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ORIGINAL PAPER

Effects of heat waves on daily excess mortality in 14 Korean cities during the past 20 years (1991–2010): an application of the spatial synoptic classification approach

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Abstract The aims of this study are to explore the "offensive" summer weather types classified under the spatial synoptic classification (SSC) system and to evaluate their impacts on excess mortality in 14 Korean cities. All-cause deaths per day for the entire population were examined over the summer months (May–September) of 1991–2010. Daily deaths were standardized to account for long-term trends of subcycles (annual, seasonal, and weekly) at the mid-latitudes. In addition, a mortality prediction model was constructed through multiple stepwise regression to develop a heat–health warning system based on synoptic climatology. The result showed that dry tropical (DT) days during early summer caused excess mortality due to non-acclimatization by inhabitants, and moist tropical (MT) plus and double plus resulted in greater spikes of excess mortality due to extremely hot and humid conditions. Among the 14 Korean cities, highly excess mortality for the elderly was observed in Incheon (23.2%, 95%CI 5.6), Seoul (15.8%, 95%CI 2.6), and Jeonju (15.8%, 95%CI 4.6). No time lag effect was observed, and excess mortality gradually increased with time and hot weather simultaneously. The model showed weak performance as its predictions were underestimated for the validation period (2011–2015). Nevertheless, the results clearly revealed the efficiency of relative and multiple-variable approaches better than absolute and single-variable approaches. The results indicate the potential of the SSC as a suitable system for investigating heat vulnerability in South Korea, where hot summers could be a significant risk factor.

Keywords Spatial synoptic classification · Excess mortality · Heat–health warning system · Korea

Introduction

Summer heat waves are significant risk factor associated with heat-related mortality and morbidity in many developing and developed countries (Honda et al. 1998; Kalkstein 1991; Kim et al. 2006a; Koppe and Jendritzky 2005; Kysely 2004; Matzarakis et al. 2011; McMichael et al. 2003; Tan et al. 2007). Excessive heat events (EHEs) cause more deaths than any other severe weather phenomena (typhoons, floods, lightning, etc.) in mid-latitudinal regions (Kalkstein et al. 2008; Sheridan and Kalkstein 2004). In Korea, 3384 heat-related deaths were reported during the summer of 1994 (Kysely and Kim 2009). In same period, heat strokes accounted for 67% of mortality in Japan (Nakai et al. 1999). In 1995, Chicago, USA, observed temperatures reached 41 °C that caused the loss of 521 lives (Klinenberg 2002; Whitman et al. 1997). The 2003 European heat wave caused over 30,000 excess deaths (Botelho et al. 2004; Diaz et al. 2006; Grynszpan 2004; Trigo et al. 2005; WHO 2004). In addition, the Russian heat wave of 2010 caused 11,000 excess deaths among only the elderly (Shaposhnikov et al. 2014). Global

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climate change simulation models have predicted future heat waves with increasing intensity, duration, and higher frequency (Meehl and Tebaldi 2004).

Most studies analyzing heat vulnerability in Korea have focused on single- or dual-weather factors (Kim et al. 2006a, 2007a; 2009a; Kysely and Kim 2009; Kysely et al. 2009; Lee et al. 2007; Lerchl 1998). Moreover, the national heat warning system for the public provided by the Korea Meteorological Administration (KMA) is based on daily maximum temperature as a threshold (33 °C for advisory, 35 °C for warning). The criterion was constructed through the absolute approach only for Seoul, although heterogeneous characteristics of the heat–health association in Korea have been already proven (Kim et al. 2006a; 2009b; Lee et al. 2010).

Many efforts have been made globally to examine the effects of "weather conditions" on daily mortality. McGregor (1999) analyzed synoptic climatology and IHD (ischemic heart disease) and reported significant differences across weather types and mortality. Kassomenos et al. (2007) analyzed synoptic climatology and mortality in Athens and found that southerly flow types significantly affected increasing winter and summer mortalities (9 and 7%). In particular, Kim et al. (2007b) and Kysely et al. (2009) conducted synoptic analyses based on the temporal synoptic index (TSI) and mortality in South Korea. They applied hierarchical (average linkage) and non-hierarchical (k-means) clustering and suggested the significance of synoptic approaches in analyzing the heat–health association.

As an "objective" classification scheme for identifying weather types (usually referred to as "air masses"), the spatial synoptic classification (SSC) (Sheridan 2002) has become a widely used tool in biometeorological studies (Hondula et al. 2014; Kalkstein 1991). The major concept of this "synoptic" approach is that the human physiology responds to the whole "umbrella of air," and not just a single-weather factor or pressure patterns (Kalkstein et al. 1996; Kassomenos et al. 2007; Kysely et al. 2009; Sheridan 2000). The SSC diagnoses meteorological situation based on several decades of climate data for any location. Hence, as an important relative approach, it is well suited for analyzing hot and cold weathers and their effects on human health (Hondula et al. 2014). It has gained recognition in the IPCC-FAR (Chapter 14 of Working Group II) (Field et al. 2007), and it has been developed for approximately 400 stations spanning the USA, Canada, Europe, and Asia (Hondula et al. 2014; Lee et al. 2010; Sheridan 2002; Tan et al. 2004).

In this study, we investigated the effects of weather types on mortality through the synoptic approach using the SSC. The objective was to quantify the relative effects of the days of "offensive" weather types on human health in 14 Korean cities. We estimated net increases of excess mortality for each city, because the "absolute approach" or "single temperature" values may not be an efficient measure of weather severity. Furthermore, we established an operational heat–health warning system (HHWS) in real time using 48-h numerical weather prediction (NWP) model output of the KMA. The efficiency of HHWS was proved by several studies (Ebi et al. 2004; Sheridan and Kalkstein 2004; Tan et al. 2004).

This paper is organized into four parts. The "Data and methods" section presents the climate and health data as well as the methodology used in this study. The main results of variation in mortality with each weather types and verification of the mortality prediction model are described and discussed in the "Results" section. The establishment of the operational HHWS is also introduced briefly. Finally, several conclusions are drawn in the "Conclusion" section.

Data and methods

Climate data

The geographical location of South Korea and the 14 cities considered under the SSC are shown in Fig. 1. The total population of South Korea was 48,580,593 in 2010. The Korean Peninsula lies in a mild climate zone, with a mixture of continental and maritime influences leading to relatively cold winters and warm summers driven by the East Asian monsoon system (Kysely and Kim 2009). Hot summer usually starts with the expansion of a North Pacific High system in late July and is closely associated with the end of the rainy period (Changma) (Yihui and Chan 2005).

Table 1 lists 17 Korean SSC networks and their climate records (Hondula et al. 2014). Climate data were obtained from the National Climate Data Service System (NCDSS) of the KMA. All of the meteorological data has passed by quality control procedure (physical limit test, step test, internal consistency test, etc.) based on the WMO standard. For a single synoptic observatory, the following climate factors were used per day (Sheridan 2002): temperature; dew point depression (temperature-dew point); diurnal temperature range; diurnal dew point range all at 03, 09, 15, and 21 LST (local standard time), as well as averages of mean sea level pressure; and mean cloud cover (03, 09, 15, and 21 LST).

Six weather types were classified under the SSC, and each day was considered in this study has been classified as one of them. The moist tropical (MT) subsets were designed to classify more severe days according to apparent temperature (Eq. 1) of the "seed day" (Steadman 1979a, b; Kalkstein 1991). Ta is temperature and Td is dew point.

$$\mathrm{AT} = -2.653 + 0.994Ta + 0.0153\mathrm{Td}^2 \qquad (1)$$

This study focused on the health effects of offensive weather types (DT, MT+, and MT++) classified under the SSC (Sheridan 2002; Tan et al. 2004), after considering all the weather types.

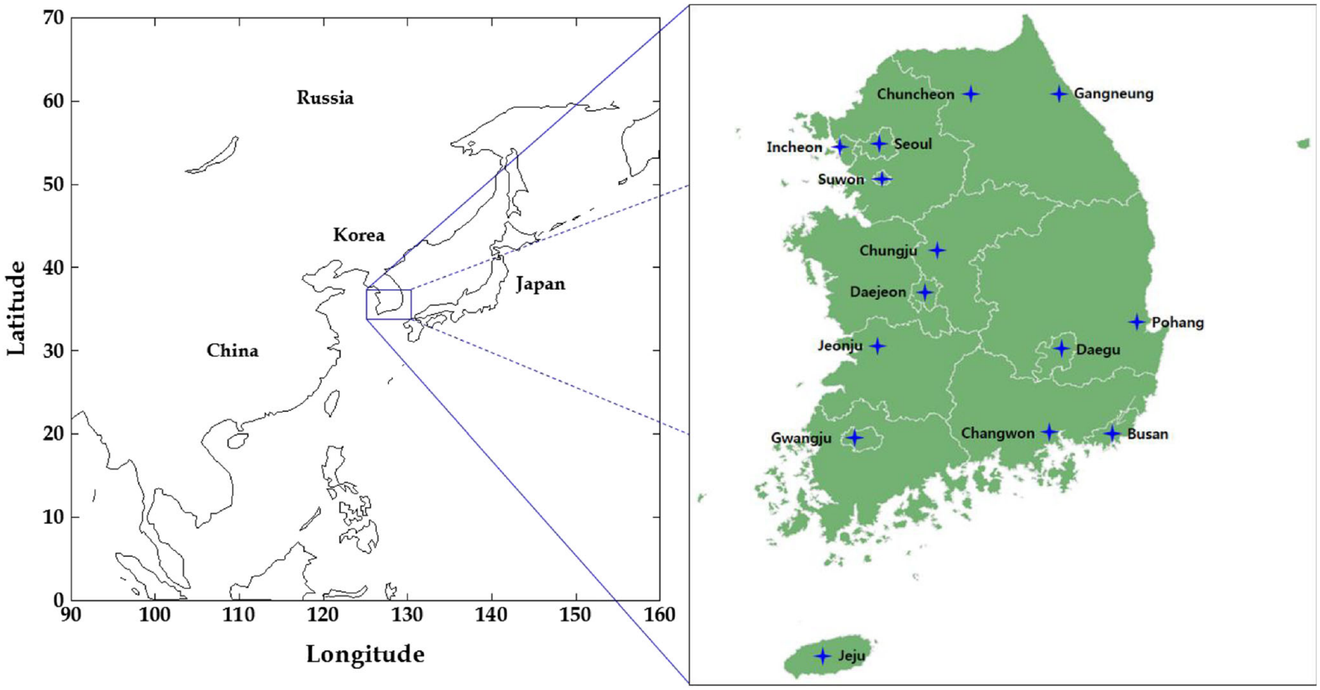

Fig. 1 Geographical location of South Korea. Symbols indicate the 14 Korean cities studied in this paper

Table 1 17 SSC networks in Korea

No.	Location	Population (in 2010)	Position of synoptic observatory			SSC period				
			Latitude (°C)	Longitude (°C)	Altitude (m)	Start	End	Year	Days	Missing
1	CAS (Cheonan)	574,623	36.7796217	127.1212681	21.3	19860101	20161231	31	11,322/11,322	0 day, 100%
2	CHN (Jeonju)	649,728	35.821472	127.154953	61	19650101	20161231	52	18,990/18,991	1 day, 99.99%
3	CJJ (Daejeon)	1,501,859	36.3690367	127.3742636	62.6	19690101	20161231	48	17,531/17,531	0 day, 100%
4	CJU (Jeju)	401,192	33.514194	126.529678	19.9	19650101	20161231	52	18,982/18,987	5 days, 99.97%
5	CWS (Changwon)	1,058,021	35.1670928	128.5750828	36.8	19850701	20161231	32	11,506/11,506	0 day, 100%
6	ICN (Incheon)	2,662,509	37.4776	126.6249	68.95	19650101	20161231	52	18,988/18,990	2 days, 99.99%
7	KAG (Gangneung)	218,471	37.751434	128.890976	26.1	19650101	20161231	52	18,986/18,989	3 days, 99.98%
8	KNY (Chuncheon)	276,232	37.902637	127.73571	76.8	19660101	20161231	51	18,627/18,627	0 day, 100%
9	KTU (Chungju)	666,924	36.6363322	127.4428019	56.4	19670101	20161231	50	18,260/18,261	1 day, 99.99%
10	KWJ (Gwangju)	1,475,745	35.172848	126.891563	74.5	19650101	20161231	52	18,991/18,992	1 day, 99.99%
11	PHS (Pohang)	511,390	36.032684	129.379669	1.3	19650101	20161231	52	18,992/18,992	0 day, 100%
12	PUS (Busan)	3,414,950	35.104683	129.032013	69.2	19650101	20161231	52	18,992/18,992	0 day, 100%
13	SEL (Seoul)	9,794,304	37.5714111	126.9657917	85.5	19650101	20161231	52	18,984/18,988	4 days, 99.98%
14	SWU (Suwon)	1,071,913	37.2700253	126.9876392	34.5	19650201	20161231	52	18,833/18,897	64 days, 99.66%
15	TAE (Daegu)	2,446,418	35.885155	128.619003	57.3	19650101	20161231	52	18,988/18,990	2 days, 99.99%
16	ULL (Ulreungdo)	7764	37.5	130.9167	220	19650101	20161231	52	18,892/18,942	50 days, 99.74%
17	USN (Ulsan)	1,082,567	35.560143	129.320251	34.6	19650101	20161231	52	18,990/18,991	1 day, 99.99%

Health data

Daily observed deaths in the 14 Korean cities during 1991–2015 were obtained from Statistics Korea (data during 2011–2015 was used only for model validation). And it was divided into two age groups: all ages under 65 and elderly over 65. To consider the entire population first, we did not classify detailed causes of death in this study. To remove long-term, annual, seasonal, and weekly cycles of mortality, a direct standardization was applied. For instance, an annual summer (May–September) mortality trend line was constructed based on the mean daily mortality for each summer. An annual regression line has constructed for mean daily mortality for each year, and the excess mortality was then expressed as a deviation of this temporal baseline value (Kalkstein 1991; Tan et al. 2004).

We computed trends of annual, seasonal, and weekly weighting factors (WF) in mortality. Employing the WF, baseline number of deaths (Mb(y, d)) for the year (y) ($y = 1991, \ldots, 2010$) and the day (d) ($d = 1, \ldots, 365$) was set according to the following equation (Kysely 2004).

$$\mathrm{Mb}(y, d) = \mathrm{Mo} \times \mathrm{Mo(d)} \times W(y, d) \times Y(y) \quad (2)$$

Mo(d) denotes the mean mortality number of deaths on day (d) in a year (the mean annual cycle was smoothed by 7-day running means). $W(y, d)$ is a WF for the observed weekly cycle of mortality. $Y(y)$ is a WF for the observed year-to-year changes in mortality. More details on the method are available in Guest et al. (1999), Lee et al. (2007), Smoyer et al. (2000), and Whitman et al. (1997).

Once each day has been classified into a weather type associated with elevated mortality, a multiple stepwise regression was run to examine factors of weather types responsible for increasing positive excess mortality. In addition, we considered non-weather variables (days in sequence and time of season), to explore the temporal effects on daily mortality.

Results

The highest mortality peak was observed in July 1994, during a record-breaking heat wave occurred. In 1994, estimated excess deaths in Seoul were 584 (all age) and 431 (elderly), accounting for 74% of elderly deaths for the entire year. These values indicate a 16% net increase in elderly mortality. However, no distinct episodes were observed during the summer of other years.

During this period, East Asian countries suffered severe drought, which prolonged to August. Many researches have already determined the cause of the Korean heat wave in 1994. Park and Shubert (1997) reported abnormal development of the Eurasian wave with the Tibetan anticyclone causing early development of the East Asian high. Kim et al. (2006b) suggested that strong anticyclonic circulation caused downward air motion with adiabatic heating, and the dried air column subsequently reduced the release of latent heat and precipitation.

Figure 2 presents significant severity in offensive weather types, and elderly susceptibility corresponding to wide variations in empty columns. In general, DT occurs during early summer (May–June) in the Korean Peninsula. During this season, 4% (95%CI 2.3) and 4.6% (95%CI 3.1) excess mortality of all ages and elderly occurred. The most popular heat stress index is AT15, and it had lower severity during DT than MT. Correspondingly, excess mortality had higher severity during DT. The result reveals the importance of the effects of the phase (timing) of seasonality on public health, and multiple effects of weather parameters (McGregor et al. 2004).

Usually, MT days become more frequent after Changma, under the influence of the North Pacific (Yihui and Chan 2005). On MT+ days, excess mortalities of 8% (95%CI 3) and 11% (95%CI 4) were recorded for all ages and elderlies, respectively. Surprisingly, on MT++ days, excess mortalities of 20% (95%CI 8.2) and 32% (95%CI 14.2) were recorded for all ages and elderlies, respectively. These results reveal that Korean residents are more susceptible to MT+ and MT++ days than DT. Furthermore, the total counts of MT+ and MT++ days were less than that of DT days, which were 88 and 157, respectively. Hence, the positive summer excess deaths could be successfully analyzed with the synoptic climatology approach, and the results agreed with current results of Korean studies (Greene et al. 2016; Kalkstein et al. 2008; Lee et al. 2010).

Figure 3 describes the regional rank of the results. For all ages (Fig. 3a), the highest mortality was observed for Incheon (14.6%, 95%CI 4.5), Jeonju (13.3%, 95%CI 1.5), Seoul (10.5%, 95%CI 1.9), and Jeju (10.5%, 95%CI 4.8). For the elderly (Fig. 3b), Incheon (23.2%, 95%CI 5.6), Seoul (15.8%, 95%CI 2.6), Jeonju (15.8%, 95%CI 4.6), and Chungju (10.7%, 95%CI 5.9) showed higher vulnerability.

Seoul is a historical capital and dense large city hosting one-fifth of the Korean population. The neighboring city Incheon is the third biggest metropolitan city in South Korea with the least frequency of offensive weather types. Hence, specific heat vulnerability in dense mega cities were determined, and acclimatization was found to be a key factor affecting heat vulnerability in Korea (Kim et al. 2006a, 2009b; Lee et al. 2007). Besides, Daegu is an inland city well known for stressful summer weather in Korea. In this study, 22% of summer days were classified as offensive days, with 4.3 and 7.3% excess mortality for all ages and elderly, respectively. Nevertheless, Daegu ranked 7th regarding all ages and 9th regarding the elderly. For Jeonju and Jeju, this is the first study to present abnormal levels of heat-related deaths. Previous studies have suggested similar ranks using daily maximum

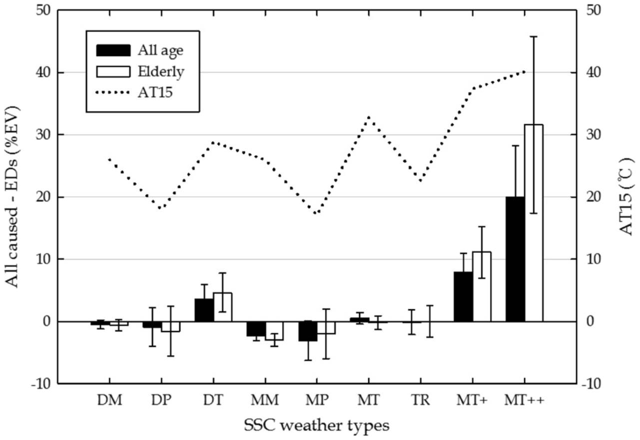

Fig. 2 Offensive weather (DT, MT+, MT++) and excess mortality (%) in Seoul, Korea (May–September, 1991–2009)

temperature or AT but they considered only six metropolitan cities in Korea (Kim et al. 2006a, 2009b). Cheonan exhibited the lowest heat susceptibility. We believe that the low susceptibility is a result of appropriate social adaptation or preparedness of the residents to heat. Furthermore, Cheonan was included as a city in this study as a population size, but thermal environment characteristics could be divided as a rural area.

In particular, Jeju island is located at the lowest latitude in Korea, and mean night temperature is 25.9 °C, indicating tropical nights. However, the afternoon temperature has the lowest value (30.6 °C) among other inland cities. Nevertheless, high excess mortalities of 10.5% (4th) for all ages and 8.2% (7th) for elderlies were observed. This high mortality could be attributed to tropical night temperature regardless of age, although Jeju is considered to have the most comfortable climate in Korea (Kim et al. 2009b). Vulnerability of the elderly was observed in almost all cities, except for Cheonan, Busan, Daejeon, and Jeju. For these cities, more efficient measures are required for larger vulnerable groups, particularly the occupational health sector.

Figure 4 presents the effects of the persistence of offensive summer days on human health. According to days in sequence (DIS) of offensive weather, excess mortality linearly increased. Premature excess mortality attributable to heat wave was observed on the 1st day, and "harvesting effect" or "mortality displacement" (deriving less sample size on next day) was observed on the 2nd day. Sample of days was gradually reduced with increasing duration. Nevertheless, the same trends were observed in a previous study using the SSC approach for seven Korean locales (Lee et al. 2010).

We explored the distribution of excess mortality by SSC types in Korea; the SSC successfully captured significant heat susceptibility for each locale based on relative aspects, considering multiple weather factors.

Discussion

Predetermining parameters of offensive weather days (DT, MT+, MT++), which are most closely linked to elevated mortality, is of utmost importance. Independent variable for regression was selected by stepwise regression. The parameters basically include meteorological factors (temperature, dew point, AT of morning and afternoon) and non-meteorological factors (season of the offensive weather, TOS, and number of consecutive days (DIS)). Table 2 presents the constants and coefficients of the prediction algorithm. The suggested excess mortality algorithm for Seoul is as follows:

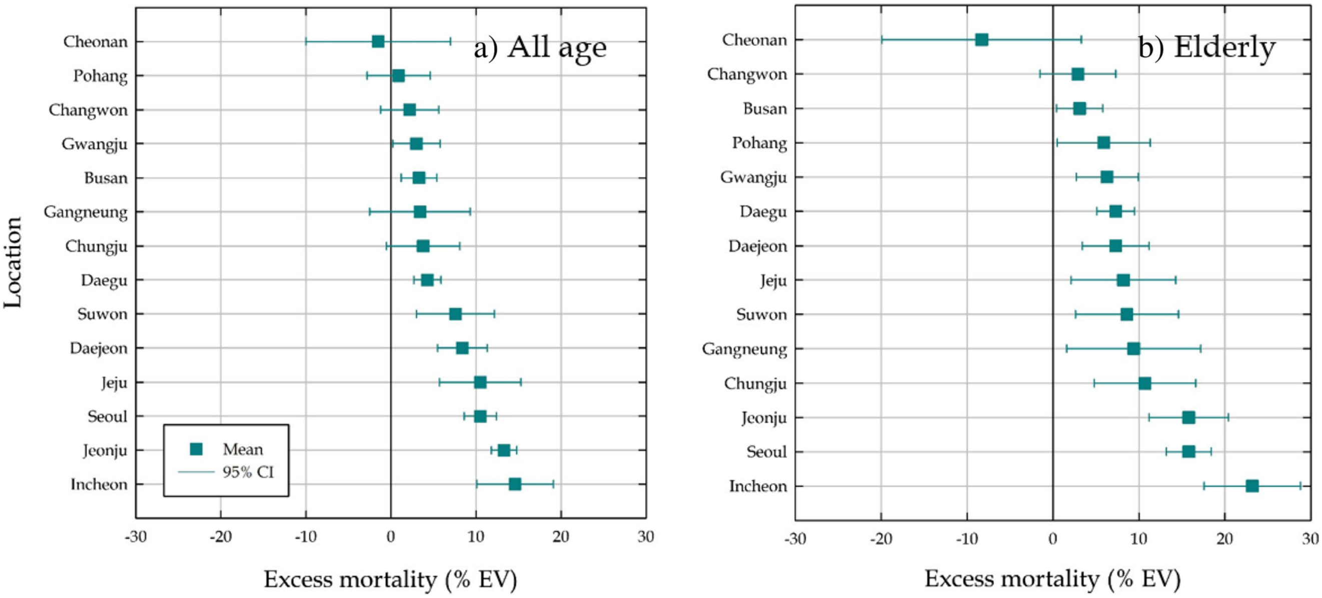

Fig. 3 Offensive weather (DT, MT+, MT++) and excess mortality (%) for all ages (**a**) and elderlies (**b**) during summer (May–September) in 14 Korean cities (1991–2009)

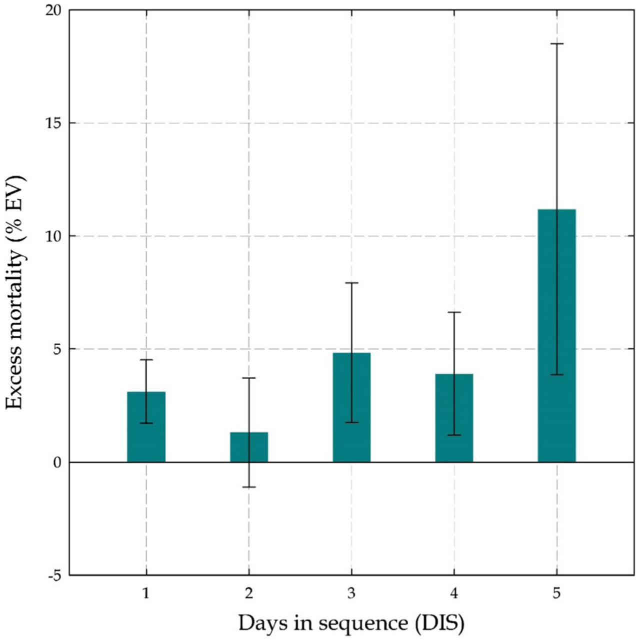

Fig. 4 Effects of the persistence of offensive weather in summer on excess mortality in 14 Korean cities (1991–2009)

$$\begin{aligned} \mathit{Excess\ mortality} &= -51.7-0.75(\mathrm{TD15}) \\ &\quad +5.12(\mathrm{DIS})-0.07(\mathrm{TOS}) \\ &\quad +2.01(\mathrm{AT15}). \end{aligned} \tag{3}$$

For instance, a 27.3% increase in excess mortality could be estimated for 32 °C of TD15, 4th day of DIS, 45th day of TOS (June 15), and 42 °C of AT15. To evaluate model performance, we started from the conservative p value of 0.05, and the significance of the model finally reached 0.15 for satisfying every locale. In the investigation of statistics in epidemiology, the significance level can be flexibly designated from 95 to 80% a stepwise manner (Ghaemi 2016). Full models (all possible regressions) cannot be realized; therefore, the primary purpose of the stepwise regression is to determine an appropriate formula for the predictor that best describes dependent variables.

And we simulated frequencies for advisory and warning signals, which are based on climate data. We tailored the system to produce less warning issues in a year to minimize false positives. For validation, the model was run using observed weather data during 2011–2015. The prediction model can be evaluated using four general methods: map (spatial distribution), scatter diagram, time series, and validation score. In this study, the linearity in statistical prediction was analyzed on the basis of scatter diagrams. Figure 5 presents validation results for Seoul during the recent 5 years (2011–2015), for which mortality data are available. As shown in the scatter plot, the model underestimated positive excess mortality. Although the model predicted 18% excess mortality, the observed excess mortality exceeded 27% for 3 days and 45% for 1 day. This result suggests the model was developed with conservative aspects with trying to get lowest p value. In addition, the results suggest spikes in heat-related mortality have increased recently. That means heat vulnerability due to heatwaves has increased significantly in recent years. Therefore, we need to keep tailoring the prediction algorithm with using recent dataset of weather and health.

Table 2 Constants and coefficients for independent variables for each city generated through stepwise multiple linear regression

No.	Location	Intercept	Independent variable								Dummy		
			T03	TD03	T15	TD15	DIS	TOS	AT03	AT15	DT	MT+	MT++
1	Cheonan	−29.64	−11.04**		3.38				7.44**				−69.5
2	Jeonju	−54.2			2.24**			−0.15**					
3	Daejeon	11.23						−0.04			−6.3		
4	Jeju	80.22	2.03		−4.02**								
5	Changwon*	20.12					−2.67**	−0.11					
6	Incheon	−4.15					8.87***						
7	Gangneung*	0.70					3.33						
8	Chungju	11.84						−0.08					
9	Gwangju	−22.27			0.82								
10	Pohang	−30.45	1.07								17.07		
11	Busan	−14.13								0.49			
12	Seoul*	−51.70				−0.75	5.12***	−0.07		2.04**			
13	Suwon	−4.46					3.48						
14	Daegu*	7.78			−4.88	−1.43		−0.1**		5.5**		−11.83**	

* denotes prediction model constructed for elderlies, ** p value < 0.05, and *** p value < 0.0001)

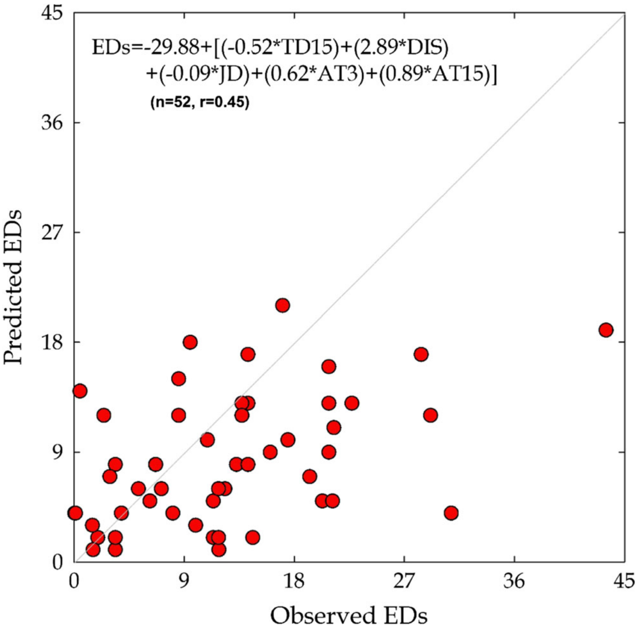

Fig. 5 A validation between the observed and forecasted excess deaths. A coefficient of correlation of about 0.45 was obtained according to a forecast equation of excess deaths using the number of consecutive days, seasonal timing, and the apparent temperature value in Seoul (2011–2015)

There are many confounding factors that can exacerbate effectiveness of the system. Such factors include timing, severity, duration, night-time condition, socio-economic status, heat acclimatization, prevalence of chronic disease on personal levels, and urban heat islands, especially on mega cities. Inclusion of all these factors in one model may not be possible because of the limited availability of data and complexity of analytical techniques (Toloo et al. 2013). Nevertheless, evidence suggests that the implementation of an HHWS is associated with lower mortality, and the costs of running such systems are estimated at US$210,000 compared to the US$468 million benefits of saving 117 lives (Ebi et al. 2004). However, further researches are required to assess the impact of implementing warning system on morbidity in Korea.

Conclusion

It is obvious that thermal comfort has multiple confounders, rather than a single predictor. Therefore, the synoptic climatological approach must be applied to diagnosing heat waves during the onset of a season, and help people acclimatize to changing climates in locations where the heat–health association cannot be determined by a single factor. Hence, we implemented the SSC and HHWS in Korean cities (Hondula et al. 2014; Lee et al. 2010; Sheridan 2002; Sheridan and Kalkstein 2004) and estimated excess mortality based on oppressive weather types specified in the SSC.

The heat–health effects varied according to the locale because of regional variations in susceptibility of the people to the same weather condition in Korea. In contrast to using a single index, which does not provide clear associations, heat-related deaths could be successfully estimated using the SSC. Incheon exhibited the highest vulnerability (14.6%, 95%CI 4.5), followed by Jeonju (13.3%, 95%CI 1.5), and Seoul (10.5%, 95%CI 1.9). DT days during early summer resulted in excess mortality because inhabitants were not acclimatized; MT+ and MT++ caused stronger mortality spikes than DT due to persistent hot and humid weather. Susceptibility of the elderly was observed for ten cities, except for Cheonan, Busan, Daejeon, and Jeju.

Excess mortality significantly increased with days of oppressive weather, despite the decrease in sample size. Excess mortality increased from the 1st day (3%) to the 5th day (10%) of oppressive weather. The results are consistent with those of the study using same approach for seven Korean cities (Lee et al. 2010). A linear increasing trend was found between heat susceptibility and DIS, regardless of temporal or regional acclimatization. In other words, consecutive hot synoptic conditions could have extreme (or epidemic) effects on human health.

In addition, excess mortality showed a linear decreasing from the hottest day when the “time lag effect” was considered from the first day of offensive weather. The highest mortality (total of 21 excess deaths) was estimated on the 0 lagged day, and at least ten deaths were prolonged until the 4 lagged days in Korea. Premature deaths were observed on 1st day and “mortality displacement” on the 2nd day with less sample size, which was gradually reduced through time.

This study has revealed the association between summer weather types and mortality and pioneered a research theme implementing the SSC in Korean cities. The SSC provides an objective weather type classification scheme considering relative hot summer weather condition for each locale. A prediction model was constructed through stepwise regression. We verified the performance of the SSC and found that its prediction ability for excess mortality was superior to the current absolute system. The spatial scale of association between a single index and mortality, which has not been well defined, still requires further consideration. For instance, Daegu (inland city) and Busan (coastal city) showed the least correlation between single temperature and mortality. On the other hand, estimated heat-related mortality could be successfully analyzed with more statistical significance in Daegu (4.3%) and Busan (3.3%). These results reveal that the HHWS based on the SSC can actually contribute to mitigating the health effect of hot weather, although improved personal recognition and response, execution of nationalized warning system, and environmental health policy are also critical factors. The recent dense urbanization and obvious increasing trend of intensity and frequency of heat waves have become concerning issues regarding human thermal comfort. In addition, summer heat waves are a significant risk factor for human health, particularly for vulnerable people in Korea. Therefore, improvements in the HHWS are required.

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