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Suicide and Ambient Temperature: A Multi-Country Multi-City Study

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Background: Previous literature suggests that higher ambient temperature may play a role in increasing the risk of suicide. However, no multi-country study has explored the shape of the association and the role of moderate and extreme heat across different locations.

Objectives: We examined the short-term temperature–suicide relationship using daily time-series data collected for 341 locations in 12 countries for periods ranging from 4 to 40 y.

Methods: We conducted a two-stage meta-analysis. First, we performed location-specific time-stratified case-crossover analyses to examine the temperature–suicide association for each location. Then, we used a multivariate meta-regression to combine the location-specific lag-cumulative nonlinear associations across all locations and by country.

Results: A total of 1,320,148 suicides were included in this study. Higher ambient temperature was associated with an increased risk of suicide in general, and we observed a nonlinear association (inverted J-shaped curve) with the highest risk at 27°C. The relative risk (RR) for the highest risk was 1.33 (95% CI: 1.30, 1.36) compared with the risk at the first percentile. Country-specific results showed that the nonlinear associations were more obvious in northeast Asia (Japan, South Korea, and Taiwan). The temperature with the highest risk of suicide ranged from the 87th to 88th percentiles in the northeast Asian countries, whereas this value was the 99th percentile in Western countries (Canada, Spain, Switzerland, the UK, and the United States) and South Africa, where nearly linear associations were estimated. The country-specific RRs ranged from 1.31 (95% CI: 1.19, 1.44) in the United States to 1.65 (95% CI: 1.40, 1.93) in Taiwan, excluding countries where the results were substantially uncertain.

Discussion: Our findings showed that the risk of suicide increased with increasing ambient temperature in many countries, but to varying extents and not necessarily linearly. This temperature–suicide association should be interpreted cautiously, and further evidence of the relationship and modifying factors is needed. https://doi.org/10.1289/EHP4898

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Introduction

Suicide is a significant public health concern. It is the second leading cause of death among young people 15–29 years of age, and there were an estimated 803,900 deaths by suicide globally in 2012 (WHO 2014). Suicide is a complex event. Previous literature has shown that individual characteristics and social factors such as demographic, psychiatric, psychological, and biological factors and stressful life events may increase the risk of suicide (Nock et al. 2012).

Some evidence also indicates that atmospheric environmental factors may be associated with suicide risk (Carleton 2017; Helama et al. 2013; Kim et al. 2016, 2018). Seasonality of suicide has been reported over a century (Durkheim 1951), with a clear fluctuation of suicide counts showing a major peak in spring or early summer and a trough in winter in many countries in both the Northern and Southern Hemisphere, particularly in temperate climate regions (Ajdacic-Gross et al. 2010; Christodoulou et al. 2012; Kim et al. 2011; White et al. 2015).

Outdoor ambient temperature has been investigated as one source of the seasonality of suicide, although many factors other than temperature vary seasonally (e.g., hours of sunlight, vitamin D levels, outdoor activity, diet), and consistent findings have suggested that higher ambient temperature may increase the risk of suicide (Bando et al. 2017; Burke et al. 2018; Dixon and Kalkstein 2018; Kim et al. 2016; Likhvar et al. 2011; Page et al. 2007; Williams et al. 2015). For example, a study using time-series analysis in England and Wales reported a larger risk of suicide associated with each 1°C increase in mean ambient temperature above 18°C (Page et al. 2007). Another study using time-stratified case-crossover analysis also reported a positive association between temperature and suicide over multiple cities in northeast Asia (Kim et al. 2016).

However, most previous studies have assumed a linear relationship between ambient temperature and suicide, thus raising a question about whether extremely high temperature, such as in heat waves, also continuously increases the risk of suicide. A few studies have attempted to examine a nonlinear temperature–suicide association without quantifying the risk of suicide associated with ambient temperature (Dixon and Kalkstein 2018; Likhvar et al. 2011). The patterns of the nonlinear association varied depending on study location, and in some locations the risks of suicide were not associated with increased heat during extremely hot temperatures. In addition, the variety of modeling approaches makes it difficult to compare risks across countries.

In this study, we hypothesized that the nonlinear association between ambient temperature and suicide may exist and that there might be a critical range of temperature that maximizes the risk of suicide. A comprehensive study covering multiple countries with a range of climate and suicide rates is needed to test the hypothesis. We examined the nonlinear association between ambient temperature and suicide across 341 locations in 12 countries using a two-stage meta-analysis.

Methods

Data

We collected daily time-series data of suicide and weather variables for each of 341 locations over 12 countries. The study periods varied depending on country, ranging from 4 to 40 y. Details of the country name, the number of locations, and the study period for each country are listed in Table 1. In this study, suicide was defined as intentional self-poisoning and self-harm using the eighth, ninth, and tenth revisions of the *International Statistical Classification of Diseases and Related Health Problems* [ICD-8 (WHO 1966); ICD-9 (CDC 2013); ICD-10 (WHO 2016)]: codes E950.0–E958.9 for ICD-8 and -9 and codes X60–X84 for ICD-10. We collected daily means of temperature (°C) and relative humidity (%) and the daily total of sunshine duration (hours), measured at central monitoring sites. Limited data were available on relative humidity and sunshine duration, including 236 locations in eight countries and 124 locations in six countries, respectively. Details about the data collection and data sources are described in "Data collection" in the Supplemental Material and in Tables S1 and S2.

Statistical Modeling

We conducted a two-stage analysis. First, we used a time-stratified case-crossover design with distributed lag nonlinear functions to examine the association between temperature and suicide for each location. Next, we used a multivariate meta-regression model to combine the location-specific estimates across all locations and by country and to identify the range of ambient temperatures exhibiting the highest risk of suicide. We used R (version 3.4.4; R Development Core Team) with the packages gnm and dlnm for the time-stratified case-crossover analysis, and mvmeta for the meta-regression.

First-stage modeling. We fitted a conditional Poisson regression model, taking overdispersion into account, to implement the time-stratified case-crossover analysis (Armstrong et al. 2014). We designed a stratum by a three-way interaction term of year, calendar month, and day of week to compare exposure levels between case and control days matched within the stratum. It indicates that each case was matched to several controls on the same day of week in the same month and the same year (i.e., 1:3 or 1:4 matching). Thus, the design adjusted for seasonality, long-term time trend, and the day of week based on the assumption that unmeasured time-varying confounders are constant within a stratum (Lu et al. 2008). Strata with no suicide events were excluded from the analysis.

We modeled the association between ambient temperature and suicide using a distributed lag nonlinear function, obtained by the combination of two functions for modeling the potentially nonlinear exposure–response and the additional lag–response associations, respectively, that examine delayed effects (Gasparrini et al. 2010). Specifically, we used a quadratic B-spline for the exposure–response association with three internal knots placed at the 25th, 50th, and 75th percentiles of location-specific temperature distributions. This choice for the optimal number of knots was guided by our study objectives (to explore nonlinearity), minimizing the quasi-Akaike Information Criteria (AIC modified with overdispersion) (Gasparrini et al. 2010), and the log-likelihood ratio test (LRT for significance of nonlinearity). We considered, in particular, larger locations (capital cities), which provide the most power to detect potentially complex associations. The QAIC and the LRT indicated that nonlinear models fitted best in the northeast Asian locations (Tokyo, Seoul, and Taipei), whereas linear models fitted best in most of the locations overall (see Table S3; Figure S1). The LRT pooled across all locations for each country also indicated that nonlinear models fitted best in Canada, Japan, and South Korea (see Table S3), although the pooled QAIC indicated that linear models fitted best in general. We chose a model sufficiently flexible to show nonlinearity for all locations in our study to provide comparable results across countries while accepting that, for some of them, that flexibility may not be needed. For the lag–response association, we applied dummy parameterization-defining intervals with lag 0 and lag 1–2. The lag period was chosen in sensitivity analysis.

Then, we reduced the high dimensional effect estimates obtained from the distributed lag nonlinear function. The reduced parameters represent the temperature–suicide association cumulated over the lag days for each location, and they were pooled in the second-stage analysis (Gasparrini and Armstrong 2013).

Second-stage modeling. We used the multivariate meta-regression analysis to pool the location-specific reduced coefficients. We fit the meta-regression with and without country indicators to estimate the country-specific and overall associations, respectively. To better explain the between-location variability, we included location-specific summer temperature average and temperature range into the model as meta-predictors. The summer temperature was defined as the daily ambient temperature during June to September in the countries in Northern Hemisphere and during December to March in the countries in Southern Hemisphere. In addition, we investigated how the between-location variability of the temperature–suicide association are explained by the meta-predictors. We used a multivariate Wald test for the significance of the meta-predictors and presented the results of the multivariate extension of Cochran Q-test and I^2 statistic to examine how the residual heterogeneity changes with different meta-predictors (Gasparrini et al. 2012a; Higgins and Thompson 2002).

Based on the pooled estimates across all locations and by country, we identified the temperature–suicide association curve and two temperature values corresponding to the lowest risk of suicide between the first and 50th percentiles of the temperature and the highest risk of suicide between the 51st and 99th percentiles, respectively. Hereafter we refer to the former as the minimum suicide temperature (MinST) and the latter as the maximum suicide temperature (MaxST). Then, we recentered the exposure–response curve at the MinST and estimated a relative risk (RR) between the MinST and the MaxST.

In addition, from the model fit, we obtained the best linear unbiased prediction (BLUP) for the location-specific estimates. The BLUP is calculated as a weighted average between the location-specific association estimated in the first-stage and the pooled association, where the weight is inversely proportional to the first-stage estimation variance. This approach allows the locations with low numbers of suicide cases or short time-series, usually accompanied by estimates with large uncertainty [i.e., wide confidence intervals (CIs), to borrow information from locations with larger populations (Gasparrini et al. 2012a). Based on the BLUP for each location, we identified the temperature–suicide association curve with the MinST and the MaxST and calculated the RR for each location.

Subgroup analysis. We conducted stratified analyses using the first- and second-stage modeling approaches described above for each category (men, women, <65, and ≥65 years of age) to obtain the sex- and age-specific RRs. We included 245 and 206 locations in the analyses for sex and age groups, respectively, because of the low numbers of suicide cases in women and older adults in small cities or regions that induced analytical errors (e.g., convergence failures). Specifically, we excluded 96 cities for the analysis by sex (i.e., 14, 17, and 65 cities in South Africa, Spain, and the United States, respectively, where the number of suicides in women was less than the country-specific minimum suicides in men) and 135 cities for the analysis by age groups (i.e., all cities in Brazil, the Philippines, South Africa, and Vietnam that showed highly unstable results and 78 cities in the United States where the number of suicides in older adults was less than the minimum number of suicides in younger people across the U.S. cities). We used the same MinST and MaxST for total suicides identified above when calculating the location- and country-specific RRs for each subgroup.

Sensitivity analysis. To assess robustness of our findings, we did several sensitivity analyses. First, we applied a linear distributed lag model over the same lag of 0–2 d and estimated the RR between the 1st and the 99th percentiles of mean temperature. Next, we altered the number of internal knots for the exposure–response curve from three (at the 25th, 50th, and 75th percentiles of temperature) to one (at 50th percentile) and two (at the 33rd and 66th percentiles). We also changed the functional form of spline for the exposure–response curve from a quadratic B-spline to a cubic B-spline. The lag period was extended to 6 d using a natural cubic B-spline with an intercept and two internal knots at equally spaced values in the log scale, and the lag of 0–2 d was chosen in the final model by visual inspection of the lag–response curves (see Figure S2). We additionally adjusted for the averages of relative humidity and sunshine duration from the current day to the day before using a natural cubic B-spline with three degrees of freedom for the locations where data were available (see Table S1).

Results

Table 1 shows summary statistics for each country. A total of 1,320,148 suicides were included in this study. The annual average temperatures varied considerably from 6.7°C in Canada to 28.5°C in Vietnam, according to latitude of the study locations: from higher latitude (Canada and the UK), temperate latitude in Central Europe (Switzerland), the Mediterranean (Spain), northeast Asia (Japan and South Korea) to the subtropics (Brazil, South Africa, and Taiwan) and tropics (the Philippines and Vietnam). A broad range of the temperature distributions was also observed within a country in some regions (i.e., Brazil, Canada, Japan, South Africa, Spain, and the United States). The study locations and their latitude and longitude information are shown in Figure 1 and Table S1.

Figure 2 illustrates the seasonal patterns of monthly suicide aggregated across all locations for each country. The monthly counts were adjusted for the number of days for each month and standardized as a z-score for each country. Overall, the monthly suicides were higher in warm seasons (April–June) and lower in cold seasons (November–January) for all Northern Hemisphere countries other than the Philippines and Vietnam in the tropics

Table 1. Summary statistics by country.

Country	Cities/region (n)	Study period	Total suicides [n (%)][a]	Suicides in men (%)[b]	Suicides <65 years of age (%)[c]	Suicide rate (per 100,000)[d]	Temperature (°C) [mean (range)][f]	Summer temperature (°C) [mean (range)][f,g]
Brazil	13	1997–2005 (9 y)	8,801 (0.53)	77.1	93.0	5.8	23.5 (17.6–27.6)	25.0 (20.7–27.8)
Canada	26	1986–1999 (14 y)	25,619 (1.56)	75.7	86.8	10.9	6.7 (2.7–10.7)	17.3 (13.5–20.7)
Japan	47	1973–2012 (40 y)	976,346 (2.76)	66.8	74.1	19.1	15.1 (8.8–22.9)	24.3 (19.4–27.8)
South Korea	6	1992–2013 (22 y)	83,825 (4.28)	67.3	79.1	29.1	13.6 (12.4–14.9)	23.8 (23.1–24.5)
Philippines	4	2006–2010 (5 y)	1,267 (0.46)	71.0	88.3	2.9	28.1 (27.4–28.6)	28.3 (27.6–28.8)
South Africa	39	2000–2013 (14 y)	5,128 (0.08)	77.9	94.5	1.1	17.8 (12.4–22.7)	21.8 (15.0–26.7)
Spain	50	1990–2013 (24 y)	21,998 (0.57)	71.1	70.6	6.9	15.6 (10.9–21.6)	22.3 (17.5–26.9)
Switzerland	8	1995–2013 (19 y)	16,022 (2.02)	69.1	66.6	12.0	10.4 (8.6–12.9)	17.9 (15.8–20.6)
Taiwan	3	1994–2007 (14 y)	17,883 (2.33)	67.4	78.7	16.8[e]	24.0 (23.2–25.2)	28.4 (28.1–28.6)
UK	10	1990–2011 (22 y)	78,115 (0.66)	77.2	83.1	6.9	10.3 (9.4–11.6)	15.6 (14.5–17.2)
USA	134	2001–2006 (6 y)	84,684 (1.32)	78.1	83.3	13.0	14.9 (8.2–25.0)	23.6 (17.2–33.8)
Vietnam	1	2010–2013 (4 y)	460 (0.45)	73.0	93.9	5.0	28.5 (28.5–28.5)	28.4 (28.4–28.4)

[a]Proportion of total suicides over the number of total or non-external deaths for the study periods.
[b]Proportion of suicides in men over the total number of suicides for the study periods.
[c]Proportion of suicides in younger people (<65 years of age) over the total number of suicides for the study periods.
[d]Suicide rate in 2012 collected from the WHO report (WHO 2014) for the Philippines and Vietnam and from Health Status, Organisation for Economic Co-operation and Development (https://data.oecd.org/healthstat/suicide-rates.htm?context=OECD) for other countries.
[e]Suicide rate in 2010 collected from National Statistics, Taiwan (http://eng.stat.gov.tw/lp.asp?ctNode=2267&CtUnit=1072&BaseDSD=36&mp=5).
[f]Location-specific mean temperature (range).
[g]Summer temperature was defined as the average temperature during June to September in the Northern Hemisphere and during December to March in the Southern Hemisphere.

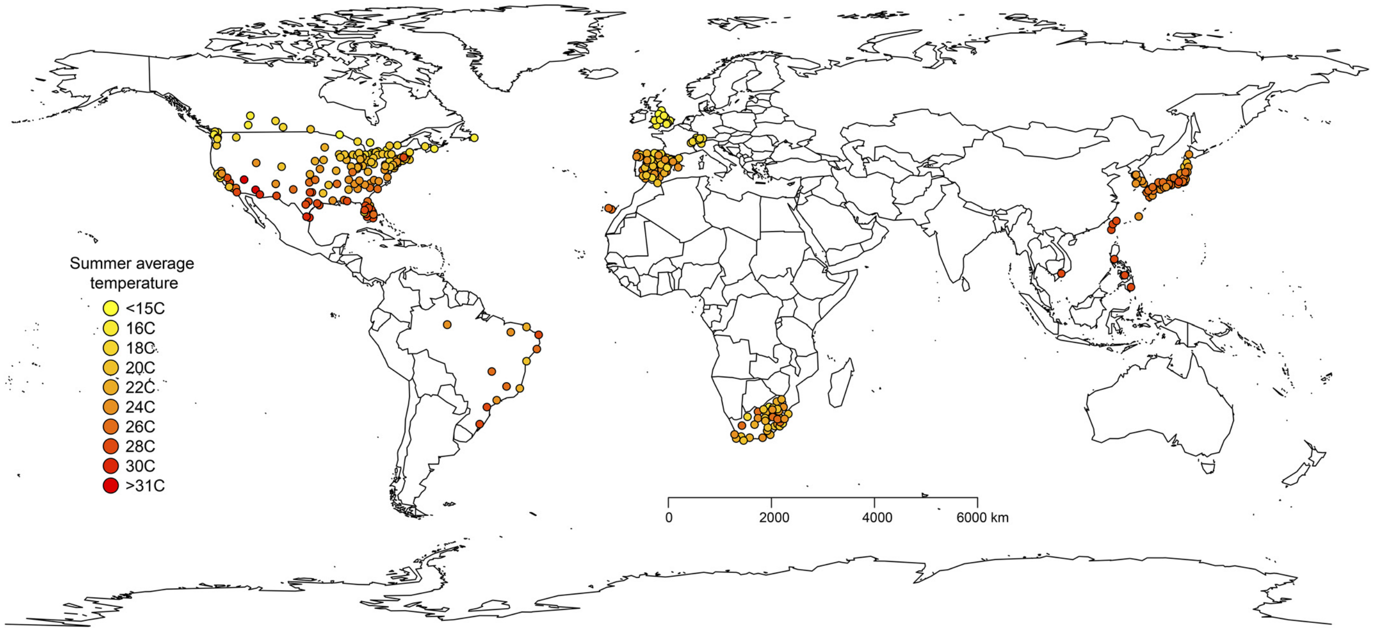

Figure 1. Study area including 341 locations in 12 countries for periods ranging from 4 to 40 y and the location-specific average summer temperature defined as the daily temperature during June to September in the countries in the Northern Hemisphere and during December to March in the countries in the Southern Hemisphere. See Table 1 for corresponding numeric data and Table S1 for additional information about each country.

where no seasonality of suicide was observed. The seasonal patterns for the Southern Hemisphere countries (Brazil and South Africa) were less clear, but the suicide counts tended to be lower during cool seasons (May–July).

Association between Temperature and Suicide

Figure 3A shows the overall temperature–suicide association across all countries. We identified the MaxST at the 93rd percentile of the temperature distribution that corresponds to 27°C. The RR for the MaxST versus MinST calculated from the pooled nonlinear association was 1.33 (95% CI: 1.30, 1.36). The country-specific RRs are depicted in Figure 3B along with the overall RR and suggest that cross-national heterogeneity may exist (Table 2 presents the numerical estimates of the RRs).

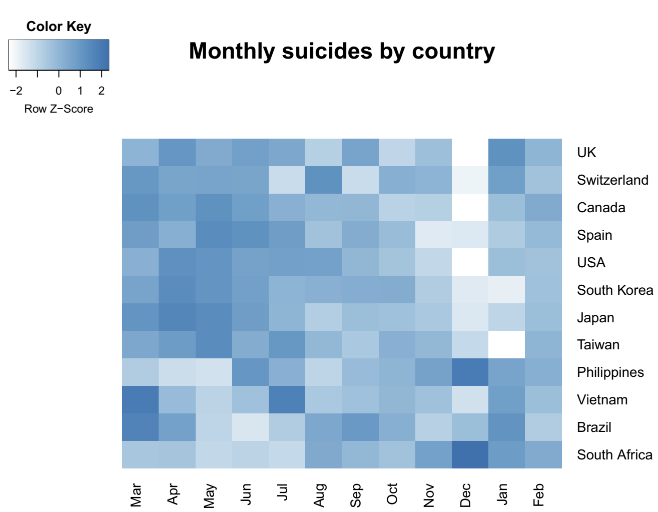

Figure 2. Seasonality of suicide for each country, illustrated by the aggregated monthly suicides adjusting for the number of days for each month and standardized as a *z*-score. The countries are listed in order of latitude from the UK in the Northern Hemisphere to South Africa in the Southern Hemisphere.

Figure 4 shows the lag-cumulative temperature–suicide associations by country (see Figure S3 for specific estimates for every location within each country). In general, a higher ambient temperature was associated with an increased risk of suicide. However, the suicide risk leveled off or decreased at extremely high temperatures in some countries (i.e., Japan, South Korea, and Taiwan) where populations are exposed to high temperatures more often compared with other countries in temperate regions. The associations in Brazil, the Philippines, South Africa, and Vietnam were unclear or showed large uncertainty. The lag–response associations were fairly immediate, with the highest RR on the current day declining toward the null within 1 or 2 d (see Figure S4).

In the three northeast Asian countries (Japan, South Korea, and Taiwan), the relative measure of the MaxST (the median for each country) tended to be lower, ranging from the 87th to 88th percentiles, compared with those in Western countries (Canada, Spain, Switzerland, the UK, and the United States) and South Africa at the 99th percentile (Figure 4; Table 2). The absolute measures of MinST and MaxST reflected the difference of ambient temperature distributions among locations, showing relatively high variation in MinST (from −15.3°C in Canada to 26.5°C in Vietnam) and low variation in MaxST (from 20.7°C in the UK to 30.0°C in Vietnam) (Table 2; Figure S5). These findings suggest that MaxST is less likely to be driven by adaptation to the local temperature but, rather, is prone to be universal, and therefore the range of MaxST might be regarded as a critical range of temperature showing the highest risk of suicide, probably by physiological and/or behavioral responses.

Similar patterns for the association were observed in the locations with the largest number of reported suicides for each country depicted in Figure 5A, where a variety of temperature distributions were measured (Figure 5B). The MaxST values from the city-specific curves were concentrated in between 21.2°C in South East, UK, and 29.0°C in Taipei, Taiwan, except for the tropical cities (see Table S2).

The point estimates of the country-specific RRs seemed to fall within one of three groups (Figure 3B; Table 2)—low-RR (the UK, the United States, and Japan), range 1.31–1.37; middle-

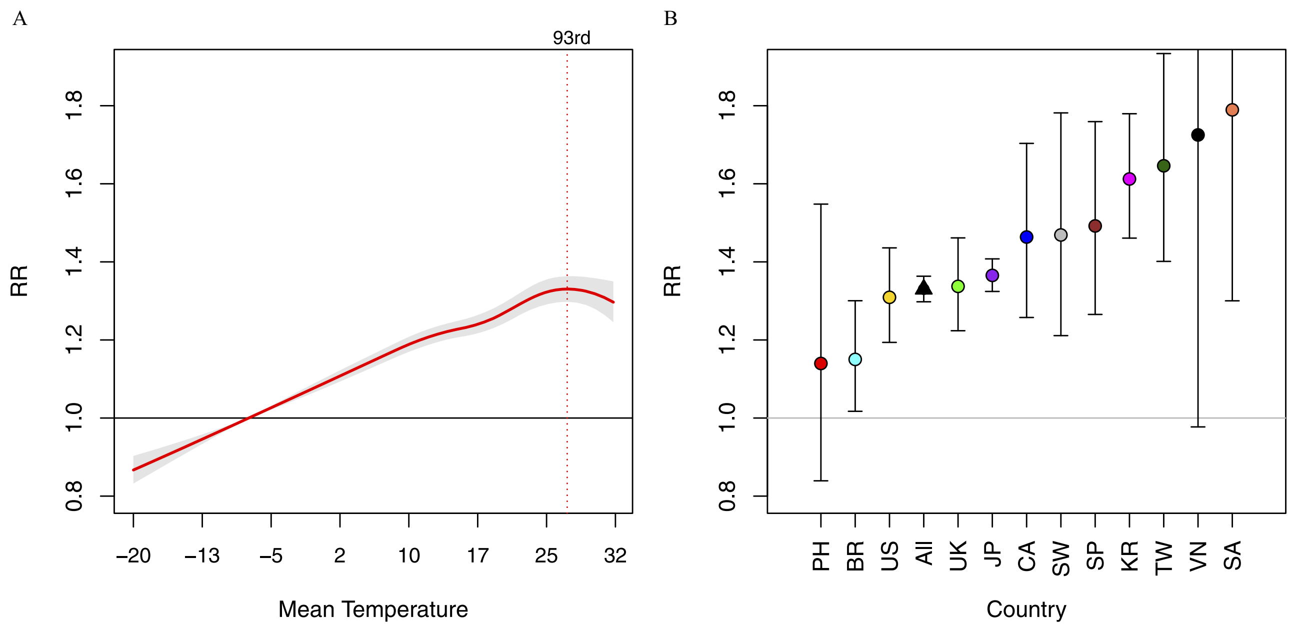

Figure 3. (A) Overall lag-cumulative temperature–suicide association across all 341 locations against daily mean temperature from −20.0°C to 32.2°C (corresponding to the 0.1st to the 99.9th percentile of the temperatures), with the 95% CI (shaded gray). The vertical dotted line indicates the maximum suicide temperature (MaxST) representing a temperature value with the highest risk of suicide, identified at the 93rd percentile of the temperature or 27°C. (B) overall (All) and country-specific lag-cumulative relative risks (RRs) for overall or country-specific MaxST vs. minimum suicide temperature (MinST) and 95% CIs (vertical bars). See Table 2 for corresponding numeric data. The associations were estimated by using a conditional Poisson model adjusting for seasonality, long-term time trend, and the day of week. The triangle (All) indicates the RR across all locations. BR, Brazil; CA, Canada; CI, confidence interval; JP, Japan; KR, South Korea; PH, the Philippines; SA, South Africa; SP, Spain; SW, Switzerland; TW, Taiwan; UK, the UK; US, the United States; VN, Vietnam.

RR (Canada, Switzerland, and Spain), range 1.46–1.49; and high-RR (South Korea, and Taiwan), range 1.61–1.65—besides the estimates for the Philippines, Brazil, Vietnam, and South Africa, where the nonlinear curves were unclear or showed a large uncertainty (see Figure S6). For comparison, we additionally provide the RRs per 1°C increase within a range in between the MaxST and MinST in Table S1. The magnitude of the RRs per 1°C increase tended to vary across the range of ambient temperature distributions, indicating that the broader the temperature distribution, the smaller the estimated RRs.

In the meta-regression analysis to investigate if any of the meta-predictors explained the between-location variability in the association, we observed that the residual heterogeneity was reduced from an I^2 of 3.3% in the intercept-only model to an I^2 of 1.0% in both the single-predictor model including the country indicator and the full model including summer temperature average and, additionally, temperature range (see Table S4). The Wald test results also show that the country indicator played a significant role in both single-predictor and full models ($p < 0.001$), suggesting that the temperature–suicide associations varied across countries.

Table 2. Overall (All) and country-specific minimum suicide temperature (°C) (MinST) and maximum suicide temperature (°C) (MaxST) with their corresponding percentiles (MinSTP and MaxSTP) and pooled cumulative RRs (95% CIs).

Country	MinST (MinSTP)[a]	MaxST (MaxSTP)[a]	RR (95% CI)[b]
All	−7.5 (1)	27.0 (93)	1.33 (1.30, 1.36)
Brazil	21.4 (20)	24.8 (66)	1.15 (1.02, 1.30)
Canada	−15.3 (2)	24.2 (99)	1.46 (1.26, 1.70)
Japan	0.4 (1)	25.5 (87)	1.37 (1.32, 1.41)
South Korea	−5.2 (1)	25.0 (88)	1.61 (1.46, 1.78)
Philippines	26.0 (6)	28.2 (51)	1.14 (0.84, 1.55)
South Africa	7.6 (1)	26.4 (99)	1.79 (1.30, 2.46)
Spain	3.7 (1)	27.8 (99)	1.49 (1.27, 1.76)
Switzerland	−4.7 (1)	24.6 (99)	1.47 (1.21, 1.78)
Taiwan	13.1 (1)	29.2 (88)	1.65 (1.40, 1.93)
UK	−0.7 (1)	20.7 (99)	1.34 (1.22, 1.46)
USA	−3.6 (1)	28.8 (99)	1.31 (1.19, 1.44)
Vietnam	26.5 (7)	30.0 (87)	1.73 (0.98, 3.05)

Note: Pooled cumulative RRs (95% CIs) were estimated by using a conditional Poisson model adjusting for seasonality, long-term time trend, and the day of week. CI, confidence interval; RR, relative risk.
[a]Temperature and temperature percentiles: median values.
[b]Pooled cumulative associations for MaxST vs. MinST.

Subgroup Analysis

Figure 6 depicts the pooled cumulative RRs stratified by sex and age groups in each country. The results by age were inconsistent across countries and the confidence intervals generally overlapped, except for in Japan and South Korea, where the RRs were higher in older people. The RRs in Spain and the United States also tended to be higher for older people, whereas they were in the opposite direction in Taiwan. Results by sex were also inconsistent and generally had overlapping confidence intervals, except for in Japan where the RRs were higher in women. A similar tendency, with higher risks in women, was also observed in Brazil and Taiwan. However, the RRs in Spain and the UK were higher in men. (See Table S5 for numerical estimates of the RRs and 95% CIs.)

Sensitivity Analysis

The pooled effect estimates for the temperature–suicide associations for each country were fairly robust, except for those in the Philippines and Vietnam, when applying the linear distributed lag model, altering the model specifications (the different number of knots and the other functional form of the spline for the temperature–suicide association), and adjusting for relative humidity or sunshine duration (see Figure S7). In addition, the results with extended lags of up to 6 d tended to be less precise, with wider confidence intervals.

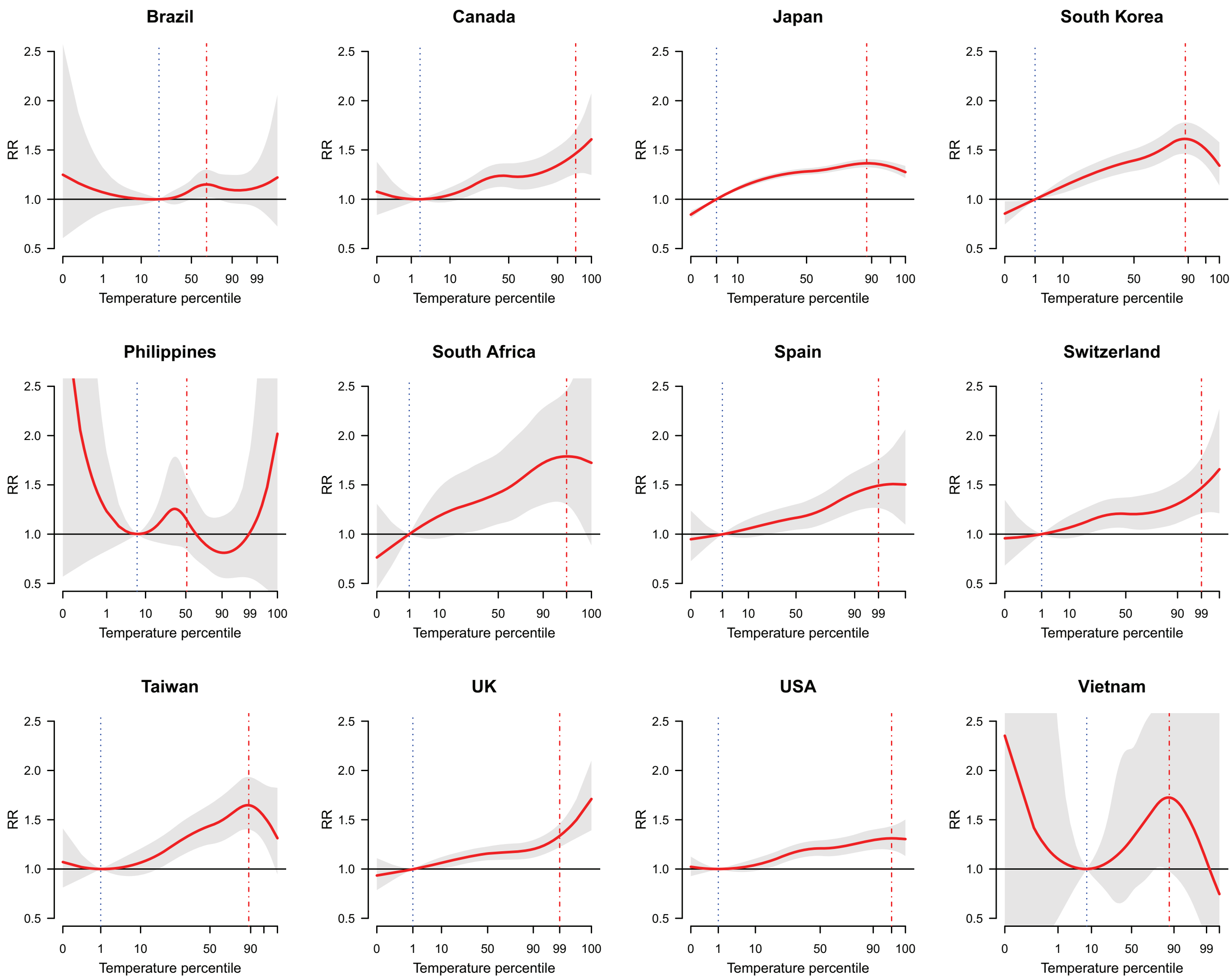

Figure 4. Pooled lag-cumulative temperature–suicide associations with 95% CIs (shaded gray) for each country, estimated by using a conditional Poisson model adjusting for seasonality, long-term time trend, and the day of week. Two vertical lines indicate the minimum suicide temperature (MinST) as a dotted line in blue and the maximum suicide temperature (MaxST) as a dash-dotted line in red, respectively. CI, confidence interval; RR, relative risk. (See Figure S3 for location-specific estimates.)

Discussion

In this study, we found that higher ambient temperature was associated with an increased risk of suicide based on large-scale data from 341 locations across 12 countries. The association between temperature and suicide over multiple days showed nonlinearity in some locations, with the risk of suicide no longer increasing with temperature above a high threshold. Based on the broad range of temperature distribution across the locations, we identified the critical temperature values to maximize the risk of suicide (MaxST) that were less variable across locations compared with the temperature at the lowest risk of suicide (MinST). To the best of our knowledge, this is the largest study to investigate the short-term association between ambient temperature and suicide. The results of this study has important implications for public health given the high rates of suicide in young populations and the progressively warming climate.

Our findings indicate that the country-specific temperature–suicide associations could be clustered regarding two main aspects: *a*) the shape of the association curve, and *b*) the relative risk, except for the countries where large uncertainties were estimated.

The shape of curves in Western countries (Canada, Spain, Switzerland, the UK, and the United States) and South Africa were nearly linear, with the MaxST at the 99th percentile of temperature. In contrast, the three northeast Asian countries (Japan, South Korea, and Taiwan) showed an inverted J-shaped temperature–suicide association, with the lower MaxST ranging in the 87th to 88th percentiles, relative to the 99th percentile of temperature. These findings are consistent with some previous studies conducted in Toronto (Canada) (Dixon et al. 2014), Japan (Likhvar et al. 2011), England and Wales (UK) (Page et al. 2007), and the United States (Burke et al. 2018). In addition, the different shape of the curves could support the previous mixed findings of the heat-related suicide deaths from the two studies conducted in England and Wales (UK) (Gasparrini et al. 2012b) and Seoul (South Korea) (Kim et al. 2015) using comparable methodologies. The former study in the UK reported the percent increase of heat-related suicide at 2.8% per 1°C increase above a threshold (the 93rd percentile of lag 0–1 maximum temperature), whereas the latter study in Seoul reported a decreased risk of suicide (RR = 0.97) per 1°C increase above a threshold (the 90th percentile of maximum temperature).

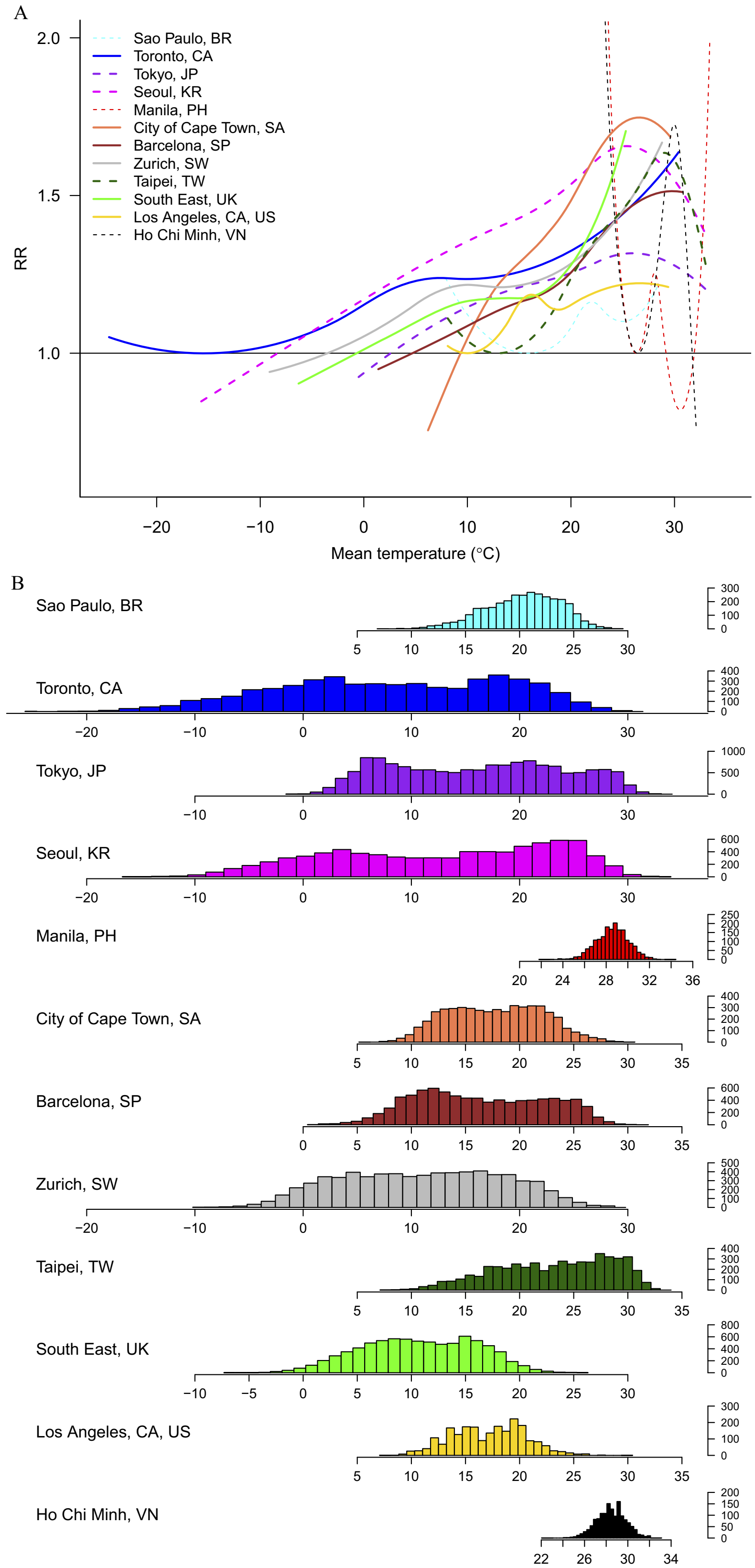

Figure 5. (A) Lag-cumulative temperature–suicide associations for the locations with the largest number of suicides in each country, estimated by using a conditional Poisson model adjusting for seasonality, long-term time trend, and the day of week. Solid lines are the cities where the curves were nearly linear. Thick dashed lines are the cities with the inverted J-shaped curves. Thin dashed lines are the cities with large uncertainty. BR, Brazil; CA, Canada; JP, Japan; KR, South Korea; PH, the Philippines; RR, relative risk; SA, South Africa; SP, Spain; SW, Switzerland; TW, Taiwan; UK, the UK; US, the United States; VN, Vietnam. (B) Temperature distributions (°C) for the selective locations with the largest number of suicides for each country. The *x*-axis indicates mean temperature, and the *y*-axis indicates the number of days.

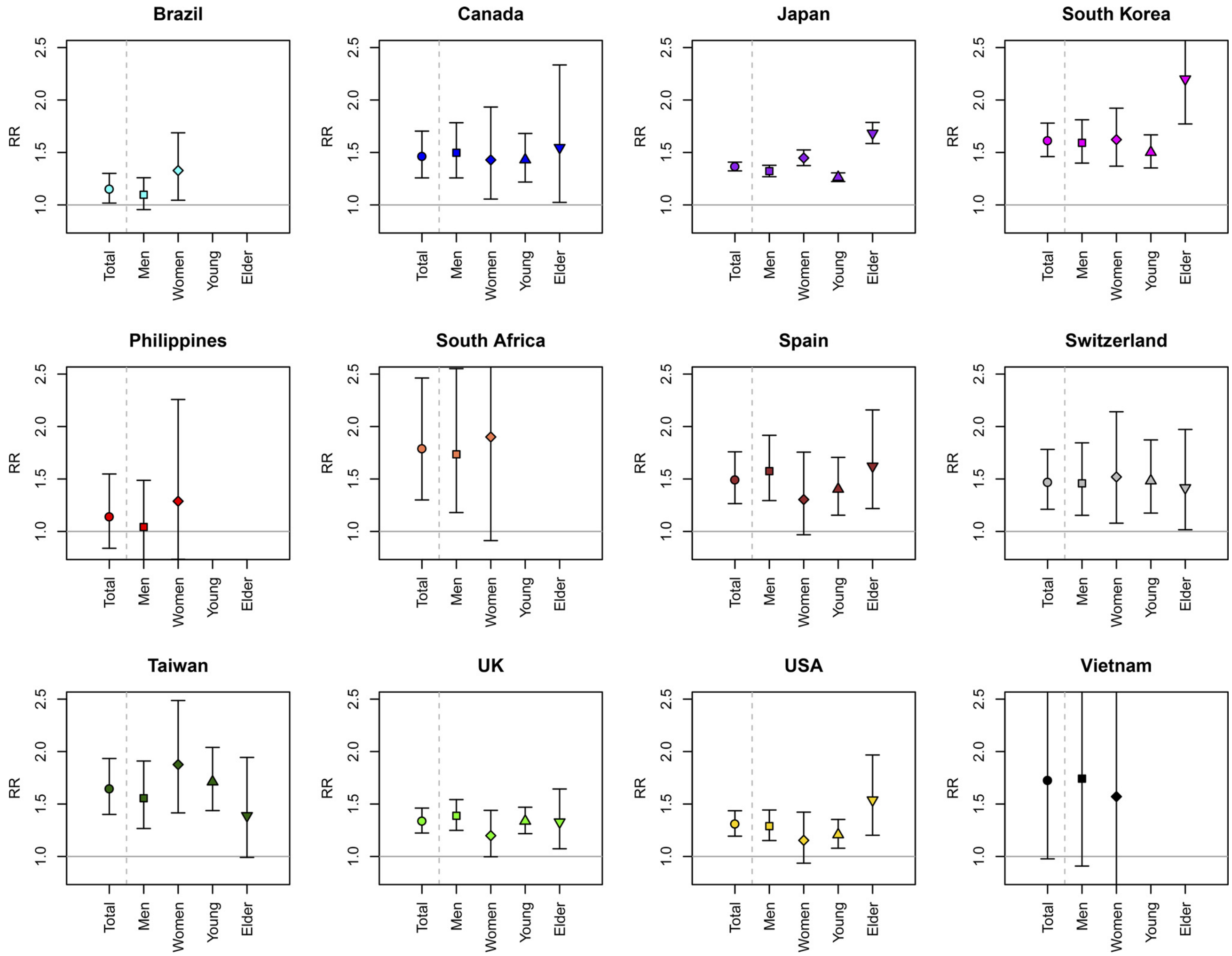

Figure 6. Pooled lag-cumulative relative risks (RRs) with 95% CIs (vertical bars) by country in subgroup analyses by sex and age groups (young, <65 years of age; elder, ≥65 years of age) using a conditional Poisson model adjusting for seasonality, long-term time trend, and the day of week. All 341 locations were included for total. The subgroup analyses included 245 locations for sex and 206 locations for age groups because of the low numbers of suicide cases in women and older adults in small cities/regions. Data not shown for age groups in Brazil, the Philippines, South Africa, and Vietnam, where the results were highly unstable due to the low numbers of suicide cases. CI, confidence interval.

We hypothesized that the difference in shapes of curves for the association was due to different climates (i.e., linear in cooler areas vs. nonlinear in warmer areas) because the larger number of hot days in the warmer areas would allow more precise estimates for the risk of suicide at extremely high temperature. Our underlying assumption was that a nonlinear temperature–suicide relationship, characterized by a critical range of ambient temperature mainly including moderate high temperatures, may be universal given a broad range of temperature distribution. Consequently, in cooler areas where extremely hot days rarely occur, it is more likely to observe a linear relationship because the regression curves estimated may barely reach the critical range of temperature. In fact, we observed a tendency that the number of hotter days was smaller in the UK, Canada, and Switzerland followed by South Africa, Spain, and the United States where the curves were nearly linear, whereas the number of hotter days was larger in South Korea, Japan, and Taiwan where the nonlinear curves were more obvious (see Table S1). However, our findings alone may not completely support this hypothesis because there might be other factors that explain the results, such as the higher proportion of suicides in women in the three Asian countries (Table 1). Exploring more potential determinants and including more study areas could help clarify these results.

Another aspect is that countries could be clustered into three groups based on the magnitude of the estimated RR: low-RR (Japan, the UK, and the United States), middle-RR (Canada, Switzerland, and Spain), and high-RR (South Korea and Taiwan) (Table 2; Figure 3B). This clustering was not consistent with the grouping structure based on the different shapes of curve as described above. For example, among the three Asian countries with the inverted J-shaped curves, the lower RRs were found in Japan only. Similarly, among the group with approximately linear curves, the lower RRs were estimated in the UK and the United States. Suicide rates for each country also did not explain such clustering structure with low versus middle versus high RRs (Table 1). For example, the suicide rate in Spain was as low as the rate in UK in the low-RR group (6.9 per 100,000 in 2012 for both). It is interesting that some populations are more sensitive to ambient temperature exposure than others in terms of the temperature–suicide association. We presume that some other factors might have modified the role of temperature on suicide such as antidepressant drug use and/or special holidays that could be potentially associated with suicide and vary depending on the countries. For example, in the areas with a higher rate of the antidepressant drug use, the temperature–suicide association might be attenuated or enhanced depending on the effectiveness and possible side effects of the drugs used (Makris et al. 2013). Special holidays such as New Year's and Christmas days and possibly other traditional holidays in Western and Eastern cultures could be associated with the risk of suicide in a specific season (or in a specific range of temperature), which might, in turn, modify the role of ambient temperature on suicide in areas with the effects of the special holidays. Future studies to reveal other explanatory factors, including those described above, could help explain the spatial difference in the temperature–suicide associations.

The mechanism behind the association between temperature and suicide has not yet been established, but the hypothesis based on the serotonergic system in the brain has been discussed as the most plausible explanation. Extensive evidence, with findings of biomarkers (Bach and Arango 2012), supports that serotonin (5-HT) deficits are associated with suicide attempts and completed suicides. Several studies attempting to investigate the link between ambient temperature and the biomarkers of serotonin—for example, cerebrospinal fluid 5-hydroxy-indoleacetic acid (5-HIAA) (Brewerton et al. 2018), L-tryptophan (Maes et al. 1995), and platelet serotonin transporters densities (Tiihonen et al. 2017)—have reported negative correlations. This implies that changes in serotonin function influenced by ambient temperature may induce impulsiveness and aggression and possibly lead to suicidal behaviors.

We acknowledge several limitations in this study. First, although we summarized our findings for each country, the effect estimates from most of the countries were based on their urban populations, and only a few of the countries covered their general populations across almost the entire country (i.e., Japan and the UK). Second, our results for the Philippines, Vietnam, and South Africa have large uncertainties. Low suicide rates have been reported for these countries, but the smaller samples make the results more uncertain because of the lack of statistical power. The lower quality of the suicide data in Vietnam could be another limitation (WHO 2014). Routinely collected vital statistics in South Africa are also known to underreport and/or misclassify violent deaths including suicides (Pillay-van Wyk et al. 2016; Prinsloo et al. 2017). Besides the data issues, the less robust results in the tropical countries might result from their less variable temperature distributions compared with other countries in temperate regions (Fernández-Niño et al. 2018). Last, we did not account for uncertainty in MinST and MaxST when estimating the RRs. A simulation study demonstrated that not addressing the uncertainty in a reference temperature such as a minimum mortality temperature (MMT) for the temperature–mortality association could induce extra uncertainty in the estimation of the MMT-referenced RR (Lee et al. 2017).

It is challenging to accurately predict where and when the risk of suicide becomes much higher because numerous risk factors are engaged in the elevated risk of suicide. However, we believe that a better understanding of the temperature–suicide association could potentially provide significant insight into the risk of suicide at the population level, in addition to considering individual risk factors. For example, population-level campaigns that coincide with an optimal period to take into account the role of ambient temperature on suicide may be worth reviewing in order to deploy resources for suicide prevention more efficiently and to increase people's awareness of the risk of suicide during warmer periods. Furthermore, a better understanding may help in developing a prediction model for suicide prevention (Helama et al. 2013).

From the perspective of climate change and mental health, the potential for an increased risk of suicide attributable to extreme heat has been discussed previously (Berry et al. 2010; Bourque and Willox 2014; Burke et al. 2018; Prüss-Ustün et al. 2016). However, according to our findings, it seems this concern was accurate for some countries but not generalizable to others. In addition, the present study shows that some populations may be less sensitive to ambient temperature than others, as noted in previous findings for heat-related all-cause deaths (Gasparrini et al. 2015). To best address suicide (as one of the significant parts in mental health) in light of climate change, we suggest that more evidence of the exposure–response relationship itself, and the factors that modify it, are needed.

Conclusions

Suicide is a complex event, but it is preventable. The evidence we observed that higher ambient temperatures are associated with the risk of suicide in multiple countries gives a better understanding of suicide epidemiology and may help to improve decision making for suicide prevention programs at a population level, in addition to considering individual risk factors. Our study also indicates that the heterogeneity of the temperature–suicide associations across countries should be considered when discussing the suicide issue with respect to climate change and corresponding extreme heat. This study can also help in generating future projections of mortality burdens from suicide under climate change.

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