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Seasonal Variations in Temperature–Suicide Associations across South Korea

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ABSTRACT

South Korea has among the highest rates of suicide in the world, and previous research suggests that suicide frequency increases with anomalously high temperatures, possibly as a result of increased sunshine. However, it is unclear whether this temperature–suicide association exists throughout the entire year. Using distributed lag nonlinear modeling, which effectively controls for nonlinear and delayed effects, we examine temperature–suicide associations for both a warm season (April–September) and a cool season (October–March) for three cities across South Korea: Seoul, Daegu, and Busan. We find consistent, statistically significant, mostly linear relationships between relative risk of suicide and daily temperature in the cool season but few associations in the warm season. This seasonal signal of statistically significant temperature–suicide associations only in the cool season exists among all age segments, but especially for those 35 and older, along with both males and females. We further use distributed lag nonlinear modeling to examine cloud cover–suicide associations and find few significant relationships. This result suggests that that high daily temperatures in the cool season, and not exposure to sun, are responsible for the strong temperature–suicide associations found in South Korea.

1. Introduction

Suicide is the fourth-leading cause of death in South Korea, which has among the highest rates of suicide in the world (B. Kim et al. 2015). Further, the prevalence of suicide in South Korea has risen dramatically in recent years, with suicide rates increasing by approximately 400% since the early 1990s (J. W. Kim et al. 2017). The observed increase has been especially pronounced among males and the elderly (Jeon et al. 2016), although explanations behind the rise in suicides vary and include changes in economic conditions and employment (Chan et al. 2014; Min et al. 2015), the prevalence and media coverage of celebrity suicide (Lee et al. 2014; Kim and Woo 2016; Park et al. 2016), improvements in data classification of suicide (Chan et al. 2015), and beyond (K. Kim et al. 2017).

Like many other midlatitude locations, South Korea displays a seasonal pattern in suicide, with suicides peaking in the late spring and early summer (Kim et al. 2011;

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TABLE 1. Average maximum temperature (MaxT; °C), minimum temperature (MinT; °C), and cloud cover (in tenths) for Seoul, Daegu, and Busan across the entire year, the warm season (April–September), and the cool season (October–March). Standard deviations are given in parentheses.

	Seoul			Daegu			Busan		
	Annual avg	Warm season	Cool season	Annual avg	Warm season	Cool season	Annual avg	Warm season	Cool season
MaxT	17.41 (10.65)	25.76 (5.26)	9.04 (7.71)	19.73 (9.65)	27.23 (5.20)	12.20 (6.82)	19.16 (7.78)	24.74 (4.61)	13.56 (6.11)
MinT	9.10 (10.49)	17.39 (5.66)	0.78 (7.07)	10.16 (9.63)	17.79 (5.57)	2.51 (6.14)	11.80 (8.64)	18.21 (5.07)	5.36 (6.40)
Cloud cover	4.85 (3.16)	5.79 (3.06)	3.91 (2.97)	4.83 (3.17)	5.86 (2.99)	3.76 (2.99)	4.74 (3.33)	5.80 (3.16)	3.68 (3.15)

Y. Kim et al. 2015). Further, there is increasing evidence that environmental factors might play a role in contributing to the likelihood of suicide across South Korea. For example, previous research suggests suicide across the country increases during periods of higher surface temperatures (Kim et al. 2011), and Y. Kim et al. (2015) link increases in suicide to elevated levels of surface ozone. Jee et al. (2017) conclude suicide frequency rises in association with periods of additional solar radiation, although Kim et al. (2016) disagree and find no relationship between sunlight and suicide.

The comprehensive study by Kim et al. (2016) highlights weather–suicide associations prevalent across several East Asian countries, including South Korea, even after controlling for natural seasonal and day-of-week cycles using a time-stratified case-crossover design (Janes et al. 2005). Consistent with Kim et al. (2011), Kim et al. (2016) uncover strong temperature–suicide associations across South Korea with elevated temperatures associated with increases in suicide. However, Kim et al. (2016) examine these relationships only throughout the entire year, and as a result, it remains unclear whether these associations are always evident or occur only in certain seasons. Thus, the goal of this research is to examine whether temperature–suicide associations across South Korea remain valid during distinct ''warm'' and ''cool'' seasons by examining three major cities with different climates: Seoul, Daegu, and Busan. An examination of temperature–suicide associations on a seasonal level will not only be a valuable tool for health practitioners, but also has the potential to shed light on the causal mechanisms responsible for any observed temperature–suicide relationships, a topic on which many questions remain.

2. Data and methods

Three major cities across South Korea were selected on the basis of size, climate, and geography, with each city representing a unique climate and geographical location (Table 1; Fig. 1). Seoul, the capital of South Korea, is the largest city in the country, with a population over 10 million, and it sits in the far northwestern portion of South Korea adjacent to the Yellow Sea. Daegu, located in the more mountainous south-central portion of South Korea, is the fourth-largest city, with a population over 2.5 million. Busan, a coastal city in the southeast portion of the country, is South Korea's second-largest, with a population exceeding 3.5 million. Among South Korea's four largest cities, only Incheon was excluded because of its proximity to Seoul. Further, current analytical methods do not allow us to analyze smaller cities across South Korea properly because of reduced sample sizes that are inadequate for a comprehensive study of temperature–suicide associations.

Daily suicide counts for each city were obtained from Statistics Korea (http://kosis.kr) and include 19 years of data, spanning from 1998 through 2016; The data include only those who have committed suicide. Suicides were determined from the International Classification of Diseases (ICD) codes E950-E959 (ICD-9; suicide and self-inflicted injury) and X60-X84 (ICD-10; intentional self-harm). Suicide data were further broken down by

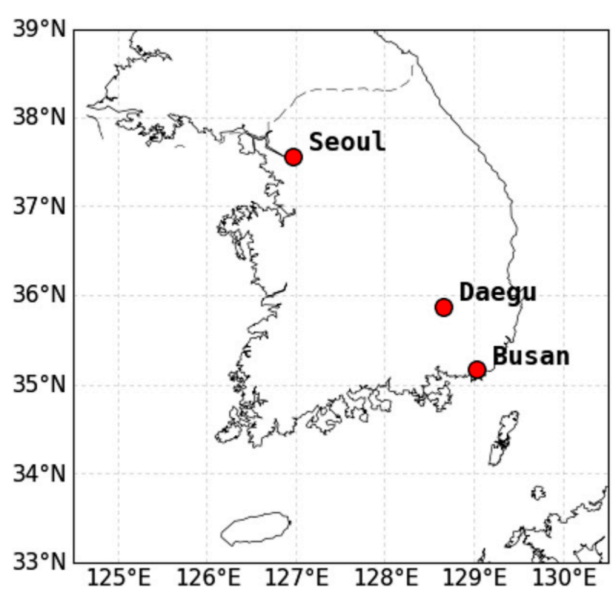

FIG. 1. Locations of Seoul, Daegu, and Busan in South Korea.

TABLE 2. Average daily suicides in Seoul, Daegu, and Busan across the entire year, the warm season (April–September), and the cool season (October–March), broken out by gender and age. Standard deviations are given in parentheses.

	Seoul			Daegu			Busan		
	Annual avg	Warm season	Cool season	Annual avg	Warm season	Cool season	Annual avg	Warm season	Cool season
Male	3.62 (2.29)	3.86 (2.33)	3.39 (2.22)	1.00 (1.04)	1.05 (1.04)	0.96 (1.04)	1.68 (1.40)	1.81 (1.44)	1.56 (1.35)
Female	1.80 (1.54)	1.87 (1.52)	1.73 (1.56)	0.50 (0.73)	0.53 (0.75)	0.47 (0.71)	0.74 (0.88)	0.78 (0.90)	0.70 (0.86)
0–34	1.36 (1.26)	1.40 (1.26)	1.31 (1.25)	0.34 (0.59)	0.35 (0.60)	0.32 (0.58)	0.51 (0.74)	0.53 (0.75)	0.48 (0.72)
35–64	2.84 (1.97)	2.99 (1.97)	2.69 (1.96)	0.84 (0.95)	0.87 (0.95)	0.81 (0.94)	1.36 (1.23)	1.44 (1.27)	1.29 (1.19)
65+	1.22 (1.22)	1.33 (1.26)	1.11 (1.17)	0.32 (0.59)	0.35 (0.61)	0.30 (0.57)	0.55 (0.78)	0.62 (0.82)	0.48 (0.74)
Total	5.42 (3.02)	5.72 (3.03)	5.11 (2.98)	1.50 (1.33)	1.58 (1.33)	1.42 (1.31)	2.42 (1.72)	2.58 (1.77)	2.26 (1.67)

gender, along with three distinct age segments (0–34, 35–64, and 65+), and then were plotted over time to reveal both seasonal and long-term trends in the data.

Meteorological data were obtained from the Korea Meteorological Administration (KMA) and include daily maximum and minimum temperatures, along with average daily cloud cover, spanning the 1998–2016 period of record. Meteorological data were collected by KMA observatories in Seoul (37.571 42°N, 126.965 80°E), Daegu (35.877 97°N, 128.652 95°E), and Busan (35.104 68°N, 129.032 03°E).

DLNM

Given that many environmental–health relationships, including suicide, often display lagged effects and nonlinear responses, we utilize a distributed lag nonlinear model (DLNM), a method that is becoming increasingly common for epidemiological research (Gasparrini et al. 2015; Cox et al. 2016; Allen and Sheridan 2018). DLNM has the ability to estimate the nonlinear and lagged effects of an exposure variable such as temperature on a specific human health outcome. Further, DLNM is effective at controlling for cyclical patterns such as day-of-week and seasonal effects along with long-term trends such as population change and the implementation of suicide prevention efforts, all of which have been highlighted in previous environment–suicide research as having important impacts on suicide rates (Dixon and Kalkstein 2009; Mok et al. 2012; Hiltunen et al. 2014; Kong and Kim 2016; Sun 2016; Dixon and Kalkstein 2018).

Consistent with Dixon et al. (2014), we used a generalized linear model with a quasi-Poisson family within the DLNM statistical package in R (Gasparrini 2011; http://cran.r-project.org/web/packages/dlnm) to create estimations of daily suicide counts that are based on either daily temperature (maximum and minimum) or cloud cover values. Natural cubic splines allow for normalization with respect to various time scales. We compiled the model for only the annual scale, which requires 11 equally spaced spline knots roughly equivalent to the start/end of months. We also employed a categorical ''day of week'' variable to account for weekly cycles/patterns. Informed by previous research (Dixon et al. 2014), we employed a 6-day lag (equivalent to 1 week because ''day 0'' was the first exposure day), and splines for the response functions (temperature and cloud cover) and the lag polynomials were tested using 2–4 degrees of freedom. Akaike information criterion (AIC) values were used to choose the best arrangement (i.e., degrees of freedom for response function and lag polynomial) for each model. Final results for suicide are presented as a relative risk as compared with a temporally and geographically dependent relative baseline.

It is possible that weather–suicide associations vary with the time of year; therefore, we also analyzed distinct ''warm'' and ''cool'' seasons, defined here as April–September, and October–March, respectively. These two periods were selected on the basis of the climates of the study cities. Additional analyses were conducted for both males and females along with all three age segments, although these analyses were restricted to Seoul because it was the only city with a large enough sample size to allow for this analysis.

3. Results

Climatological conditions among the three cities vary somewhat, with Seoul generally experiencing the lowest temperatures and largest variability because of its higher latitude (Table 1). Although Daegu has the highest average maximum temperatures, Busan has higher minimum temperatures throughout the year and the lowest temperature variability as a result of its lower latitude and coastal location.

Consistent with previous research, historical suicide counts from Statistics Korea reveal that male suicides outnumber those of females in all three cities (Table 2). Further, all cities show a general increase in suicide rates across the period of record, but it appears that this trend has stopped, and possibly even reversed slightly, since 2009 (Fig. 2). The overall increase in suicide is largest among males and is evident in all three age categories,

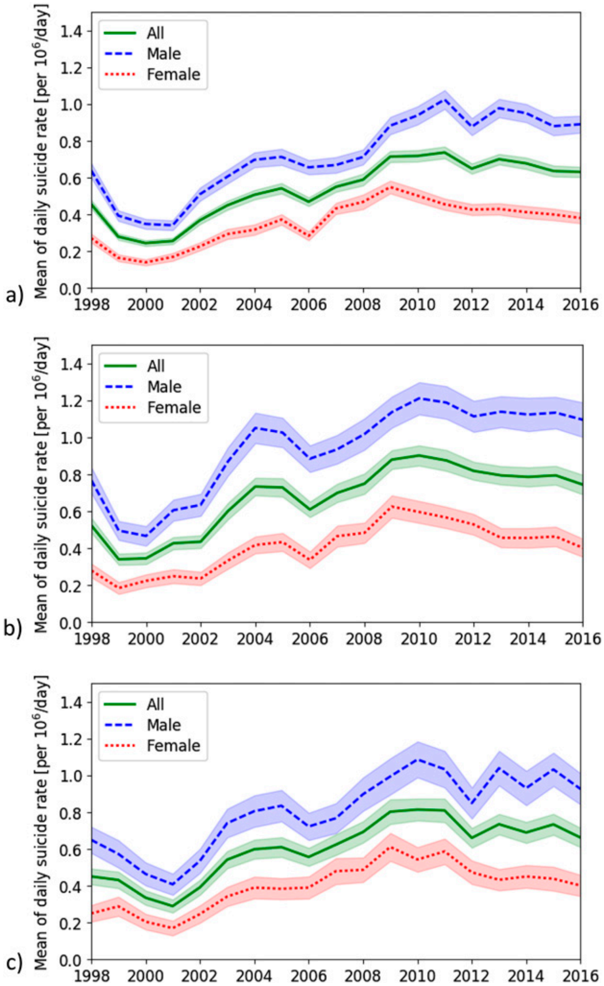

FIG. 2. Average daily suicide rates per year and 95% confidence intervals (shaded region) for the total population, males, and females for (a) Seoul, (b) Daegu, and (c) Busan.

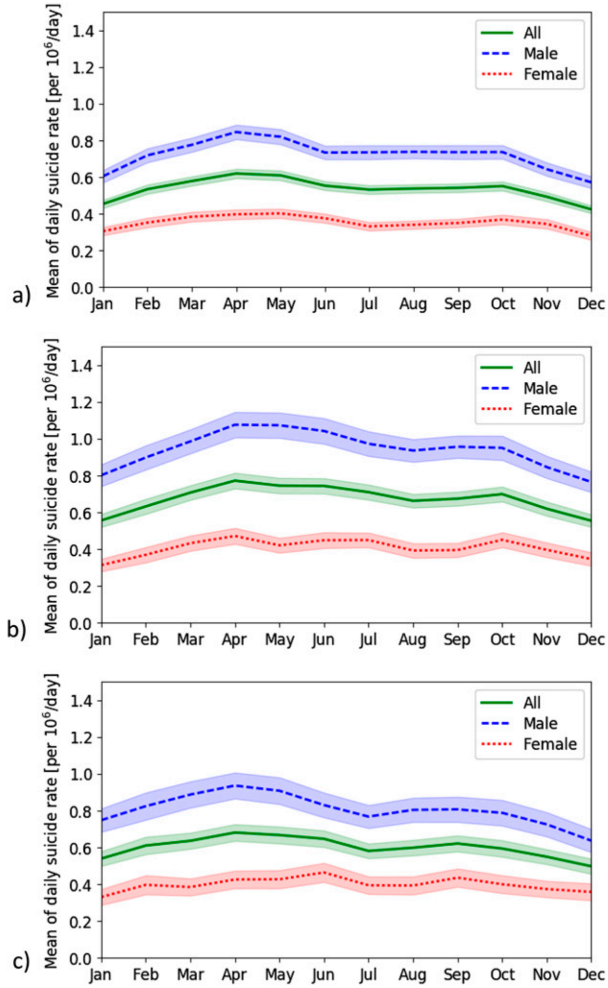

FIG. 3. As in Fig. 2, but per month.

although it is most pronounced within the 35–64 and 65+ segments.

Also consistent with previous research, an apparent seasonal pattern is evident within the historical suicide dataset. All three cities display the highest average daily suicide counts in April and lowest in December (Fig. 3). The shape of this seasonal pattern is also consistent across the three cities. Average daily suicides begin the year lower in January and increase to the annual peak in April before decreasing slightly throughout the late spring and early summer. Average daily suicides then remain constant or increase slightly through October before decreasing again to their annual minimum in December.

AIC values varied somewhat for the different versions (e.g., cities and seasons) of the temperature–suicide model (see the appendix). All reported model results culminated by assigning the appropriate degrees of freedom according to the lowest AIC values. Throughout the entire year, annual temperature–suicide associations are mixed. Seoul displays the most pronounced associations with the relative risk (RR) of suicide increasing almost linearly with temperature. Below-average maximum and minimum daily temperatures in Seoul are associated with reduced RR of suicide, and above-average maximum temperatures are associated with elevated RR (Fig. 4). Statistically significant, quasi-linear trends in temperature–RR associations in Seoul are also evident for both males and females, along with all three age segments. Annual temperature–suicide relationships in Daegu are less pronounced, with only modest decreases in RR associated with below-average maximum temperatures. In Busan, both below-average maximum and minimum temperatures are associated with reduced RR of suicide (see the online supplemental material).

An examination of weather–suicide associations during warm (April–September) and cool (October–March)

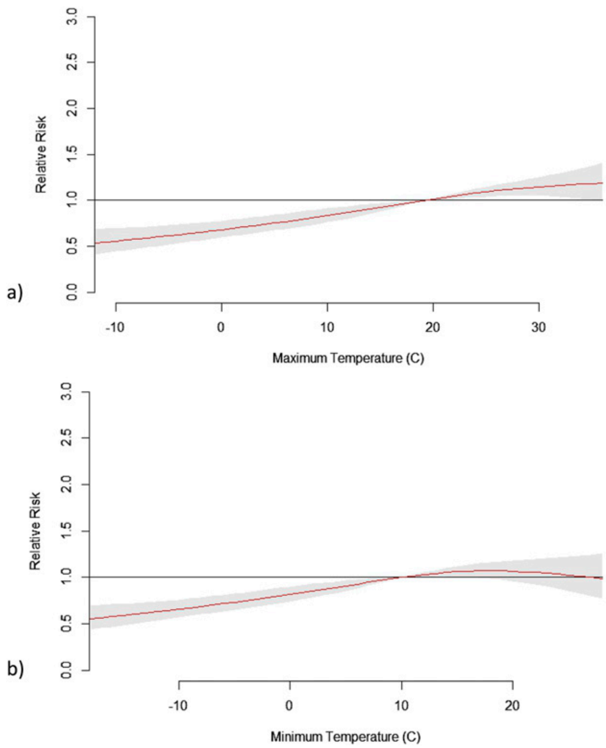

FIG. 4. Impact of (a) maximum and (b) minimum temperature on the relative risk of suicide in Seoul throughout the entire year. The shaded area represents 95% confidence intervals.

seasons reveals that temperature–suicide relationships are more pronounced throughout the cool season (Fig. 5). Seoul displays statistically significant, nearly linear associations for both maximum and minimum temperature and RR during the cool season, but no consistent results are evident during the warm season. Results are similar in Busan but less apparent in Daegu. The statistically significant temperature–suicide associations in the cool season are evident among all three age segments in Seoul and are especially pronounced among the 35–64 and 65+ groups. Likewise, both males and females display more apparent temperature–suicide associations in the cool season in Seoul (see the online supplemental material).

4. Discussion

The research here presents additional evidence to a growing literature outlining temperature–suicide associations, with above-average temperatures associated with higher RR of suicide and below-average temperatures associated with lower RR of suicide. However, we find that statistically significant associations are more apparent within the cool season, which is at least somewhat consistent with previous research across the United States noting stronger weather–suicide associations during the winter when compared with summer in many locations (Dixon and Kalkstein 2018). This is an important finding and highlights the need for future investigations of weather–suicide associations to examine distinct seasons individually since weather–suicide associations do not appear to remain constant throughout the entire year.

While the overall increasing trend in suicide rates across South Korea is consistent with previous research, it appears as if this general increase has leveled off in recent years. This is an important pattern to monitor and might indicate extensive suicide prevention efforts are beginning to have an effect. For example, televised service announcements have shown promising results and have been correlated with increases in suicide hotline calls (Song et al. 2017). Other intervention techniques have targeted specific age groups, where increased screening and intervention by counsellors and caregivers have likely reduced suicide rates among the elderly (Sun 2016). Likewise, a series of school-based approaches has had an impact reducing suicide among younger age groups (Kong and Kim 2016).

The seasonality in suicides is evident in all three cities with suicide counts highest in April and lowest in December. While the overall seasonal pattern is consistent with previous research, the remarkable consistency between the three South Korean cities is surprising, as their seasonal patterns are nearly identical. By comparison, suicide seasonality across the United States displays much more variation from city to city (Dixon and Kalkstein 2018). Further, suicide rates in September and October either cease their seasonal decline or even increase slightly in all three cities, a feature that is also present in Japan, Iran, and several locations in North America and Europe (Christodoulou et al. 2012; Amiri et al. 2015; Liu et al. 2015; Dixon and Kalkstein 2018). While most previous research examining suicide seasonality focuses on the primary springtime peak, this secondary increase in autumn is often underemphasized and is deserving of more attention (Partonen et al. 2004; Christodoulou et al. 2012).

Temperature–suicide associations are apparent across several different climates in South Korea. When temperature–suicide associations are statistically significant throughout the cool season, Busan displays a climate that is consistently warmer and less variable than Seoul, indicating that weather can play a similar role on suicide risk across different climate types. The specific environmental factors responsible for temperature–suicide associations are still debated, with some previous work suggesting increased sunshine has a larger impact than temperature (Vyssoki et al. 2014; Jee et al. 2017) while others disagree (Tsai and Cho 2012; Kim et al. 2016).

However, an examination of cloud cover during the cool season, when temperature–suicide associations are most

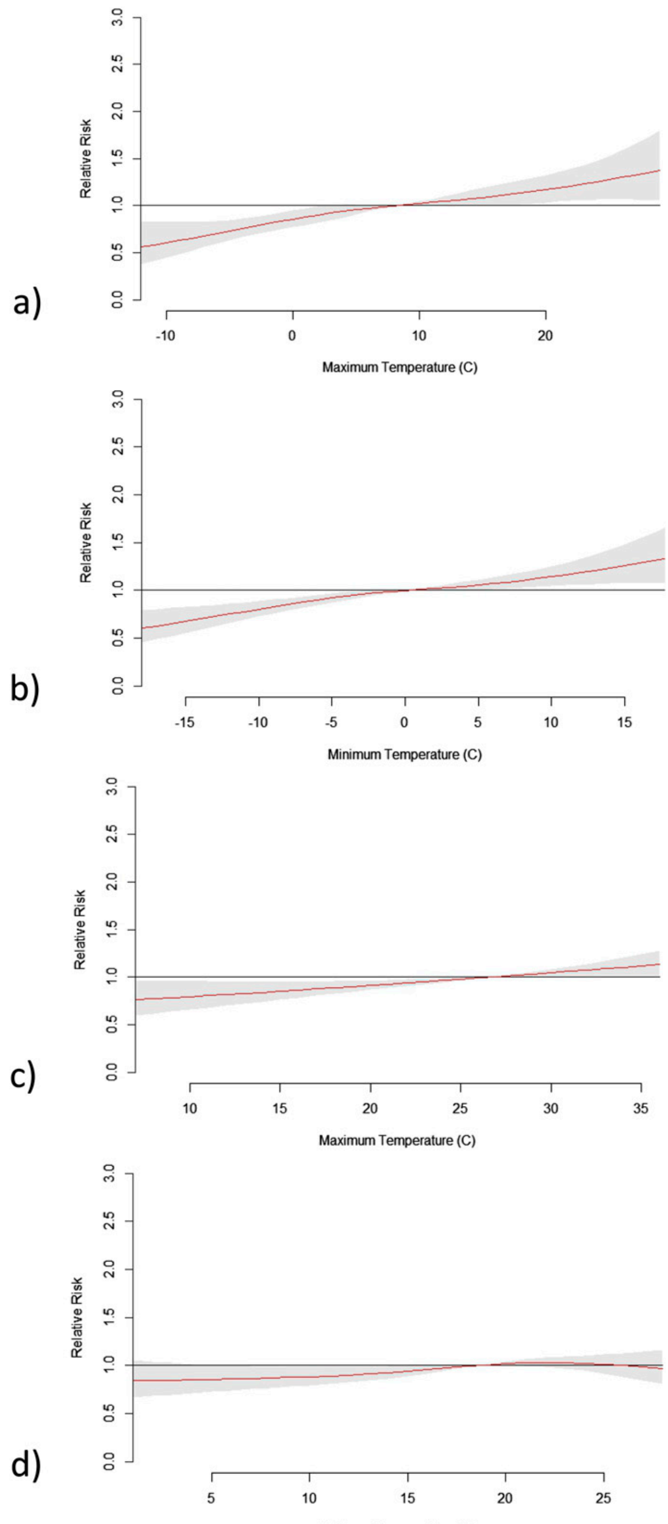

FIG. 5. Impact of temperature on the relative risk of suicide in Seoul for (a) maximum and (b) minimum temperature in the cool season and for (c) maximum and (d) minimum temperature in the warm season. The shaded area represents 95% confidence intervals.

TABLE A1. AIC values for the temperature–suicide DLNMs using daily maximum temperature data from the three study cities and a lag of 6 days.

		Busan			Daegu			Seoul		
Lag polynomial *df*	Temperature spline *df*	Annual	Warm	Cool	Annual	Warm	Cool	Annual	Warm	Cool
2	2	25 058	12 847	12 164	21 277	10 789	10 458	31 336	15 844	15 421
2	3	25 062	12 851	12 165	21 275	10 791	10 456	31 330	15 846	15 422
2	4	25 062	12 851	12 164	21 278	10 793	10 459	31 330	15 848	15 420
3	2	25 060	12 847	12 160	21 281	10 794	10 460	31 339	15 838	15 426
3	3	25 065	12 853	12 162	21 280	10 797	10 460	31 336	15 841	15 429
3	4	25 059	12 854	12 162	21 285	10 801	10 464	31 336	15 844	15 426
4	2	25 063	12 850	12 163	21 287	10 797	10 456	31 342	15 841	15 433
4	3	25 069	12 858	12 166	21 288	10 802	10 450	31 339	15 844	15 437
4	4	25 064	12 860	12 166	21 294	10 808	10 456	31 339	15 848	15 436

pronounced, in Seoul, Daegu, and Busan reveals no significant relationships (see the online supplemental material). As a result, it appears that the temperature–suicide associations observed here are, in fact, temperature-dependent and not caused by increased exposure to sun.

The causal mechanisms behind temperature–suicide associations are complex, with no scientific consensus. However, leading theories suggest that the relationship is likely due to either a change in physiology under certain environmental conditions or a weather-dependent variation in culture or behavioral norms. For example, suicide and suicidal behavior have been linked with a variety of hormones and neurotransmitters, many of which are known to fluctuate throughout the year (Petridou et al. 2002; Rocchi et al. 2007; Reutfors et al. 2009). Likewise, seasonal changes in culture such as school and even the timing of the harvest have also been known to impact suicide rates. However, these changes generally occur over months, not on the daily timeframe used in this study. Further, these explanations do not adequately account for why the temperature–suicide associations discovered here only occur in the cool season.

A potential physiological explanation for the observed results centers on brown adipose tissue (BAT), or brown fat, which aids in thermoregulation among many mammals. Previous research has found that BAT is often overactive among those who are suicidal or depressed (Hiltunen et al. 2014; Holopainen et al. 2014). Further, overactive BAT tends to improve cold tolerance at the expense of heat tolerance (Holopainen et al. 2014). As a result, it is possible that above-average temperatures in the winter, when BAT would be most active, could be a physical mechanism linking higher temperatures with elevated risk of suicide, particularly in the cold season (Holopainen et al. 2013).

Several potential limitations of this study are worthy of future consideration and mostly focus on the social components of suicide, a topic that is generally outside of the scope of the research here. For example, previous research notes an association between suicide and holidays or long weekends, a factor that is not considered in this study (Fernández-Niño et al. 2018). The link between holidays and suicide is complex and is likely based on changes in behavior and attitude that include increased alcohol consumption, changes in sleep habits or routine, and even a ''temporal broken-promise effect,'' all of which are factors associated with increases in suicide (Gabennesch 1988; Jessen and Jensen 1999; Schneider 2009). A deeper examination of gender and behavior

TABLE A2. As in Table A1, but for minimum temperature.

		Busan			Daegu			Seoul		
Lag polynomial *df*	Temperature spline *df*	Annual	Warm	Cool	Annual	Warm	Cool	Annual	Warm	Cool
2	2	25 067	12 858	12 172	21 305	10 823	10 459	31 350	15 861	15 420
2	3	25 068	12 860	12 172	21 309	10 826	10 462	31 347	15 859	15 421
2	4	25 068	12 860	12 172	21 312	10 829	10 466	31 351	15 863	15 425
3	2	25 072	12 856	12 174	21 310	10 823	10 463	31 353	15 863	15 422
3	3	25 074	12 860	12 177	21 314	10 827	10 468	31 351	15 863	15 426
3	4	25 072	12 863	12 176	21 320	10 833	10 474	31 358	15 869	15 427
4	2	25 073	12 851	12 180	21 315	10 828	10 468	31 359	15 867	15 427
4	3	25 077	12 857	12 184	21 321	10 834	10 475	31 357	15 869	15 430
4	4	25 077	12 862	12 185	21 328	10 841	10 480	31 359	15 877	15 432

could help to explain the social factors responsible for the large differences in observed male and female suicide rates (Oliffe et al. 2016). From a methodological perspective, the primary limitation of this study is DLNM's somewhat subjective selection of model parameters such as degrees of freedom and spline knots (Gasparrini et al. 2017).

5. Conclusions

This research provides evidence that higher daily temperatures are associated with an elevated relative risk of suicide across South Korea while lower daily temperatures are associated with a reduced relative risk. This pattern is evident among both males and females along with all age groups, but especially those 35 and older. Further, similar associations were uncovered for different climates ranging from the more variable climate of Seoul in the north to the more moderate climate of Busan in the south. These results add to a growing literature linking above-average temperature and increased suicide risk in many locations around the world (Hiltunen et al. 2014; Kim et al. 2016; Dixon and Kalkstein 2018).

However, the primary finding of this study is that the temperature–suicide associations observed here appear to exist only during the cool season, demonstrating the importance of examining weather and suicide on a seasonal scale rather than annual, since weather–suicide associations do not remain constant throughout the year. Further, there are no significant cloud cover–suicide associations present in the cool season, suggesting that daily temperature, and not increased sunlight, is responsible for the findings. We hope that these findings can be used by medical and mental health experts to better explore the causal mechanisms behind the increased risk of suicide during periods of above-average temperatures and also to increase intervention techniques during periods in which suicide is most likely to occur.

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APPENDIX

AIC Values for Different Versions of the Model

AIC values varied somewhat for the different versions (e.g., cities and seasons) of the temperature–suicide model, as seen in Tables A1 and A2.

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