non-accidental deaths of 9.15 % and 12.90 % in the 1990s and 8.25 % and 11.10 % in the 2000s; in CVD-related deaths of 14.78 % and 18.61 % in the 1990s and 5.73 % and 9.21 % in for the 2000s in all ages and the 65 years and over population, respectively).

Discussion

Changes by decade in the relationship between high temperature and mortality were examined for all non-accidental and CVD-related deaths in Seoul for the period 1993–2009.

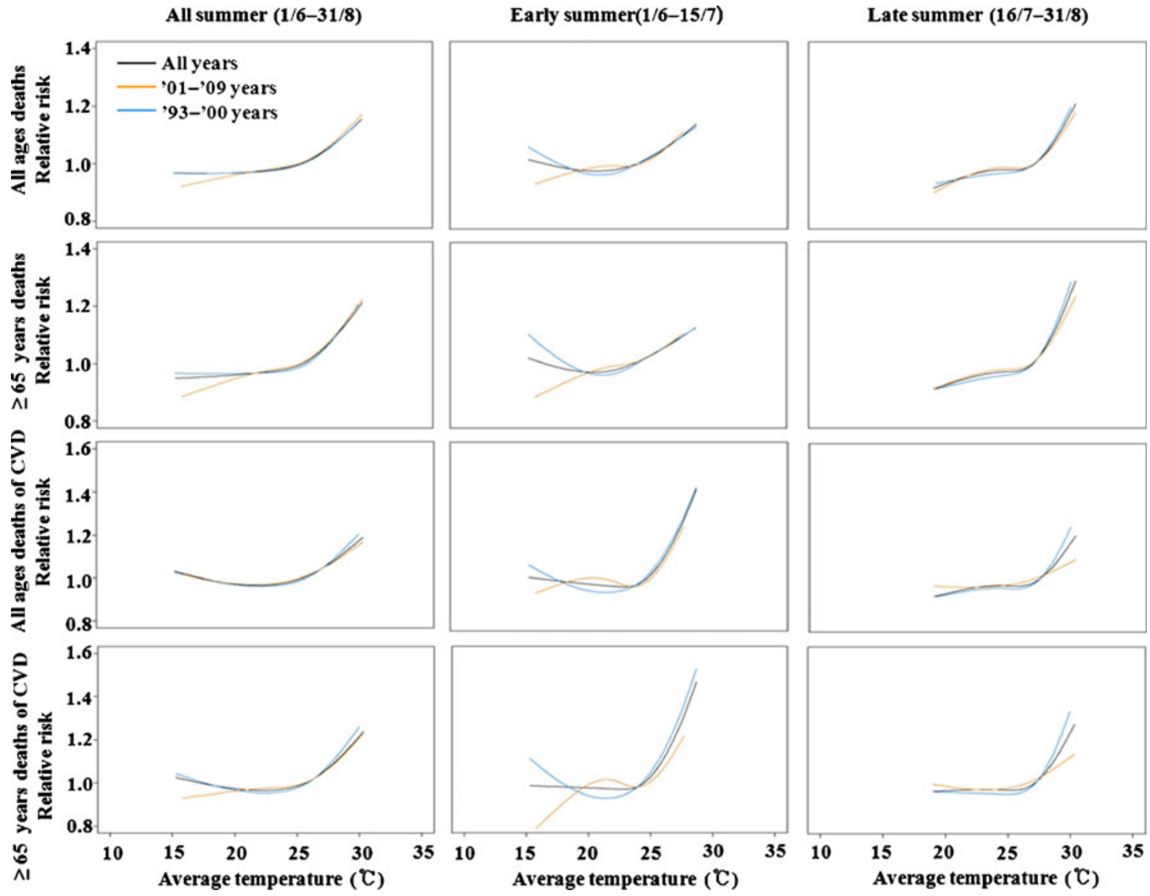

Fig. 2 Combined exposure–response curve for mean daily temperature (0–1 day lag) and daily death counts (all non-accidental deaths and cardiovascular disease deaths) for all ages and among those ≥65 years of age in summer (June–August), 1993–2009 (excluding 1994), with and without partition into two "decades" of approximately equal length (1993 and 1995–2000, and 2001–2009)

The results showed that temperature-related mortality during summer over the past 17 years has declined, but a significant relationship remained between high temperature and mortality. These decreasing patterns were stronger in CVD-related mortality than in those of all non-accidental deaths. This observation is consistent with the hypothesis that temperature-related mortality is larger for CVD-related deaths than for all non-accidental deaths. Conversely, CVD-related deaths may have been reduced more than any other related deaths over the past 17 years. Our findings are consistent with the results of previous studies (Donaldson et al. 2003; Davis et al. 2003a, b; Kyselý and Kriz 2008; McGeehin and Mirabelli 2001), but there was difficulty quantifying which factors mitigated mortality.

Previous studies have suggested that this relative "desensitization" of the population to high temperature could be explained by adaptation, including improved medical care, air conditioning, better public awareness programs relating the potential dangers of heat stress, and human biophysical and infrastructural adaptations (Donaldson et al. 2003; Davis et al. 2003a, b; Kyselý and Kriz 2008; McGeehin and Mirabelli 2001). Among major risk factors for heat-related morbidity and mortality, air conditioning is recommended to mitigate many of the factors that increase the risk of heat-related illness and death (Centers for Disease and Control and Prevention 1995a, b, 1996; Kilbourne et al. 1982; Rogot et al. 1992). Furthermore, several studies have reported that air conditioning is a critical factor in reducing heat-related mortality (Davis et al. 2003a, b; Mcgeehin and Mirabelli 2001).

In an effort to assess the availability of air conditioning on our observed declines in mortality, we cursorily examined the percentage of households with available air conditioning according to the Korea Power Exchange. Overall, the number of households having air-conditioning in Seoul increased from 15 % to 71 % between 1994 and 2009. Although, this trend in available air conditioners is consistent with the observed decline in temperature-related deaths, air conditioning is only one of many major factors involved. In the case of South Korea, total health expenditures are also related to the observed decline in temperature-related mortality. Total health expenditures increased from 4.1 % to

Table 2 Estimated increases in mortality [95 % confidence interval (CI)] associated with a 1 °C increase in temperature above the threshold in Seoul, South Korea

Age group	Summer group[a]	Percentage increase[b] (95 % CI) above the threshold[c]			*P*-value[d]
		All years	1990s	2000s	
All non-accidental deaths					
All ages					
	All summer	5.36 (4.14–6.60)	4.73 (3.15–6.33)	6.05 (4.34–7.79)	0.302
	Early summer	2.25 (1.49–3.02)	2.14 (1.20–3.08)	2.38 (1.36–3.42)	0.729
	Late summer	8.73 (6.52–10.98)	9.15 (6.28–12.11)	8.25 (5.27–11.32)	0.693
≥65 years					
	All summer	7.31 (5.83–8.81)	6.78 (4.85–8.74)	7.89 (5.86–9.97)	0.488
	Early summer	2.46 (1.53–3.39)	2.25 (1.11–3.40)	2.69 (1.46–3.94)	0.615
	Late summer	11.98 (9.30–14.72)	12.90 (9.37–16.55)	11.10 (7.52–14.81)	0.540
Deaths from CVD[e]					
All ages					
	All summer	7.06 (4.70–9.49)	8.69 (5.58–11.90)	5.27 (0.27–10.51)	0.770
	Early summer	4.73 (3.24–6.24)	5.45 (3.59–7.34)	3.98 (2.02–5.98)	0.285
	Late summer	10.43 (6.18–14.86)	14.78 (9.05–20.80)	5.73 (0.19–11.57)	0.030
≥65 years					
	All summer	8.91 (6.17–11.72)	10.47 (6.83–14.23)	7.29 (3.62–11.72)	0.268
	Early summer	5.11 (3.39–6.86)	6.50 (4.33–8.71)	3.69 (1.46–5.97)	0.084
	Late summer	13.86 (8.89–19.05)	18.61 (11.84–25.78)	9.21 (2.85–15.97)	0.064

[a] Defined in Table 1

[b] Percentage increase in daily mortality with a 1 °C temperature increase above the threshold

[c] The temperature (27.2 °C, 22.8 °C, and 27.9 °C for all summer, early summer, and late summer, respectively) at which the risk of mortality begins to increase with increasing temperature

[d] *P*-value indicates the statistical significance of change by two period (1990s and 2000s) in the relationship between high temperature and mortality

[e] Cardiovascular disease

6.5 % of the gross domestic product in South Korea between 1993 and 2008 (MHW 2010). Although no direct link was found between total health expenditures and observed declines in mortality, the increase in total health expenditures could have been associated with warning about the dangers associated with high temperatures, and could particularly be attributed to the lowering of the mortality rates in susceptible groups. However, other technological and biophysical changes over time, such as advances in medical care, forecasting systems to predict dangerous weather conditions, adaptation plans, and human biophysical adaptation most likely have some influence as well.

The novel finding of this study was that the extent of decline in temperature-related mortality was different during the summer. When summer was divided into early summer (1June–15 July) and late summer (16 July–31 August), declines in temperature-related mortality were particularly noteworthy for late summer. A large change in temperature could impact mortality because humans cannot adapt to sudden temperature changes, particularly people with certain medical conditions (Guo et al. 2011; Plavcova and Kyselý 2010). Figure 3 shows the distribution of daily temperature change (calculated as current day's average temperature − previous day's average temperature) in June for 1993–2009. The monthly mean daily temperature change increased in Seoul during June. If the temperature changed sharply between adjacent days, it would result in adverse impacts on daily mortality according to period (i.e., summers in the 1990s vs. summers in the 2000s). However, the assumption that sudden temperature changes during early summer are associated with fewer declines in temperature-related mortality than during late summer is unreasonable if there are many possible factors, such as the schedule or effectiveness of the adaptation plan, which mitigate mortality and truly reflect the reduction in temperature-related mortality during early summer. Future studies considering adaptation-related factors may clarify whether sudden temperature changes during early summer account for our results.

The existence of a threshold effect suggests that a risk estimate based on the assumption of linearity may underestimate the true risk (Kim et al. 2004). We used a common threshold temperature, defined in all study

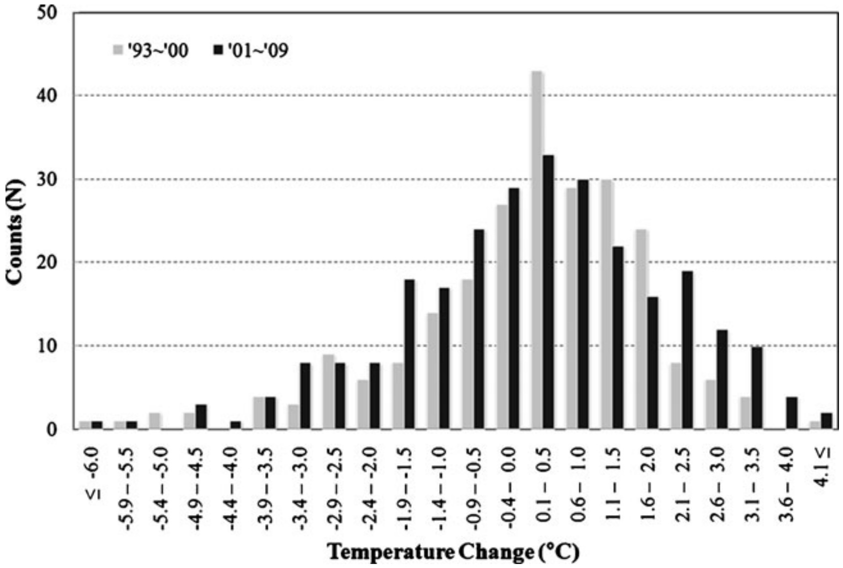

Fig. 3 Distribution of temperature change (calculated as current day's mean temperature − previous day's mean temperature) from 1 June–30 June

periods as a baseline, to determine whether temperature–mortality relationships changed over time. We used different thresholds that varied by timing in summer (i.e., for early summer and late summer) (Table 2). A function of this interpretation is that a common temperature threshold is required to directly compare effect estimates for temperatures above a threshold (Ha et al. 2011). However, if the threshold increases and temperature-related mortality above the threshold remain constant, this suggests that the population was more robust. In this case, we may say that some degree of adaptation has occurred. Our analysis focused on a comparison of the heat slope. Thus, we used a common temperature threshold for all study periods and specific thresholds for early summer and late summer.

Most temperature-related mortality studies have considered particulate matter and ozone, as these pollutants are associated with mortality and correlated with high temperatures (Basu and Ostro 2008; O'Neill et al. 2005; Vaneckova et al. 2008; Zanobetti and Schwartz 2008). We could not control for air pollution for the full period analyzed due to limited data from 1997–2009; moreover, no previous study has reported whether the effect of air pollution decreases over time.

We excluded the 1994 data from the analysis to assess the changes by decade in temperature-related mortality in Seoul from 1993–2009, because of unusually hot weather and high mortality. In South Korea, temperature effects on mortality during July–August 1994 were particularly high (Choi et al. 2005; Kyselý and Kim 2009), with the total death counts exceeding 3,000 representing a net excess mortality. Thus, if we had included 1994 (including daily deaths from July to August in that year) in the study period, our results may have been overestimated due to the net excess mortality that appeared during that year.

To determine if our findings were robust, we first separated summers into three groups (1993–1998, 1999–2003, and 2004–2009) rather than only two groups (1990s and 2000s) and evaluated whether there was a decreasing pattern of temperature-related mortality over time. The main results still remained (results not shown), but there was insufficient power to create more than two groups for the comparison.

Second, relative humidity and temperature are inherently highly correlated. Thus the assumptions of regression analysis might be violated and the validity of the results might be compromised. We also used a dew point temperature variable instead of a relative humidity variable. There are few changes in temperature thresholds, which were 27.2, 22.7, and 27.9 °C for the entire summer, early summer, and late summer, respectively. However, estimated relationships still supported our early conclusions (Supplemental material Table 1).

Many countries have systematically planned and employed public health strategies to mitigate adverse health impacts during the hot months. Our study examined how the health response to high temperature depends on various conditions at a given time (i.e., decade-scale change and timing in summer). Although the factors influencing the decline in the relationship between high temperature and mortality remain unresolved, useful information for detailed public health strategies may be generated when our findings are replicated.

In conclusion, the results of our study show that temperature-related mortality decreased in Seoul from 1993–2009. Moreover, these decreasing trends were particularly noteworthy during late summer. We recommend that public health strategies to minimize adverse health impacts due to high temperature should be finely adjusted and account particularly for the unchanged risk during early summer.

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