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The association between elevated temperatures and mortality has been reported since the early 20th century. For example, Gover (1938) reported excess deaths associated with elevated ambient temperature exposure in 86 U.S. cities from 1925 to 1937. Studies of army recruits published in the 1940s (Schickele 1947) and 1950s (Stallones et al. 2008; Stafoggia et al. 2009), and both Rocklöv et al. (2008; Staňková et al. 2009), and both reported that low levels of winter mortality were associated with higher estimated temperatures the next summer.

We previously reported that mortality increases with temperatures above city-specific thresholds during the hot season in six major South Korean cities (Kim et al. 2006). The aim of this study was to assess the extent to which the association between summer (June–August) temperatures and mortality is modified by the mortality level of the previous winter (December–February).

Materials and Methods

Scope of the study. The cities selected for this study were Seoul, Daegu, and Incheon, South Korea. The study period ranged from 1992 through 2007, with the exception of the summer of 1994, which was excluded because of unusually hot weather. Summer and winter were defined as June–August and December–February, respectively. We examined deaths that occurred in all ages and among persons ≥ 65 years of age.

Weather and mortality data. Measurements of relative humidity and ambient temperature were obtained from the Korea Meteorological Administration for the period 1992–2007. Daily mean temperature and humidity were calculated as the average of the 3-hr measurements from one representative meteorological station in each city. No important changes in station locations occurred during the study period, and each station recorded complete data series for the period 1992–2007.

Based on previous work (Kim et al. 2006), we estimated associations between daily mortality counts and the average daily mean temperature during the same day and the previous day (referred to hereafter as a 0- to 1-day lag).

The Korean National Statistical Office provided daily mortality counts. Deaths of individuals who were not residents of the study area and accidental deaths [International Classification of Diseases, 10th Revision (ICD-10), codes V00–V99] (World Health Organization 1993) were excluded. We estimated associations with all other causes of mortality (ICD-10, codes A00–U99) in all three study areas and estimated associations with cardiovascular disease (CVD)-related mortality (ICD-10, codes 100–199) in Seoul only (because of limited power due to relatively small numbers of CVD-related deaths per day in Daegu and Incheon).

Modeling approach. Poisson regression models adapted for time-series data were used to estimate the sensitivity of heat-related mortality in summer (June–August) to mortality in the previous winter (December–February) in Seoul, Daegu, and Incheon in South Korea, from 1992 through 2007, excluding the summer of 1994.

Methods: Poisson regression models adapted for time-series data were used to estimate associations between a 1°C increase in average summer temperature (on the same day and the previous day) above thresholds specific for city, age, and cause of death, and daily mortality counts. Effects were estimated separately for summers preceded by winters with low and high mortality, with adjustment for secular trends.

RESULTS: Temperatures above city-specific thresholds were associated with increased mortality in all three cities. Associations were stronger in summers preceded by winters with low versus high mortality levels for all nonaccidental deaths and, to a lesser extent, among persons ≥ 65 years of age. Effect modification by previous-winter mortality was not evident when we restricted deaths to cardiovascular disease outcomes in Seoul.

Conclusions: Our results suggest that low winter all-cause mortality leads to higher mortality during the next summer. Evidence of a relation between increased summer heat-related mortality and previous wintertime deaths has the potential to inform public health efforts to mitigate effects of hot weather.

Key words: high temperature, mortality, preventive health services, South Korea, weather. Environ Health Perspect 119:542–546 (2011). doi:10.1289/ehp.1002080 [Online 13 January 2011]
to estimate short-term temperature effects on mortality levels. To control for intrasummer seasonal patterns, we included in the all models, natural cubic spline (NCS) functions with 3 degrees of freedom (df) for summer date (i.e., from day 1 to day 91 of the summer season). Long-term temporal trends were accounted for by modeling indicator terms for each year (14 terms for 15 years). Indicator terms were also used to control for day of week and holiday effects—one term for the reference and three terms for the four categories of day of week and 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- to 1-day lag) was modeled using NCS (with 4 df).

We used three different models to estimate temperature effects. The first modeled mean temperature (0- to 1-day lag) used NCS (with 4 df) with 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:

\[
\log[E(Y)] = \beta_0 + \alpha_j(\text{day of week and holiday}) + \gamma_i(\text{calendar year}) + \text{NCS}(\text{summer date, df} = 3) + \text{NCS}(\text{humidity, df} = 4) + \beta_1(\text{temperature}) + \beta_2(\text{temperature} - \text{threshold}),
\]

where \(E(Y)\) denotes expected daily death counts, and the subscript \(i\) refers to 1, 2, . . . , 14 for calendar year. To quantify the temperature effect, temperature was modeled as a log-linear term that assumed no association below city-, age-, and cause-specific threshold temperature values and a linear increase in mortality above the threshold:

\[
\log[E(Y)] = \beta_0 + \alpha_j(\text{day of week and holiday}) + \gamma_i(\text{calendar year}) + \text{NCS}(\text{summer date, df} = 3) + \text{NCS}(\text{humidity, df} = 4) + \beta_1(\text{temperature}) + \beta_2(\text{temperature} - \text{threshold}),
\]

where (temperature – threshold) refers to max(temperature – threshold, 0) [i.e., 0 if the average temperature (0- to 1-day lag) was less than the city-, age-, and cause-specific threshold value].

Temperature threshold values used in this model were determined based on the best fitting model [as determined by Akaike’s information criterion (Akaike 1973)] among models that used different threshold values (in 0.1°C increments of potential threshold values based on graphical inspection). The precision of the threshold estimate for each series was determined using a resampling technique in which the models used to identify the optimum threshold were repeated 1,000 times with 10% of the subjects omitted at random from each iteration. This procedure for temperature threshold values was applied to each city, age, and cause of death stratum.

A third model was used to estimate the effect of previous-winter mortality on the association between temperature and mortality in the summer months:

\[
\log[E(Y)] = \beta_0 + \alpha_j(\text{day of week and holiday}) + \gamma_i(\text{calendar year}) + \text{NCS}(\text{summer date, df} = 3) + \text{NCS}(\text{humidity, df} = 4) + \beta_1(\text{temperature}) + \beta_2(\text{temperature} - \text{threshold}),
\]

where HL refers to high–low mortality. To classify winters as having high or low mortality, we regressed yearly average winter mortality

<table>
<thead>
<tr>
<th>City</th>
<th>Year</th>
<th>All Deaths</th>
<th>Deaths ≥ 65 years</th>
<th>Winter (December–February)</th>
<th>Year</th>
<th>All Deaths</th>
<th>Deaths ≥ 65 years</th>
<th>Summer (June–August)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seoul</td>
<td>1992</td>
<td>92.7 (L)</td>
<td>54.3 (H)</td>
<td>1992 80.8</td>
<td>2012</td>
<td>20.5</td>
<td>25.4</td>
<td>2005/2006 27.4 (L)</td>
<td>12.8</td>
</tr>
<tr>
<td>Daegu</td>
<td>1992</td>
<td>92.5 (L)</td>
<td>56.1 (H)</td>
<td>1992 85.2</td>
<td>2012</td>
<td>22.8</td>
<td>25.3</td>
<td>2005/2006 29.6 (L)</td>
<td>13.4</td>
</tr>
<tr>
<td>Incheon</td>
<td>1992</td>
<td>93.3 (L)</td>
<td>59.1 (H)</td>
<td>1992 88.4</td>
<td>2012</td>
<td>25.0</td>
<td>23.2</td>
<td>2005/2006 23.9 (L)</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Abbreviations: H, high previous-winter mortality level; L, low previous-winter mortality level.

*All nonaccidental deaths. *Mean daily temperature (0-lag day).

The 1994 data were not used in any other analyses.
most summers have been positively associated with mortality, but the heat wave from July to August 1994 (Figure 1) had a particularly high impact on mortality (Choi et al. 2005; Kyselý and Kim 2009). Because the 1994 heat wave might have been an extremely rare event, we excluded 1994 data from the analysis when evaluating modification of the summertime temperature–mortality relationship by previous-winter mortality levels. However, we also conducted analyses with 1994 data included to assess the potential impact of this event.

All analyses were performed using S-Plus 2000 (Mathsoft Inc., Cambridge, MA, USA). The convergence tolerances of the regression models were set to $10^{-9}$, with a limit of 1,000 iterations to avoid biased estimates of regression coefficients and standard errors (Dominici et al. 2002; Pattenden et al. 2003).

**Results**

**Description.** The time series of daily death counts from 1992 through 2007 show a clear annual pattern in daily death counts, with peaks in winter and dips in summer, and an increasing trend in numbers of deaths during the study period (Figure 2). Average summer temperatures over the entire study period were 24.21°C, 25.11°C, and 23.54°C in Seoul, Daegu, and Incheon, respectively. However, average temperatures in summer 1994 were exceptionally high in all three cities (26.3°C, 27.5°C, and 25.2°C, respectively; Table 1).

Figure 1 shows the correlation between annual summer mortality and previous winter-time mortality from all nonaccidental causes of death (Seoul, all ages). Although not statistically significant, summer mortality was inversely associated with mortality in the previous winter. Figure 3 displays the exposure–response relationship between the moving average (lag 0–1) of daily mean summer temperature and daily death count for all summers combined and for summers stratified by low or high previous-winter mortality. All plots in the graphical analysis exhibited a rapidly increasing pattern of the risk of mortality as temperature increases above the threshold. For all summers combined, associations with higher temperatures appeared stronger for the ≥ 65 year age group than for all ages combined, for CVD-related mortality than for all-cause–related mortality (all ages combined) in Seoul, and for Seoul than for the other cities. Results for Seoul also suggest an effect of relatively low summer temperatures on
CVD risk. Associations with higher summer temperatures were stronger after low-mortality winters than after high-mortality winters for all ages combined and, to a lesser extent, for deaths among persons ≥ 65 years of age.

Quantification of effects. From model 2 (see Equation 2) for all summer data, the summer temperature thresholds (0- to 1-day lag) for all nonaccidental causes of death were 27.9°C, 28.1°C, and 25.5°C for all ages combined and 27.4°C, 27.3°C, and 24.1°C for those ≥ 65 years of age in Seoul, Daegu, and Incheon, respectively (Table 2). According to model 2 estimates, 1°C increases in summer temperatures (0- to 1-day lag) above the thresholds were associated with increases in mortality of 7.97% (95% CI, 5.50–10.49%), 6.12% (3.74–8.55%), and 3.85% (1.80–5.94%) for all ages combined, and 8.51% (6.26–10.81%), 6.82% (4.56–9.13%), and 3.89% (2.12–5.69%) among those ≥ 65 years of age in Seoul, Daegu, and Incheon, respectively (Table 2). A 1°C increase in summer temperatures above a threshold of 27.9°C was associated with a 10.16% (5.36–15.18%) increase in CVD-related mortality in Seoul (all ages combined). All effect estimates were statistically significant at \( p < 0.05 \).

Based on model 3 estimates (see Equation 3) for all nonaccidental deaths in all age groups, a 1°C increment in summer temperature above the thresholds was associated with increases of 10.57%, 8.55%, and 6.04% in summer mortality after a low-mortality winter and 4.85%, 4.00%, and 2.63% increases in summer mortality after a high-mortality winter in Seoul, Daegu, and Incheon, respectively (\( p \)-values for effect modification by a previous high- vs. low-mortality winter of 0.008, 0.014, and 0.038, respectively; Table 2). In the ≥ 65 years age group, summer mortality increased by 8.85%, 8.36%, and 4.78% in association with a 1°C increase in summer temperature above threshold values after a low-mortality winter and by 7.75%, 5.14%, and 3.32% after a high-mortality winter in Seoul, Daegu, and Incheon, respectively (\( p \)-values for effect modification of 0.585, 0.050, and 0.226, respectively). CVD-related mortality (all ages) in Seoul was comparable after low- and high-mortality winters (Table 2).

Separating winters into four groups based on mortality levels limited our power to estimate effects, but results suggested that the broad pattern of higher heat risk after low-mortality winters remained (data not shown). We did not find evidence that mortality in the previous spring modified the association between temperature and mortality in the next summer (\( p \)-values for effect modification in Seoul, Daegu, and Incheon of 0.946, 0.578, and 0.338, respectively) or that mortality two winters prior modified the association (\( p \)-values for interaction terms in Seoul and Daegu of 0.459 and 0.804, respectively). Finally, estimated effects for summer heat-related mortality after a low-mortality winter were still larger after a high-mortality winter when we included data from 1994 in analyses (estimated increases in all nonaccidental deaths among all ages of 11.03%, 7.91%, and 7.14% for low previous-winter mortality and 10.42%, 4.19%, and 2.79% for high previous-winter mortality in Seoul, Daegu, and Incheon, respectively).

**Discussion**

The results of this study confirm previous findings that summer heat exposure is an important predictor of death in South Korea, particularly in the capital city of Seoul (Kim et al. 2006). The more novel finding of this study is that the risk of heat-related death in the summer was higher when we classified the preceding wintertime mortality burden as low versus high. This observation is consistent with the hypothesis that a winter with relatively low mortality level leaves a larger pool of people susceptible to heat-related mortality in the next summer. Conversely, a high winter mortality burden may reduce the number of people at risk of heat-related mortality in subsequent months. Our findings are consistent with a process of forward mortality displacement (or “harvesting”), with initial increases in mortality (mostly in already frail

### Table 2. Summer temperature thresholds and estimated increase in mortality (95% CI) associated with a 1°C increase in temperature above the thresholds in Seoul, Daegu, and Incheon, South Korea.

<table>
<thead>
<tr>
<th>City and age group</th>
<th>Observed threshold (°C)</th>
<th>Percentage increase above the threshold*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All data</td>
<td>High</td>
</tr>
<tr>
<td>Deaths from CVD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All ages</td>
<td>27.9</td>
<td>27.9</td>
</tr>
<tr>
<td>≥ 65 years</td>
<td>27.4</td>
<td>27.4</td>
</tr>
<tr>
<td>Daegu</td>
<td>28.1</td>
<td>28.1</td>
</tr>
<tr>
<td>≥ 65 years</td>
<td>27.3</td>
<td>27.3</td>
</tr>
<tr>
<td>Incheon</td>
<td>25.5</td>
<td>25.5</td>
</tr>
<tr>
<td>≥ 65 years</td>
<td>24.1</td>
<td>24.1</td>
</tr>
</tbody>
</table>

*Percentage increase in daily mortality with a 1°C temperature increase above the threshold. **The temperature at which the risk of mortality begins to increase with increasing temperature. *\( p \)-Value for interaction term between temperature above the threshold value and previous-winter mortality (high or low). **Estimated associations with CVD-related mortality for Seoul, South Korea, only.

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**Figure 3.** Combined (all cities studied) exposure–response curve for mean daily temperature (0- to 1-day lag) and daily death counts (all nonaccidental deaths and CVD deaths) for all ages and among those ≥ 65 years of age in summer (June–August), 1992–2007 (excluding 1994), with and without stratification by the previous-winter mortality level (high or low).
individuals) that are followed by deficits in expected number of deaths sometime after the initial excess. Time-series regression studies have shown that, on a short-term basis (i.e., over a few days or weeks), some mortality associated with heat exposure can be attributed to this displacement process, but there appears to be less of an effect on cold-related mortality (Braga et al. 2001). Displacement occurring over a longer time frame (i.e., months) is more difficult to assess because of the need to control for seasonal patterns.

Our study, initially looking at year-to-year correlations, indicates that some winter-time deaths may indeed be displaced over a longer term, to the extent that mortality in the next summer may be less than expected. Although such a possibility has been postulated before (Fouillet et al. 2008), only two previous studies have demonstrated this analytically (Rocklöv et al. 2008; Stafoggia et al. 2009). As with our work, both of these studies were conducted in high-income settings (i.e., where temperature-related deaths were dominated by chronic diseases in the elderly), with both indicating a greater heat risk in summers after a low wintertime burden. We observed this pattern occurring with all-cause mortality for all ages and, to a lesser extent, among the elderly (age ≥ 65 years). The fact that the difference in heat risk between high and low winter mortality years was larger in the all-ages group than in the elderly is counterintuitive if the process is truly reflecting long-term mortality displacement of the most frail individuals. Future studies stratified by both age- and cause-specific death groups in larger samples, and possibly studies that also account for specific heat-wave periods and their duration, may clarify whether our findings are the result of such harvesting processes. In contrast to the two previous studies (Rocklöv et al. 2008; Stafoggia et al. 2009), we did not observe similar patterns for all-cause and CVD deaths, but we were able to assess CVD-related mortality in one city where power was sufficient to estimate associations with daily death counts. Previous studies have shown that, on a short-term basis, displacement is more strongly associated with heat-related CVD deaths than with deaths from other causes, including respiratory diseases (Goodman et al. 2004; Hajat et al. 2005). Our findings suggest that a displacement effect for non-CVD deaths does indeed occur but may become apparent only over a longer time scale.

Rocklöv et al. (2008) observed that influenza epidemics may contribute to a low subsequent summertime mortality, but we were unable to evaluate the effect of the influenza epidemic on the association between summer temperature and mortality because influenza data are available only at the national (vs. city) level.

Another potential limitation of our analysis is that we were unable to control for air pollution for the full period analyzed, although controlling for ozone did not affect the modification by mortality in the previous winter in the study conducted in Rome (Stafoggia et al. 2009).

The existence of threshold effects means that the risk estimates based on an assumption of linearity may underestimate mortality risks due to elevated temperatures (Kim et al. 2004). We used common temperature thresholds across all years to facilitate estimation of the main parameter of interest: the heat slope. However, it is possible that high winter mortality may reduce the temperature threshold for summer heat-related mortality by weakening individuals and therefore heightening their subsequent heat risk, or that high winter mortality may raise the temperature threshold by increasing the proportion of healthy subjects that are less susceptible to heat, thereby increasing the threshold temperature required for a heat effect to become apparent.

Sensitivity analyses suggested that effect modification by previous-winter mortality persisted when we classified winter mortality into four (vs. two) groups, although power was limited to estimate stratum-specific effects. In addition, modification was evident when we included data from 1994 (including deaths during the heat wave from July to August of that year) in analyses. However, we did not find evidence that mortality in the previous spring or in the winter 2 years prior modified heat-related mortality in the summer.

Mirroring many countries globally, South Korea has had a heat/health watch warning system in operation since 2007 to protect human health from the dangers of hot weather. Because monthly mortality data in South Korea are available only after a 3-month delay, information on the number of wintertime deaths could, in an operational sense, be used to estimate early information on expected summertime burdens. Although long-term weather forecasts are often used by some countries as part of their heat plans to prepare for expected summertime activity levels, useful information may also be provided by information on wintertime mortality levels in settings where our findings are replicated.

Conclusions

The results of our study indicate that increased summer heat-related mortality is associated with previous wintertime deaths. We recommend that public health strategies to minimize adverse health impacts of heat waves, including the South Korean heat/health watch warning system, should account for potential effects of mortality in the previous winter.

References


