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ORIGINAL PAPER

The application of the European heat wave of 2003 to Korean cities to analyze impacts on heat-related mortality

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Abstract The goal of this research is to transpose the unprecedented 2003 European excessive heat event to six Korean cities and to develop meteorological analogs for each. Since this heat episode is not a model but an actual event, we can use a plausible analog to assess the risk of increasing heat on these cities instead of an analog that is dependent on general circulation (GCM) modeling or the development of arbitrary scenarios. Initially, the 2003 summer meteorological conditions from Paris are characterized statistically and these characteristics are transferred to the Korean cites. Next, the new meteorological dataset for each Korean city is converted into a daily air mass calendar. We can then determine the frequency and character of "offensive" air masses in the Korean cities that are historically associated with elevated heat-related mortality. One unexpected result is the comparative severity of the very hot summer of 1994 in Korea, which actually eclipsed the 2003 analog. The persistence of the offensive air masses is considerably greater for the summer of 1994, as were dew point temperatures for a majority of the Korean cities. For all the Korean cities but one, the summer of 1994 is associated with more heat-related deaths than the analog summer, in some cases yielding a sixfold increase over deaths in an average summer. The Korean cities appear less sensitive to heat-related mortality problems during very hot summers than do large eastern and Midwestern US cities, possibly due to a lesser summer climate variation and efficient social services available during extreme heat episodes.

Keywords Extreme heat events · Heat-related mortality · Korea · Synoptic climatology

Capsule: This manuscript attempts to determine how an excessive heat event (EHE) of the magnitude of the 2003 European event would impact selected Korean cities and how the event would compare to other EHEs that have previously occurred.

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Introduction

A recent manuscript (Kalkstein et al. 2008a) attempted to determine how an excessive heat event (EHE) of the magnitude of the 2003 European event would impact five major cities in the USA and how the event would compare to other EHEs that had occurred in these cities. The European event was historic in two ways. First, the magnitude of this extreme event was unprecedented in recent history, and the return period in Paris for such an event, assuming no climate change trends, has been estimated to be in the thousands of years (Schär et al. 2004; Valleron and Mendil 2004). Second, the number of heat-related deaths in western Europe was beyond anything in recent recorded history; estimated mortality for the event ranges from 52,000 in nine western European countries (Larsen 2006) to 70,000 overall (Robine, et al. 2008).

The Kalkstein et al. (2008a) study also included an estimate of the magnitude of the heat-related mortality impacts on the five US cities; the numbers were impressive but not as extreme as those that occurred in Paris. For example, New York's results were the most extreme; in an average summer, the city and its standard metropolitan statistical area records about 470 excess deaths due to heat. During the 2003

European "analog summer," we estimated about 3250 excess deaths, seven times the average number and far more than any summer since 1961. However, the results in St. Louis were less remarkable; the same numbers for the average and analog summer were 216 and 688 deaths, respectively, roughly a threefold increase, and only 20 % larger than the very hot summer of 1988. Thus, the analog summer impacts, although impressive in all the evaluated US cities, were highly variable among these cities.

We have been working for several years with the National Institute of Meteorological Research (NIMR) of the Korea Meteorological Administration on a variety of extreme heat and cold health problems in six large Korean cities. Although less variable than some other midlatitude cities, Korea nevertheless exhibits the type of highly variable summer climate that has historically been most closely associated with elevated heat/health problems (Kalkstein et al. 2011; McGregor et al. 2010), and thus, an "analog summer" evaluation for these cities, and a comparison to Paris and American urban areas, is warranted. The goal of this research is to transpose, as best as possible, the unprecedented 2003 European EHE to six Korean cities (Busan, Daegu, Daejeon, Gwanju, Incheon, and Seoul) and to develop meteorological analogs for each (Fig. 1). Further, we will determine how such an event might impact heat-related mortality in these cities. The city selection is based upon evaluating cities of various sizes and climate regimes, and all six cities have been analyzed in detail in prior collaboration with NIMR to determine their sensitivities to heat-related mortality. In addition, all of these cities presently have operating heat/health warning systems (HHWS) based upon our synoptic climatological approach (Sheridan and Kalkstein 2004), which have been functioning successfully for several years (Kalkstein et al. 2008b). Since this EHE is not a modeled event but an actual occurrence, we are able to use a plausible analog to assess the risk of increasing heat on these cities instead of an analog that is dependent on general circulation (GCM) modeling or the development of arbitrary scenarios.

Fig. 1 Map of cities analyzed in this study

Methods

The actual meteorological conditions of the 2003 EHE in Paris will be initially used to construct an analog summer for each of the Korean cities. Thus, each Korean city will have its own meteorological dataset, based partly on the intensity of heat in Paris during the summer of 2003 and partly on the unique summer climate of each Korean city.

Urban weather station hourly meteorological data were provided to us from Paris (Meteo-France) for 1973–2004 and the Korean cities (Korea Meteorological Administration) for 1982 to 2012; each city was represented by one station with the most complete data record. The different periods of record could have posed a problem in the development of the standardized anomalies, so we examined the daily variability for each location over the respective time periods. The difference is less than 0.005, which will result in no impact upon this analysis. We identified 12 key meteorological variables for each day during the EHE in Paris and transferred those values to the six Korean cities based on variation, in standard deviation units, from the mean character for each variable, to develop an air mass calendar:

- Temperature every 6 h (0300, 0900, 1500, and 2100 hours)
- Dew point temperature for the same 6-h periods
- Mean daily cloud cover
- Mean daily sea level pressure
- Diurnal temperature range of the four daily values (0300, 0900, 1500, and 2100 hours)
- Diurnal dewpoint temperature range of the four daily values

The selection of these variables is based upon previous research highlighting which variables are important in heat/health research and on the data requirements for our air mass identification procedure, the spatial synoptic classification (SSC), which has been used extensively to develop a daily air mass calendar for a large number of cities around the world (Greene and Kalkstein 1996; Sheridan and Kalkstein 2004). Our research has long been based upon the premise that, rather than responding to individual weather elements, the human body responds to the combined interactions of a large number of meteorological variables simultaneously; these variables delineate our air mass types (Sheridan and Kalkstein 2004).

A daily air mass calendar was developed for each Korean city based upon its Paris 2003 analog; the summer period extended from 1 May to 31 August. These analogs were employed to develop mortality estimates for the six Korean cities using procedures that have been employed in earlier analyses and are discussed more fully below (Ebi et al. 2004; Sheridan and Kalkstein 2004; Greene et al. 2011).

The analogs for the Korean cities were developed by characterizing the conditions in Paris statistically on a daily basis (Meteo France 2006) and then transferring these characteristics to the Korean cities. For Paris and the Korean cities, the means and standard deviations for the 12 meteorological variables necessary for SSC development were computed based on the available data for each city. The use of these "relative" data units has the ancillary benefit of diminishing any climatological differences between meteorological stations and is especially important in our utilization of a synoptic approach as explained below.

The standard deviations for all the meteorological variables in Paris during the summer of 2003 were transferred to each Korean city. For example, if on July 15, 2003, Paris' temperature at 0300 hours was 2.00 standard deviations above the day's average, then each Korean city would have a temperature at 0300 hours that was 2.00 standard deviations above the average. This procedure was replicated for every day and all of the meteorological variables for each Korean city, so that a complete set of meteorological conditions analogous to Paris 2003 (the Korean city's *analog*) was developed for each city (Sheridan and Kalkstein 2004; Greene et al. 2011). Clearly, a day on July 15 with a +2.00 standard deviation for temperature at 0300 hours would vary considerably in character between Paris, Seoul, and Busan, for example. Thus, we have developed a "relative" climatology for each Korean city for the analog Paris summer of 2003.

The definition of a "heat wave" that potentially yields negative health outcomes would vary for each city in two ways. First, the same meteorological conditions on a given day would not necessarily yield similar air mass types in Paris and Seoul, for example, since certain meteorological situations might be much hotter and/or more humid in one city versus the other, even if the variance is the same for both cities. Thus, being +2.00 standard deviations from the mean temperature or dew point could be very sultry in one place, but not in the other. Second, we know through our previous research that each city has a unique health response to extreme weather; a day that is +2.00 standard deviations away from the thermal mean might lead to many extra deaths in one city, but yield little response in another (Sheridan and Kalkstein 2004; Greene et al. 2011.) Thus, using relative units allows us to evaluate similarly unusual conditions in cities within different climate zones while maintaining that health outcomes and meteorologically dangerous conditions can be quite different in both cities.

We were concerned that cities in very different geographical regions might possess meteorological data distributions that are quite different from one another. For example, skewness in the summer meteorological data might be quite different between Paris and the Korean cities or possibly, there are multiple modes in the distribution. Although this would not necessarily invalidate a study based upon relative meteorological comparisons, it would make us feel more comfortable if similarities in distribution did exist, yielding a variance in summer weather and a relationship to a normal distribution that is similar in all the Korean cities versus Paris. In fact, the cities were more similar than we thought, as demonstrated by comparing Seoul and Paris summer maximum and minimum temperature standardized anomaly distributions (Figs. 2 and 3). The distributions are not statistically different from one another using a *t* test and a 0.05 significance level, although both are clearly not precisely normal. For maximum temperature, each demonstrates at least one additional mode at values between 1 and 2 standard deviations above the mean. The skewness and kurtosis measures are surprisingly close and are not statistically significantly different from one another. For minimum temperature, distributions for both cities are skewed toward the left, but they are still quite similar to one another, with no statistically significant difference. These tests of the distributions are not meant to imply that the summer weather is the same in Paris and Seoul. We know that this is not the case. Rather, the characteristics between locales show similarities, and a wide range of available literature (e.g., Kim and Joh 2006; Kim et al. 2008; Smoyer et al. 2000; Kyselý and Kim 2009, and others) consistently shows that negative health responses of humans to summer weather are largely based upon lack of adaptation to unusual conditions, even if those actual conditions are not the same from one locale to the other. Thus, an analog approach emphasizing relative meteorological variations to compare Paris with Korean cities is quite robust.

Each Korean city's meteorological analog for the summer of 2003 in Paris was transposed to a daily air mass calendar for each city using the SSC procedure. This calendar was then compared to Paris' summer 2003 air mass calendar and to typical frequencies of the summer air masses in each Korean city. Air mass frequency comparisons were also made with the hottest summers over the past 30 years.

The following air mass categories are identified by the SSC: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), moist tropical (MT), moist tropical plus (MT+), and transition (T). A physical explanation of each air mass can be found on our frequently updated SSC website http://sheridan.geog.kent.edu/ssc.html as well as a wide number of previous papers (Sheridan and

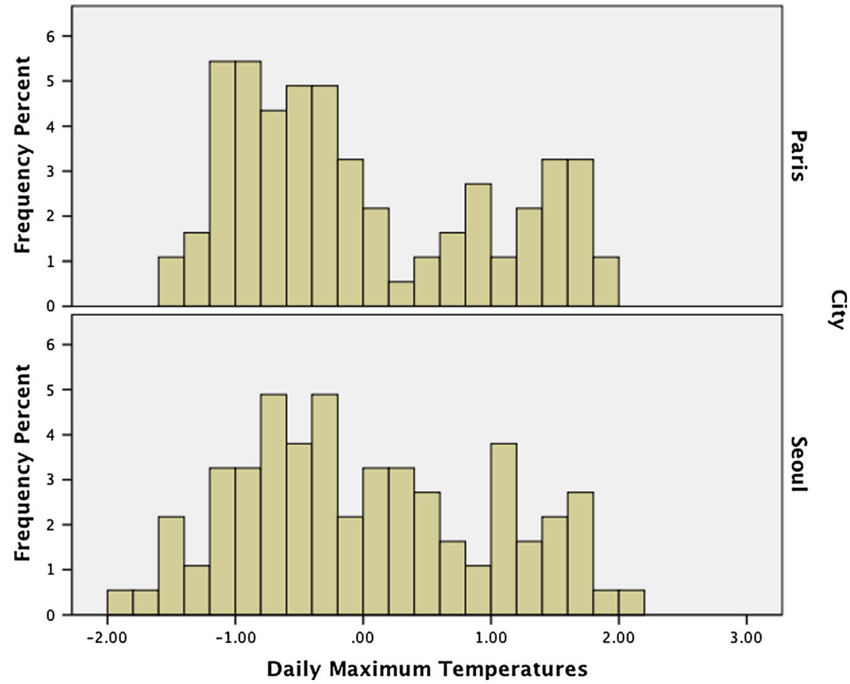

Fig. 2 Distribution of daily maximum temperatures in Seoul and Paris

Kalkstein 2004; Greene et al. 2011; Kalkstein, et al. 1996; Kalkstein 2009, etc.). This approach takes into account the geographic and climatic differences between the cities via the use of the standardized anomalies. Thus, DT air in Seoul has similarities to DT in New York and Paris because it represents the hottest and driest air mass in each location. Since we performed a separate air mass classification and statistical analysis for the Korean cities, inter-regional differences are taken into account in the analysis.

Particular attention was directed toward two of these air masses that have been historically associated with elevated mortality in Korean cities, the very hot and dry DT and the warmest and most humid subset of MT, which we call MT+; the increased health risk of these air masses within Korean cities is well documented in the literature (e.g., Kalkstein et al. 2008b). To achieve MT+ status, both morning and afternoon apparent temperatures as defined by Steadman 1984, with a personal communication update in 2011 (Steadman, 2011) must exceed mean MT values.

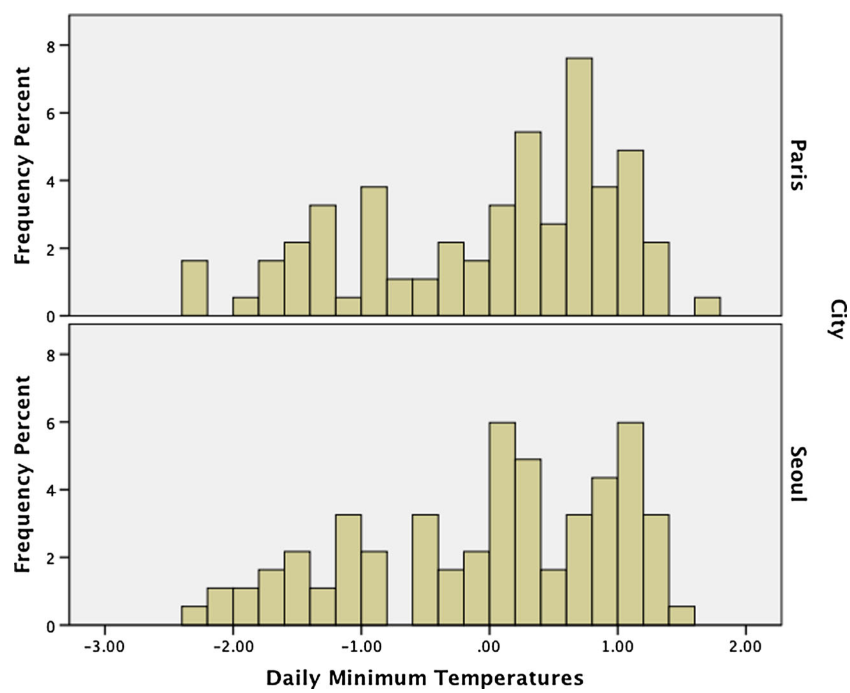

Fig. 3 Distribution of daily minimum temperatures in Seoul and Paris

Daily all-cause mortality data were obtained from the Korea National Statistical Office (KNSO; http://kostat.go.kr/portal/english/index.action). These mortality data are standardized to account for changes in the total population of the individual cities during the period of record and are compared to a baseline that results from the standardization procedure. The data used for this study thus standardized the daily all-cause mortality to account for both intra-seasonal (e.g., within a summer season) and interannual long-term population changes and follows commonly used practice to develop a synoptic heat-health relationship (refer to Sheridan and Kalkstein 2004, for further details).

For each Korean city, the mean daily mortality for each air mass type, along with the standard deviation, was determined to ascertain whether particular air masses exhibited statistically significantly elevated mortality values. The two air mass types (DT and MT+, which we deem as "offensive" air masses) showed significantly elevated daily mean summer mortality values (for example, go to Kalkstein et al. 2008a). We then developed offensive air mass-specific algorithms using multiple linear regression based on a stepwise entry method to estimate the number of deaths for each offensive air mass day (the algorithm was based on a pooled total of all offensive air mass days) derived via the stepwise regression analysis (significant variables had to exceed $p<0.05$). This procedure allows for the determination of variables that are strongly autocorrelated; for each pair of highly autocorrelated variables, the one which explained the lesser variance was removed from equation consideration. We evaluated lags of up to 2 days; in all the cases, the non-lagged model yielded the strongest relationships.

Meteorological and non-meteorological variables were included as independent variables in this regression analysis. The meteorological variables include temperature and dew point at 0300 and 1500 hours and apparent temperature at 1500 hours. The non-meteorological variables included the following:

- "Time of season" evaluates the intra-seasonal timing of a weather event, because a heat wave in August usually exerts less influence on heat-related mortality than a similar one in June mainly due to mortality displacement (a larger susceptible population is available to die of the heat in June; Sheridan and Kalkstein 2004). For example, 1 May is designated as day 1 during the summer, 2 May as day 2, June 1 as day 32, and so on.
- "Day in sequence" determines if several consecutive days of the offensive category have a greater impact on mortality than an individual, isolated day. We used a consecutive day "counter" to express this variable. For example, the developed algorithm for Seoul is:

$$Y=-21.51+2.64\mathrm{DIS}+8.98\mathrm{DT}+0.67\mathrm{AT03}$$

where Y is the estimated daily excess mortality; DIS is the day in sequence variable; DT is a DT dummy variable, where each DT day has 8.98 deaths added to the total; and AT03 is the apparent temperature at 0300 LST. All city algorithms and full developmental methodologies are found in Table 1 and in other manuscripts (e.g., Kalkstein 2009; Sheridan et al. 2012).

It is possible that there may be some non-linearity in the relationships between acute daily mortality and the variables used in this study. However, the model used is a robust predictor and statistically significant at the 0.05 level, so it can be used as an adequate predictor to estimate the heat/mortality relationships. In addition, previous research (e.g., Greene, et al. 2011; Koppe, et al. 2004, and many others) has also found similar statistically significant linear relationships. We recognize that temperature and mortality often have a non-linear relationship when considering all weather situations (in the Korean case, this has been shown by Ha and Kim (2013)). However, we consider the multiple linear regression analysis approach used here as valid because the excess mortality algorithms are developed for the *offensive* air mass days only, not the entire period of record. Thus, while there may be a non-linear response for all summer days, we found no such response between temperature and mortality within the offensive categories. In addition, this approach to identifying and examining excess mortality days is currently being used operationally by the Korean Meteorological Agency, which has tested and validated this approach for use in the Korean cities identified (Lee et al. 2010).

Results

Meteorological comparisons

The summer of 2003 in Paris was dominated by offensive air mass days in a way no other historical summer ever was (Table 2). On average, 10 % of all summer days in Paris are within offensive air masses (7.0 % DT, 3.0 % MT+; Kalkstein et al. 2008a). DT is commonly more frequent in the summer than MT+ in Paris, and during 2003, the percentage frequency of both offensive air masses increased dramatically, as one third of the summer days in Paris were within the DT air mass, over four times the average. Almost half (46 %) of all 2003 summer days were within offensive air masses. The hottest previous summer in Paris, 1990, had a combined DT and MT+ frequency of 32 %, considerably less than the 2003 frequency.

The US cities evaluated in the previous analog study somewhat mirrored Paris's results (Table 2). For example, offensive air mass days in an average summer in New York average 12.5 %, but using the Paris 2003 analog transposed to New York, over 56 % of days are within offensive air mass categories, more than a fourfold increase. Somewhat similar proportional increases are found in St. Louis. In both of these US cities, as well as Philadelphia, the Paris analog summer is

Table 1 Mortality algorithms for the selected cities

City	Equation
Seoul	−21.51+2.643*DIS+8.98*DT+0.666*AT3
Incheon	−7.37+1.573*DIS+0.241*T15
Daegu	−4.68+0.739*DT+0.171*AT15-0.01*TOS
Busan	−8.28+2.526*MTP+0.254*T15
Daejeon	−0.09+0.444*DIS
Gwangju	−2.36+0.091*T15

DIS day in sequence of offensive weather, *DT* dummy variable (=1 if day is DT), *MTP* dummy variable (=1 if day is MT+), *AT3* apparent temperature (3 h), *T15* temperature (15 h), *AT15* apparent temperature (15 h), *TOS* time of season

considerably worse than the hottest summer recorded in recent history.

However, the Korean cities behave differently than both the US cities and Paris. The increase in offensive air mass days during the analog summer is generally smaller than the US cities and Paris; at least one third of the summer days in the US cities and Paris are within offensive air masses during the analog summer (for three of the five US cities, this figure is over 50 %), while the Korean cities show offensive air mass frequencies in this summer of between 16 and 27 %, with the exception of inland Daegu. Even more dramatic is the realization that the Paris 2003 analog is not the summer with the greatest number of offensive air mass days that has occurred in recent history in any of the Korean cities. That distinction belongs to the summer of 1994, which was considerably more stressful than the analog summer, based upon numbers of offensive air mass days. With the exception of coastal Incheon, all Korean cities demonstrate frequencies of offensive air masses exceeding 40 % during this exceptionally hot summer. In Daegu, a remarkable two third of the days were within the offensive DT and MT+ air masses. Clearly, a more detailed analysis of the summer of 1994 in Seoul and the other Korean cities is warranted. The relative severity of this summer was unexpected, and it is noteworthy that use of a synoptic methodology uncovered the extreme nature of this particular summer, especially in comparison to the analog 2003 EHE.

The distribution between DT and MT+ days varies from city to city in Korea. With the exception of Busan (which has an MT+ predominance), during an average summer, there are slightly more DT days than MT+ days. For the analog summer, the DT prominence becomes even greater in the Korean cities, which is reflective of what happened in Paris during the summer of 2003, when 33 % of the days were DT. However, the exceptionally hot summer of 1994 was different, that summer was largely dominated by the more humid MT+ air mass in all the Korean cities except Incheon and Daegu. An examination of MT+ frequency in Seoul from 1962 through 2011 indicates that the percentage of MT+ days in 1994 was almost double the number of any other summer in this period. Thus, a picture has emerged through this study that the summer of 1994 was possibly even more exceptional in Korea than the summer of 2003 was in Paris.

Consecutive day runs of offensive air masses have been historically linked to dramatically increased heat-related

Table 2 Summer percentage frequencies of offensive air mass days for Paris, US cities, and Korean cities. Darkened numbers represent highest values for each city

City	Average summer frequency		Total	Analog summer frequency		Total	Hottest summer frequency		Total
	DT	MT+		DT	MT+		DT	MT+	
Detroit	2.7	6.6	9.3	25.3	11.0	36.3	29.4	8.8	38.2
New York	5.7	6.8	12.5	37.4	18.7	56.1	14.1	16.3	20.4
Philadelphia	6.0	8.4	14.4	35.1	20.9	56.0	10.9	30.4	41.3
St. Louis	4.9	12.8	17.7	31.9	22.0	53.9	22.8	19.6	42.4
Washington	4.7	9.0	13.7	24.2	8.8	33.0	21.7	13.0	34.7
Paris	7.0	3.0	10.0	33.0	13.0	46.0	26.0	6.0	32.0
Seoul	4.0	3.9	7.9	9.8	6.5	16.3	9.8	30.4	40.2
Incheon	2.3	1.4	3.7	9.8	6.4	16.2	13.0	8.7	21.7
Busan	0.4	12.3	12.7	8.7	15.2	23.9	3.3	48.9	52.5
Daejeon	6.7	4.0	10.7	18.5	6.6	25.1	15.2	26.1	41.3
Daegu	13.9	8.5	22.4	35.9	5.4	40.3	48.9	17.4	66.3
Gwanju	6.7	6.2	12.9	4.3	22.9	27.2	10.9	32.6	43.5

Table 3 Daily and all-time maximum temperature records broken in Daegu, Seoul, and Busan for the 1994 and analog summers

	1994 Daily	1994 All time	Analog daily	Analog all time	All-time record (°C)
Daegu	0	0	13	11	39.5
Seoul	1	1	16	7	38.4
Busan	3	0	12	9	38.2

mortality (Perera et al. 2012), and the analog summer coincides with long consecutive periods of DT and/or MT+ air mass days. For most of the Korean cities, the early August analog heat event, the worst of the analog summer, coincided with an approximate two consecutive week period of these two air masses (e.g., for Seoul, it was exactly 14 days); the longest run occurred in Daegu, with a 19-consecutive-day string commencing on August 1. However, this pales compared to the actual summer of 1994 in Korea. For example, in Seoul, not only were there 14 consecutive days with DT and/or MT+ air masses, there were also 31 offensive days out of 36 total days between July 12 and August 16, 1994. This represents an unprecedented string in recorded history for that city, especially considering that these air masses, on average, only occur collectively on less than 10 % of all summer days. For Daegu, there were 22 consecutive days of these air masses in 1994 (with one non-offensive air mass day intervening), and for Busan, from July 2 through August 17, 1994, a record-shattering 42 of 47 days were within offensive air masses, all but one being the very hot and excessively humid MT+. By every metric relating to offensive air mass frequency, the summer of 1994 exceeds the extreme nature of the Paris analog summer in Korea or any other summer in recorded history.

An examination of temperatures and dew points during the analog summer and the summer of 1994 demonstrates how unusual these events were and provides guidance about whether unprecedented heat for a distinct period is more dangerous than an entire summer dominated by offensive air masses. For Seoul, the analog summer would break 16 daily maximum temperature records, including 7 days that would break the all-time maximum temperature record (Table 3; here, daily maximum refers to the all-time record for each individual calendar day). Similar numbers of daily records would be broken for Busan, and Daegu would break the all-time maximum temperature record on an astonishing 11 days during the analog summer. The summer of 1994 broke many less maximum temperature records, although the all-time maximum temperature record in recorded history in Seoul, 38.4 °C, occurred on August 15, 1994.

The number of high minimum temperature records that were broken for the analog and 1994 summer is somewhat more equal, except in Daegu (Table 4). For example, in Seoul, 25 daily high minimum temperature records were broken during the summer of 1994, while this number is 21 for the analog summer. However, in general, more all-time high minimum temperature records are found in the analog summer.

The number of records broken does not reveal the entire picture when comparing these two oppressive summers. A snapshot of the temperatures for all days during the analog summer and the summer of 1994 helps explain why the latter summer was more meteorologically stressful, even though less individual temperature records were broken (Fig. 4a–c). In Seoul, Busan, and Daegu, the analog summer August maximum temperature peak exceeds any similar peaks during the summer of 1994 and is far above the average conditions for a typical summer. For Seoul and Daegu in particular, several days with temperatures exceeding 40 °C are noted in early August, including a few consecutive day runs; these days broke the historic maximum temperature record. But it is also apparent that the temporal extent of exceedingly high maximum temperatures is much greater in 1994 than the analog summer. In Seoul, from early July to well into August, 1994, maximum temperatures were generally 6–7 °C or more above average, with very few days where cooling relief occurred. During the analog summer, there are two distinct hot periods, one in mid-July and one in early to mid-August, but both are considerably shorter in duration than the hottest period in 1994, and the intervening cooler weeks provide relief from the stressfully hot conditions. Busan and Daegu show similar temporal patterns for the two summers.

However, there is a significant difference in the extent of high minimum temperatures for the two stressful summers. During the summer of 1994, it is clear that minimum temperatures are consistently higher than during the analog summer; in Seoul, for virtually the entire month of July, daily minimums approximate the average maximum temperature values. This overall pattern of high minimum temperatures is much

Table 4 Daily and all-time high minimum temperature records broken in Daegu, Seoul, and Busan for the 1994 and analog summers

	1994 Daily	1994 All time	Analog daily	Analog all time	All-time record (°C)
Daegu	0	0	20	15	27.8
Seoul	25	3	21	6	28.8
Busan	12	3	19	12	27.5

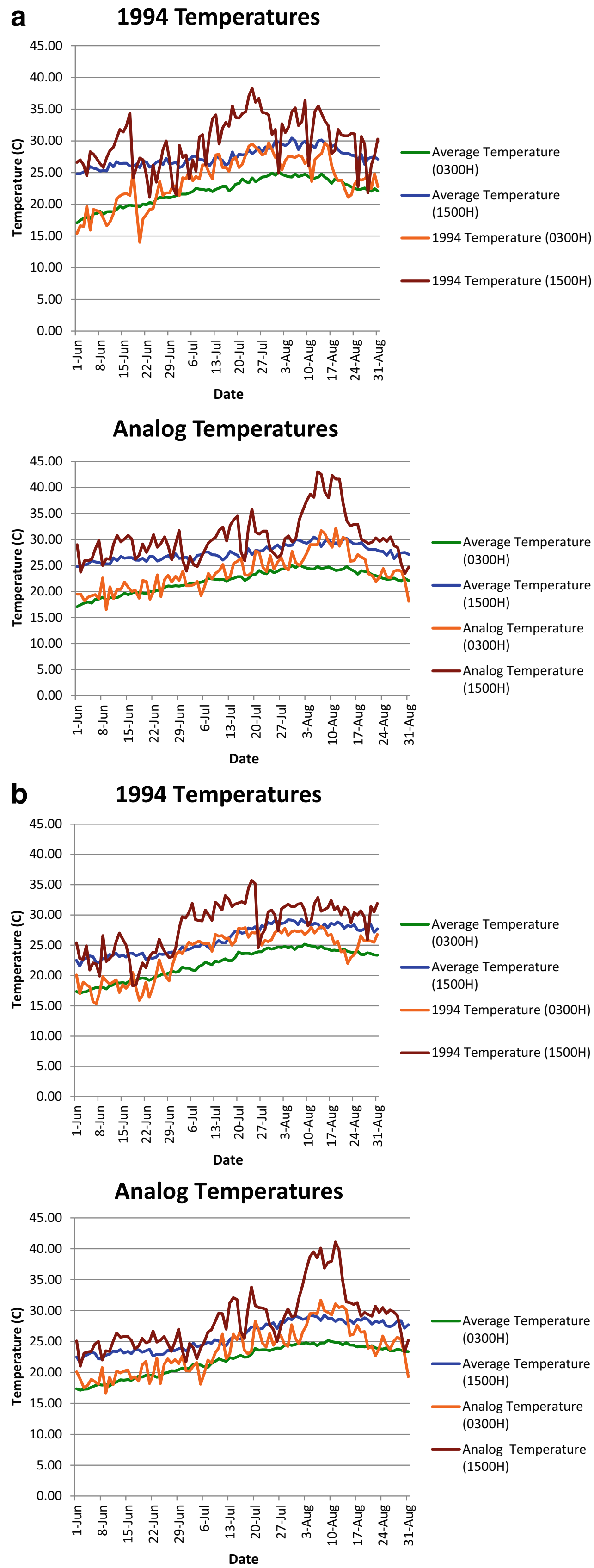

Fig. 4 **a** Analog and 1994 summer temperatures for Seoul. **b** Analog and 1994 summer temperatures for Busan. **c** Analog and 1994 summer temperatures for Daegu

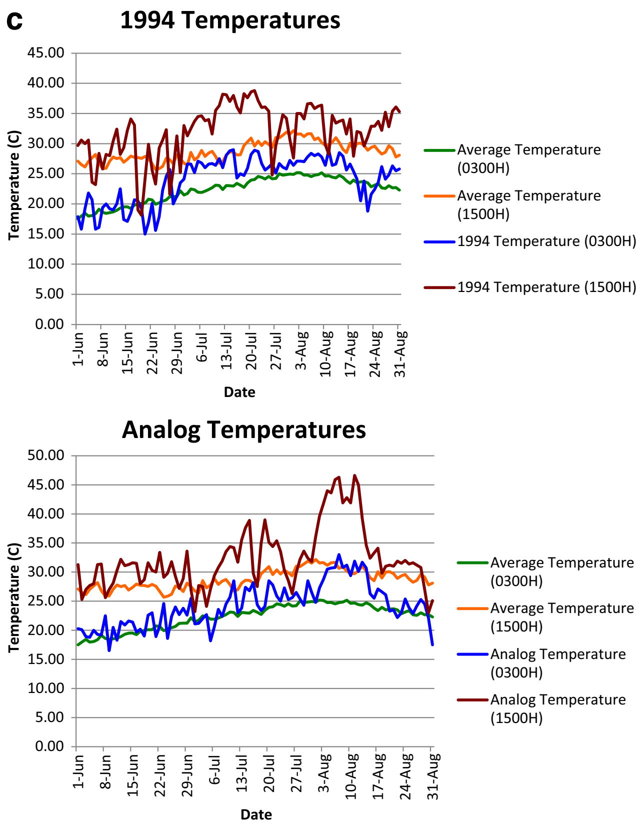

Fig. 4 (continued)

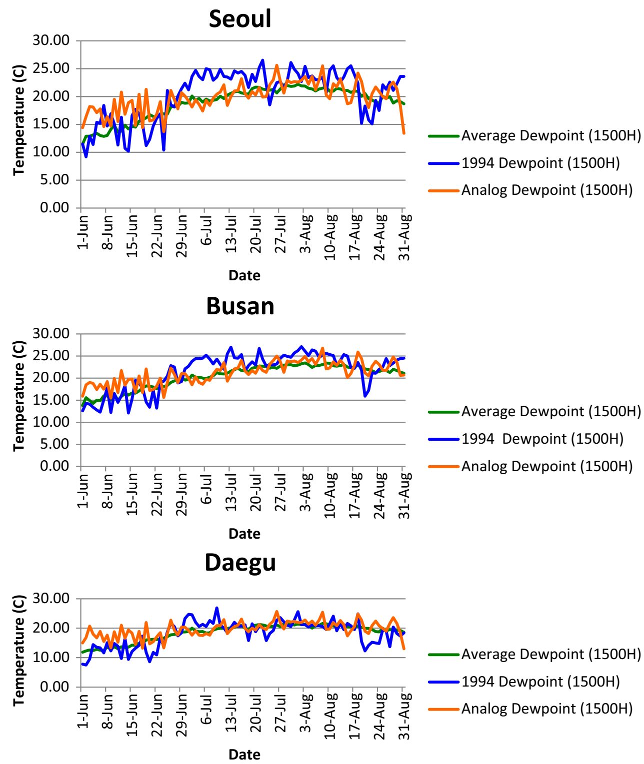

Fig. 5 Daily dew point comparisons for Seoul, Busan, and Daegu for an average summer, the analog summer, and the summer of 1994

less persistent during the analog summer. Busan and Daegu show similar minimum temperature patterns, although Daegu's stands out less.

Nevertheless, the greatest difference between the analog and 1994 summers are found in the magnitude of the dewpoint temperatures (Fig. 5). For Seoul and Busan in particular, and less so for Daegu, afternoon dew point temperatures were considerably higher during the summer of 1994 than the analog summer. The temporal extent of days with exceedingly high dew points approaching and sometimes exceeding 25 °C in Seoul and Busan extends for about a month in Seoul and about 45 days in Busan. Inland Daegu shows more similarity between the analog and 1994 summer, although there is a dramatic 3-week peak in dew point temperatures during late June into mid-July during 1994. Thus, the humidity for the summer of 1994 is generally higher than during the analog summer, creating conditions that are clearly untenable for human health outcomes.

Excess mortality during the extreme heat events

There is no doubt that heat-related mortality is an important health issue in major urban areas of Korea, and particularly hot summers show an increase in vulnerability within the population (Table 5). For example, in Seoul, approximately 70 individuals die of heat-related causes in an average summer, calculated using a "variation from the baseline" procedure discussed above and described in detail in Sheridan and Kalkstein (2004). Based upon Seoul's population, this translates to a rate of 0.7 deaths/100,000. The numbers of heat-related deaths are highly variable from year-to-year, and during some summers, the values can be near 0, while the hottest summers show deaths numbering in the hundreds.

For the analog city scenario, based upon the number of DT and MT+ days that were estimated for that scenario and using the Seoul algorithm in Table 1, the number of heat-related deaths increases more than fourfold, to over 300 (3.14 deaths/100,000). However, during the very hot summer of 1994, the number of heat-related deaths is considerably higher, exceeding 450 (4.66/100,000), representing a greater than sixfold increase over the average summer mortality. Thus, the analog summer ranks second in the number of heat-related deaths as compared to all summers in Seoul between 1991 and 2006. For the other Korean cities, the analog summer ranks second or third in numbers of heat-related deaths, with the exception of Incheon, where it barely outranks 1994. In some of the cities, the disastrous summer of 1994 is associated with a much larger number of such deaths when compared to the analog Paris summer; for Busan, mortality is more than double the analog summer total.

These results are much different than what we discovered for US cities (Kalkstein et al. 2008a), two of which are included in Table 5 for comparative purposes. There are two notable

Table 5 Heat-related mortality in the Korean cities and two US cities for an average summer, the analog summer, and the hottest summer on record

	Busan	Daegu	Daejeon	Gwanju	Incheon	Seoul	New York	Philadelphia
Metro area population (mil.)	3.6	2.53	1.5	1.47	2.64	9.79	9.3	5.1
Av. summer heat related mortality	24	31	9	6	19	69	470	86
Rate/100,000	0.67	1.23	0.6	0.41	0.71	0.7	5.05	1.69
Analog summer heat related mortality	47	80	43	23	133	307	3253	432
Rate/100,000	1.31	3.16	2.87	1.56	5.04	3.14	34.98	8.47
Rank (period 1991–2006)	3	2	2	2	1	2	1	1
Hottest historical heat related mort.	96	87	64	31	130	456	1277	412
Rate/100,000	2.67	3.44	4.27	2.11	4.92	4.66	13.73	8.08
Year of highest summer mort.	1994	1994	1994	1994	1994	1994	1995	1995

Population data for mortality rates are based on the 2010 census in Korea and the 2000 census in the USA

differences between Philadelphia and New York as compared to the Korean cities. First, it is apparent that these US cities are considerably more sensitive to heat-related mortality than those in Korea. Both cities, particularly New York, have much higher average heat-related mortality rates than the Korean cities. The Korean cities show a marked consistency in sensitivity from one location to the next; only Daegu stands out as being somewhat more sensitive, based upon rates per 100,000. Surprisingly, the average heat-related mortality rate is seven times higher in New York than in Seoul and two times higher in Philadelphia. The second notable difference between the Korean and US cities is the comparative impact of the analog summer. In New York, the analog summer produced, by far, the greatest number of heat-related deaths, exceeding the hottest summer in New York (1995) by over 2.5 times. Philadelphia's analog summer scenario also exceeded the hottest summer on record (also 1995). In fact, all five US cities evaluated in the original analog summer research (Kalkstein et al. 2008a) demonstrated greater heat-related mortality totals during the Paris analog summer than during the hottest summer within the period of record (1961–1995). This clearly deviates from the Korean city results, where the Paris analog is clearly less important in terms of heat-related mortality than the excessively hot summer of 1994.

It is also worth nothing that the differences in the heat/mortality responses between the Korean cities and the US cities may also be due in part to societal reasons. For example, there is a much more homogenous general population in the Korean cities, with considerably less racial and ethnic diversity. In addition, there are cross-generational differences between lifestyles in the US and Korea, and it is more common in Korea to find multi-generational households. Thus, many vulnerable individuals in Korea live with their children or other close family members who can help shield them from the health consequences of heat, something that is less common in the USA (Kim ad Joh 2006 et al., 2008; Kim et al. 2009' Son, et al. 2011).

Of course, it should be noted that Paris itself, during the summer of 2003 (our basis for developing the analog summer), showed a heat-related mortality sensitivity that far exceeds anything that has happened in recent memory within Korea or the USA. The 2009 population of Paris is 2.25 million, which is considerably smaller than the enormous population centers of New York and Seoul. During the 2003 heat wave, there were 7 days with deaths exceeding 100 per day; the summer mortality baseline in Paris is less than 50 deaths per day (Vandentorren and Empereur-Bissonnet 2005). Three of these days exceeded 150 deaths, and the highest day topped 320 deaths, or a single-day death rate of 14.2 deaths/100,000, higher than the entire total analog summer period for all cities except New York. The total mortality in Paris during the summer of 2003 was approximately 1100, or almost 49 deaths/100,000, which is 40 % higher than New York's analog summer death rate and over 15 times Seoul's rate, as shown in Table 5.

Discussion

The weather/mortality responses in Korea for the analog summer of 2003 seem to regionalize into three urban area groups based somewhat on climate similarities: the southern cities of Busan and Guanju, the inland cities of Daejeon and Daegu, and the northern coastal cities of Incheon and Seoul. Busan and Guanju showed the smallest heat/mortality responses during the analog summer, with death rates per 100,000 of less than 2. These two cities also responded in the least sensitive fashion during the summer of 1994; the less variable subtropical climate no doubt contributed to this lessened response, which is similar to the diminished heat/mortality responses in southern US cities. The inland cities, which are generally hotter by day and are much more influenced by the DT air mass, showed a somewhat intermediate mortality response during the analog summer. Both exhibited death rates near

3/100,000, about double the mortality response of the two southern cities. In addition, 1994 proved to be even worse than the analog summer by a sizable margin in both Daejeon and Daegu. Finally, the greatest mortality sensitivities in Korea appear to be in the two northern cities. Incheon showed the highest response of all the cities during the analog summer, and both Seoul and Incheon exhibited death rates approaching 5/100,000 during the summer of 1994. Offensive air mass frequencies were no higher in these two cities than in the other Korean locations. One possible explanation is that the increased sensitivity is attributed at least partially to a stronger urban heat island effect in this densely populated portion of the country. There are of course other possible social explanations to account for the differences including, for example, differing age compositions between the cities.

The sizably larger mortality response in the US cities as compared to the Korean cities is difficult to explain and somewhat unexpected. It is possible that social factors in Korean urban areas, such as behavioral adjustment to very hot conditions, urban structure, or even a greater urban support system for elderly and other vulnerable people (as discussed above), explain some of the differences. For example, Kim and Joh (2006) examined potential vulnerabilities of low-income elderly and suggest an awareness to increased vulnerability to EHE events in Seoul. This is also clearly the case in other urban areas where such social factors have been evaluated (Harlan et al. 2006; Shahmohamadi et al. 2011; Perera et al. 2012). Other than social factors, we tend to believe that some of the response difference, in fact, may be attributed to meteorological factors and probably relates to the differences in summer temperature standard deviations. Much of the literature on heat/health relationships strongly suggests that urban areas with summer climates that are highly variable, with short periods of extreme heat imbedded within longer, more benign periods, are much more subject to extreme increases in heat-related mortality (Medina-Ramon and Schwartz 2007; Sheridan, et al. 2009). This partially explains the great difference in response between Paris and US cities when they were directly compared (Kalkstein et al. 2008a) and may logically explain the greater sensitivity in US cities when compared to Korean urban areas. A glance at the intra-seasonal differences in afternoon temperature standard deviation (Fig. 6) shows that the large US cities, such as New York, have a larger variation in temperature than the Korean cities, especially early in the summer season when the population is most vulnerable to heat-related mortality, suggesting that this meteorological explanation might be plausible.

The unexpected surprise in this research relates to the extreme nature of summer, 1994 in the Korean cities, and its impact upon human health. Kyselý and Kim (2009) recognized the 1994 summer anomaly and noted that many lives were lost in Korea, but no one had compared this summer to the unprecedented event that occurred in Paris and much of western Europe in the summer of 2003. The results here clearly demonstrate that 1994 was the more exceptional event in terms of human health outcomes by a considerable margin in Korea. The proportion of oppressively hot air mass days during summer 1994 is more than double than that occurring during the analog summer in several Korean cities (e.g., 40 % of days for the former and 16 % for the latter in Seoul) and considerably higher in all of the cities. The number of deaths that occurred during the summer of 1994 is much higher than the estimated number for the analog summer (e.g., 48 % higher in Seoul; 456 deaths for the former vs. 307 for the latter; Table 5). Thus, unlike the US cities and Paris itself, the summer 2003 analog is not nearly as exceptional for the Korean cities, although it is still among the worst summers within our dataset.

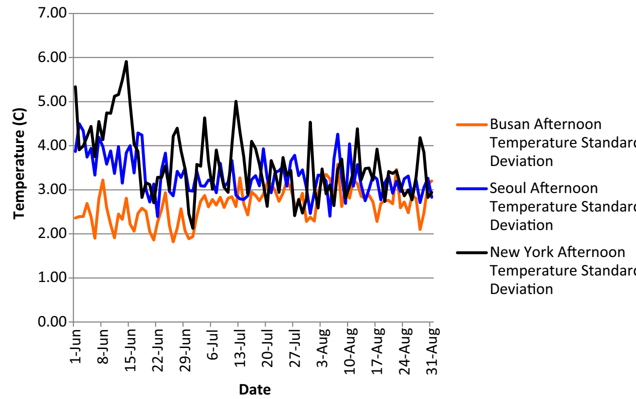

Fig. 6 Summer afternoon standard deviation in Busan, Seoul, and New York

The greater negative health impact of the summer of 1994 in Korean cities is no doubt related to the exceptional persistence of the oppressive air masses during that summer. Although more temperature records are broken during the analog summer than during 1994, there are important breaks in the hot weather found in the former. The continued presence of the MT+ and DT air masses, exceeding a month for some cities and over 45 days for Busan, takes precedence over

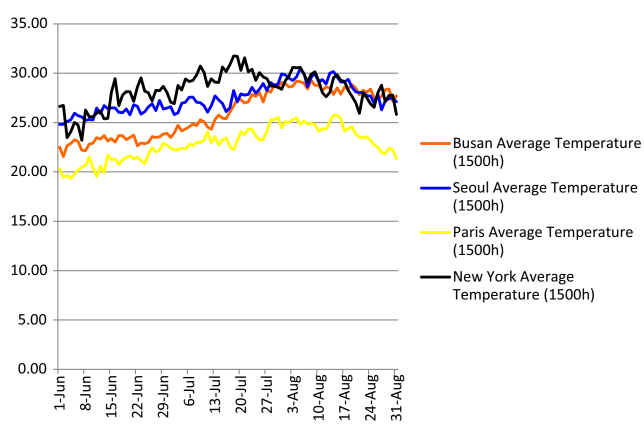

Fig. 7 Average summer afternoon temperatures

record-breaking temperatures. Although the "day in sequence" variable was not a statistically significant predictor for all of the Korean cities, it is clear that this overwhelming number of consecutive offensive days may have had some influence in impacting the mortality signal during the severe summer of 1994. The importance of such persistence in creating a very negative health environment during oppressive summers cannot be minimized, but is often overlooked by the media and health officials who concentrate on the exceedance of temperature records. In this regard, the use of a synoptic approach, such as the SSC, is most important, as raw weather data alone cannot provide sufficient information to categorize days into dangerous air mass categories that are historically associated with elevated heat-related mortality.

As discussed in the original analog heat wave paper (Kalkstein et al. 2008a), some of the differential responses between Paris, the US cities, and the Korean cities may be explained by the development of the analogs themselves (Fig. 7). Average maximum temperatures in the US cities peak in mid-July, while the marine influences in Paris and most of the Korean cities delay this peak until August. Thus, the analog values of temperatures might be skewed toward the earlier part of the summer season for the US cities as opposed to Paris and the Korean cities. However, it therefore appears that the comparisons between Paris and the Korean cities are more robust than between Paris and the US cities, which represents a positive aspect for this particular evaluation centering on Korea. Conversely, the Korean cities generally demonstrate a smaller daily temperature standard deviation. Since our analog summers were based upon standard deviations from the mean morning and afternoon temperatures, this might dampen the Korean temperature values, somewhat rendering the analog 2003 summer a bit less remarkable in Korea.

Conclusions

A number of important issues were raised in this research:

- The number of offensive air mass days in the Korean cities for the analog summer was generally over double those during an average summer. For most of the cities, the DT air mass showed a larger increase than the MT+ air mass.
- The oppressively hot summer of 1994 proved to be even more extreme than the analog summer for all the Korean cities based upon the presence of offensive air mass days. In the majority of cities, the MT+ air mass was more important than DT during the summer of 1994.
- Although more maximum and high minimum temperature records were broken in the Korean cities during the analog summer, dew point values were considerably higher for the summer of 1994 than for the analog summer in the majority of the Korean cities. In addition, the persistence of the offensive air masses, as defined by long consecutive or near-consecutive day runs, was considerably greater for the summer of 1994.
- The Korean cities appear less sensitive to heat-related mortality problems during very hot summers than do large eastern and Midwestern US cities. Nevertheless, the two large northern cities, Seoul and Incheon, appear more sensitive to heat/health mortality problems than the other Korean cities we evaluated. It is possible that an urban heat island effect may be partially responsible in this densely populated region. The southern cities, with a more equitable summer climate, seem least sensitive.
- It is difficult to ascertain why the Korean cities are less sensitive to heat/mortality problems than the large U.S. cities. Issues like urban structural differences and better family support systems for vulnerable people may play a role. In addition, most of the Korean cities show a lesser variation in summer temperatures than do the US cities or Paris (which has the largest summer temperature variation). In our previous studies, we have shown a strong direct relationship between variation in summer temperatures and mortality sensitivity to the heat.
- The extreme nature of the summer of 1994 in Korea cannot be overstated. We were most surprised to see that, unlike the US cities, the Paris analog summer would not be as oppressive as what was experienced in 1994. Thus, in terms of creating a negative health outcome during very hot summers, the persistence of oppressive air mass days that occurred during 1994 apparently trumps the breaking of daily temperature records, which shows prevalence during the analog summer.

The development of an analog summer can provide benefits for future applied climatological research. For example, it is possible to consider the analog as a surrogate of what the local summer weather might look like if the climate changes as many expect. Hov, et al. (2013) Schär (2004), and many others have examined the 2003 EHE and illustrated how events like this one are likely to become more frequent in the future due to a projected climate change. Thus, those not predisposed to using climate change modeling and emissions scenario techniques might find the analog summer approach more efficient. In addition, the comparison of the analog summer to the hottest summer within the historical record provides a perspective of how unusual and stressful an event like the Paris 2003 summer could be. In the case of this evaluation, it was most interesting to note that we determined, on a comparative basis, that the extremely hot summer of 1994 in Korea was even worse from a health standpoint than what might be expected from the oppressive analog event; this was a purely unexpected result.

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