Nonlinear temperature-suicide association in Japan from 1972 to 2015: Its heterogeneity and the role of climate, demographic, and socioeconomic factors

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ABSTRACT

It has been reported that suicide is associated with ambient temperature; however, the heterogeneity in this association and its underlying factors have not been extensively investigated. Therefore, we investigated the spatial and temporal variation in the temperature–suicide association and examined climatic, demographic, and socioeconomic factors that may underlie such heterogeneity. We analyzed the daily time-series data for the suicide counts and ambient temperature, which were collected for the 47 prefectures of Japan from 1972 to 2015, using a two-stage analysis. In the first stage, the prefecture-specific temperature–suicide association was estimated by using a generalized linear model. In the second stage, the prefecture-specific associations were pooled, and key factors explaining the spatial and temporal variation were identified by using mixed effects *meta*-regression. Results showed that there is an inverted J-shape nonlinear association between temperature and suicide; the suicide risk increased with temperature but leveled off above 24.4 °C. The nationwide relative risk (RR) for the maximum suicide temperature versus 5th temperature percentile (2.9 °C) was estimated as 1.26 (95% CI: 1.22, 1.29). The RRs were larger for females than for males (1.32 vs. 1.22) and larger for elderly people ($\geq$65 y) than for the non-elderly (15–64 y) (1.51 vs. 1.18). The RRs were larger for rural prefectures, which are characterized by smaller population, higher proportions of females and elderly people, and lower levels of financial capability and the proportion of highly educated people. The RRs were also larger in colder and less humid prefectures. These findings may help in understanding the potential mechanism of the temperature–suicide association and projecting the future risk of suicide under climate change.

1. Introduction

Several studies have reported that suicide is associated with the ambient temperature (Page et al. 2007; Likhvar et al. 2011; Hanigan et al. 2012; Dixon et al. 2014; Williams et al. 2015; Kim et al. 2016; Bando et al. 2017; Carleton 2017; Burke et al. 2018; Dixon and Kalkstein 2018; Thompson et al. 2018; Gao et al. 2019; Kim et al. 2019). Earlier studies focused on a single location or a country, reporting consistent findings that the occurrence of suicide increased with

the temperature (Page et al. 2007; Likhvar et al. 2011; Williams et al. 2015; Bando et al. 2017). More recent studies investigated the phenomenon in multiple countries, suggesting that the association may be heterogeneous over different populations (Hanigan et al. 2012; Dixon et al. 2014; Kim et al. 2016; Carleton 2017; Dixon and Kalkstein 2018; Gao et al. 2019; Kim et al. 2019). In addition, a few studies examined the temporal change in the association and observed no variation over time (Hanigan et al. 2012; Burke et al. 2018).

Although evidence for the heterogeneity in the temperature–suicide

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association is increasing, the underlying factors have not been extensively investigated. Identifying the key factors that may explain such heterogeneity can enhance the understanding of the potential mechanism of the temperature-related suicide risk, which still remains unclear (Kim et al. 2019). The literature regarding the potential determinants of the heterogeneity in the association of temperature with total or cardiorespiratory mortality are extensive (Anderson and Bell 2009; Gasparrini et al. 2015; Ban et al. 2017; Chung et al. 2017; Chung et al. 2018; Vicedo-Cabrera et al. 2018); however, other causes of mortality, including mental health-related deaths such as suicides, have been understudied.

Assessing the public health impact of climate change has become increasingly important. Suicide is a key component that should be carefully considered in the future health impact assessment related to climate change (Smith et al. 2014). Thus, a systematic evaluation of the heterogeneity in suicide risk related to the temperature is warranted to better project and manage the future risk of suicide related to the changing climate. Furthermore, the identification of various factors that influence the temperature–suicide association can help determine the vulnerable subpopulations on which the public health interventions should be focused.

Considering this background, this study was aimed to investigate the heterogeneity in the temperature–suicide association in Japan from 1972 to 2015 and the associated role of the climatic, demographic, and socioeconomic factors. This nationwide study of Japan has several strengths. First, Japan had the 6th highest suicide rate among the OECD countries in 2017 (OECD, 2019). Thus, a sufficient number of suicide counts are available to study the short-term temperature–suicide association both at the national and prefectural level. Furthermore, Japan is heterogeneous in terms of the climate from the north to the south, which helps in investigating the spatial variation. Finally, the daily data for suicide counts are available for more than four decadal periods, which allows for the examination of a long-term temporal change.

2. Methods

2.1. Data

2.1.1. Suicide and temperature

Daily time-series data for the suicide counts and weather variables for 47 prefectures in Japan (covering the whole country) for the period 1972–2015 were collected. The daily suicide counts were extracted from a computerized death certificate database maintained by the Ministry of Health, Labor and Welfare of Japan. 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. Violent suicide was identified using the codes E953.0–E958.9 for ICD-8 and −9 and the codes X70–X84 for ICD-10. The daily mean ambient temperature and relative humidity were collected as the weather variables. The daily data were obtained from the hourly measurements provided by the Japan Meteorology Agency for a single weather station in the capital city of each prefecture. Using the two weather variables, we calculated daily mean dewpoint temperature as a measure of humidity (Lawrence 2005; Davis et al. 2016).

2.1.2. Prefecture-level indicators

Data pertaining to the prefecture-level climatic, demographic, and socioeconomic indicators were collected. First, we derived the prefecture-level annual average of temperature (Tmean) and dewpoint temperature (Dewpoint) from the daily weather data described earlier. Second, several demographic variables were collected from the Statistics Bureau of the Ministry of Internal Affairs and Communications of Japan. The annual statistics for the total population (TotPop) and the

proportion of females (%Female) and people aged ≥ 65 y (%65+) were collected for 1972–2015. The annual statistics for the proportions of people who have subjective symptoms (%SubjSymp) and outpatients (%Outpt) were collected for every 3 years between 1986 and 2013. Third, for the socioeconomic variables, the yearly value of the economic power index (EPI), which represents the financial capability of the local government, was obtained for 2003–2010 from the Ministry of Internal Affairs and Communications of Japan (2009). The annual statistics for the proportion of people having completed up to college or university-level education (%CollUniv) and the unemployment rate (%Unemploy) were collected for every 10 years between 1980 and 2010 and for every 5 years between 1975 and 2015, respectively, from the Statistics Bureau. In addition, the annual prevalence of the air conditioning (ACprev) for households with two or more persons was extracted from a regional statistics database (Asahi Newspaper, 2015) for 1972–2009. Lastly, we derived the prefecture-level suicide statistics from the daily suicide data described earlier.

2.2. Statistical analysis

A two-stage analysis was performed. In the first stage, a time-stratified case-crossover analysis was performed to examine the short-term association between the temperature and suicide for each prefecture. In the second stage, multivariate *meta*-regression was used to pool the prefecture-specific associations to obtain a nationwide estimate. Furthermore, a subgroup analysis was performed by considering the gender and age, and a sub-period analysis was performed to investigate the temporal trend. Moreover, mixed effects *meta*-regression was used to identify the prefecture-level variables that explain the heterogeneity in the temperature–suicide association. We used R (version 3.4.4) with the packages "gnm" and "dlnm" for the time-stratified case-crossover analysis, "mvmeta" for the pooling the associations, and "mixmeta" for the mixed effects *meta*-regression (R Core Team 2015).

2.2.1. Two-Stage analysis

In the first stage, to conduct a time-stratified case-crossover analysis, a conditional Poisson regression was fit, considering the over-dispersion (Armstrong et al. 2014). We defined a stratum considering the three-way interaction of the calendar year, month, and day-of-week to compare the exposure levels between the case and control days matched within each stratum. That is, each case was matched with several controls on the same day-of-week in the same month of the same year (i.e., 1:3 or 1:4 matching). This case-crossover design fully adjusted for the long-term trend, seasonality, and the day-of-week under the assumption that the unmeasured time-varying confounders were constant within a stratum (Lu et al. 2008). The strata with no suicide events were excluded from the analysis to increase the statistical power.

The short-term association between temperature and suicide was modeled using the distributed lag nonlinear functions to describe a nonlinear and nonlinearly delayed association (Gasparrini et al. 2010). Specifically, a cross-basis function with a natural cubic B-spline basis having a degree of freedom (df) of 4 was used for the temperature, and a natural cubic B-spline basis with df 4 was introduced for the lag. The lag was extended up to three previous days. The choices for the df and maximal lag were based on the model selection criteria, QAIC. From the fitted model, we estimated the lag-cumulative relative risk (RR) (Gasparrini and Armstrong 2013) for the observed range of the temperature versus the 5th percentile of the prefecture-specific temperature distribution. In the second stage, the prefecture-specific association (i.e., the lag-cumulative RR curve) was pooled to obtain the nationwide association by performing multivariate *meta*-regression (Gasparrini et al., 2012). The two-stage analysis was performed for the total population and the subgroups divided by the gender and age. Furthermore, a sub-period analysis was performed to examine the temporal change. The entire period was divided into five sub-periods:

1972–1980, 1981–1990, 1991–2000, 2001–2010, and 2011–2015.

For each prefecture and each sub-period, the temperature corresponding to the maximum risk of suicide was identified from the RR curve. The RR for the maximum suicide temperature versus the 5th temperature percentile for each period was calculated as a single value summary for the temperature–suicide association (hereafter, we simply called the RR). Using the RRs, the following mixed effects *meta*-regression (Sera et al. 2019) was fit: For $i = 1,…,47$, and $j = 1,…,5$,

$$Log(RR_{ij}) = \beta_0 + factor(period) + \beta_1 x_{ij} + b_{i0} + b_{i1} factor(period) + \epsilon_{ij}$$

(1)

where RR_{ij} is the RR for the ith prefecture at the jth sub-period, and x_{ij} is the prefecture-level variable for the ith prefecture at the jth sub-period. Therefore, β_1 indicates the increment in log(RR) per unit increase in each prefecture-level variable controlling for the prefecture-specific intercept and period effects. We fit the above model for each prefecture-level variable separately. Additionally, to gain an insight into the correlations among the variables, a principal component (PC) analysis was conducted to the standardized variables.

Finally, as a sensitive analysis, we calculated the relative risk for the maximum suicide temperature versus the minimum suicide temperature (hereafter, called the max/min RR). The minimum suicide temperature happens to be the observed minimum temperature in all prefectures. Using the max/min RR, we conducted the mixed effects *meta*-regression analysis as in formula (1).

3. Results

3.1. Descriptive results

A total of 1,067,333 suicides were considered in this study. Table 1 presents the summary statistics for prefecture-level annual values for suicide and climatic, demographic, and socioeconomic indicators. Tables S1–S3 provide the prefecture-specific statistics. The total suicide count ranged from 5,591 to 96,190 over the prefectures (Table S1). The annual median of the daily mean temperature ranged from 9.2 to 23.3 (°C), and the median of the dewpoint temperature varied from 2.9 to

Table 1
Mean of prefecture-specific average annual statistics for suicide and climatic, demographic, and socioeconomic indicators.

Category	Mean (SD)[1]
Suicide	
Annual suicide count (deaths)	516.2 (435.6)
Annual suicide rate (deaths/100,000)	20.9 (3.15)
Annual proportion of violent suicide (%)	84.0 (3.01)
Annual proportion of female suicide (%)	33.7 (2.38)
Annual proportion of people aged 15–64 y in the total suicide count (%)	71.7 (4.32)
Annual proportion of people aged over 65 y in the total suicide count (%)	28.0 (4.36)
Climatic	
Annual mean temperature (°C)	15.1 (2.34)
Annual mean dewpoint temperature (°C)	9.5 (2.19)
Demographic	
Annual total population (thousands)	2,608 (2440)
Annual proportion of people aged over 65 y (%)	16.4 (2.29)
Annual proportion of females (%)	51.8 (1.02)
Annual proportion of people who have subjective symptoms (%)	29.4 (1.84)
Annual proportion of outpatients (%)	30.0 (1.78)
Socioeconomic	
Annual economic power index	0.47 (0.20)
Annual prevalence of air conditioning (%)	57.7 (16.71)
Annual proportion of people having completed up to college or university (%)	20.1 (4.91)
Annual unemployment rate (%)	4.0 (1.03)

[1] The mean and standard deviation (SD) were calculated over 47 prefectures using the prefecture-specific average annual statistics for 1972–2015.

19.0 (°C) (Table S2). The annual estimate of the total population ranged from 602 to 12,124 (thousands), and the AC prevalence exhibited a broad range from 6.1 to 82.6 (%) (Table S3).

Figure S1 shows the spatial pattern of the prefecture-specific summary statistics. The spatial distribution of the daily suicide counts (Figure S1-(A)) was similar to that of the total population (Figure S1-(E)). A strong spatial pattern was observed in both the mean ambient temperature (Figure S1-(C)) and mean dewpoint temperature (Figure S1-(D)) with higher levels in the south and lower levels in the north.

3.2. Short-term association between temperature and suicide

Fig. 1 illustrates the short-term association between the temperature and suicide occurrence in Japan. For the total population (Fig. 1-(A)), we observed an inverted J-shape nonlinear association; the risk of suicide increased as the temperature increased but leveled off for the temperature above a threshold. The maximum suicide temperature was estimated as 24.4 °C (95% CI: 23.4, 26.1), and the RR was 1.26 (1.22, 1.29). Such nonlinear associations were observed in most of the prefectures (Figure S2). Fig. 1-(B) shows that the RR varied over the prefectures from 1.02 to 1.78.

For the subgroups by gender (Fig. 1-(C)), the RR curve was higher for females than for males, with the RR of 1.32 (1.26, 1.38) for females and 1.22 (1.18, 1.27) for males. The RRs for males were generally low over the prefectures (Fig. 1-(D)) while the RRs for females were relatively high in some particular prefectures (Fig. 1-(E)). For the two age groups (Fig. 1-(F)), the RR curve was substantially higher for elderly people (≥ 65 y) than for the non-elderly individuals (15–64 y), with the RR of 1.51 (1.39, 1.63) for the elderly and 1.18 (1.15, 1.21) for the non-elderly. The RRs were low for the non-elderly in most prefectures (Fig. 1-(G)) whereas the RRs for the elderly were very high in the prefectures of the northwestern coastal area (Fig. 1-(H)).

Fig. 2 presents the temperature–suicide association over different sub-periods. For the total population (Fig. 2-(A)), the shape of the RR curve was similar over the sub-periods except that the curve plateaued at a relatively low temperature in the 2000s. In the subgroup analysis (Fig. 2-(B) and (C)), the wider plateau in the RR curve in the 2000s was more obvious for males and the non-elderly. Fig. 2-(D) indicated that the RR was substantially low in the 2000s for males and for the non-elderly, and consequently in the total population.

Fig. 3-(A) presents how the RR changed by each prefecture-level variable. Larger RRs were associated with lower levels of temperature, dewpoint temperature, and total population, and higher proportions of the elderly and females. Furthermore, larger RRs were associated with lower levels of the EPI, air conditioning prevalence, and the proportion of highly educated people. In addition, larger RRs were associated with higher values of suicide rate and the proportion of elderly suicide.

Fig. 3-(B) shows the correlation among the prefecture-level variables, and Fig. 3-(C) shows the results of the PC analysis. The variables were highly correlated with each other, and the first two PCs explained approximately 65% of the total variability. Fig. 3-(C) shows a scatter plot for the first two PC scores of each prefecture with the loadings on each variable for each PC. The first PC (PC1) explained approximately 44.1% of the total variation and acted as an indicator for the urban/rural area, with large positive loadings on total population, EPI, the proportion of highly educated people, and AC prevalence but large negative loadings on suicide rate, the proportions of females and the elderly, and the percentage of people who have subjective symptoms or are outpatients. The second PC (PC2) explained approximately 21.5% of the variability, acting as an indicator for the climate conditions (i.e., southern/northern regions), with large positive loadings on temperature and dewpoint temperature.

Using the PC scores, we divided the 47 prefectures into the urban (PC1 > 0) and rural (PC1 < 0) groups and southern (PC2 > 0) and northern (PC2 < 0) groups, and obtained the subgroup-specific associations (Figure S3). As expected, the RR curves were considerably
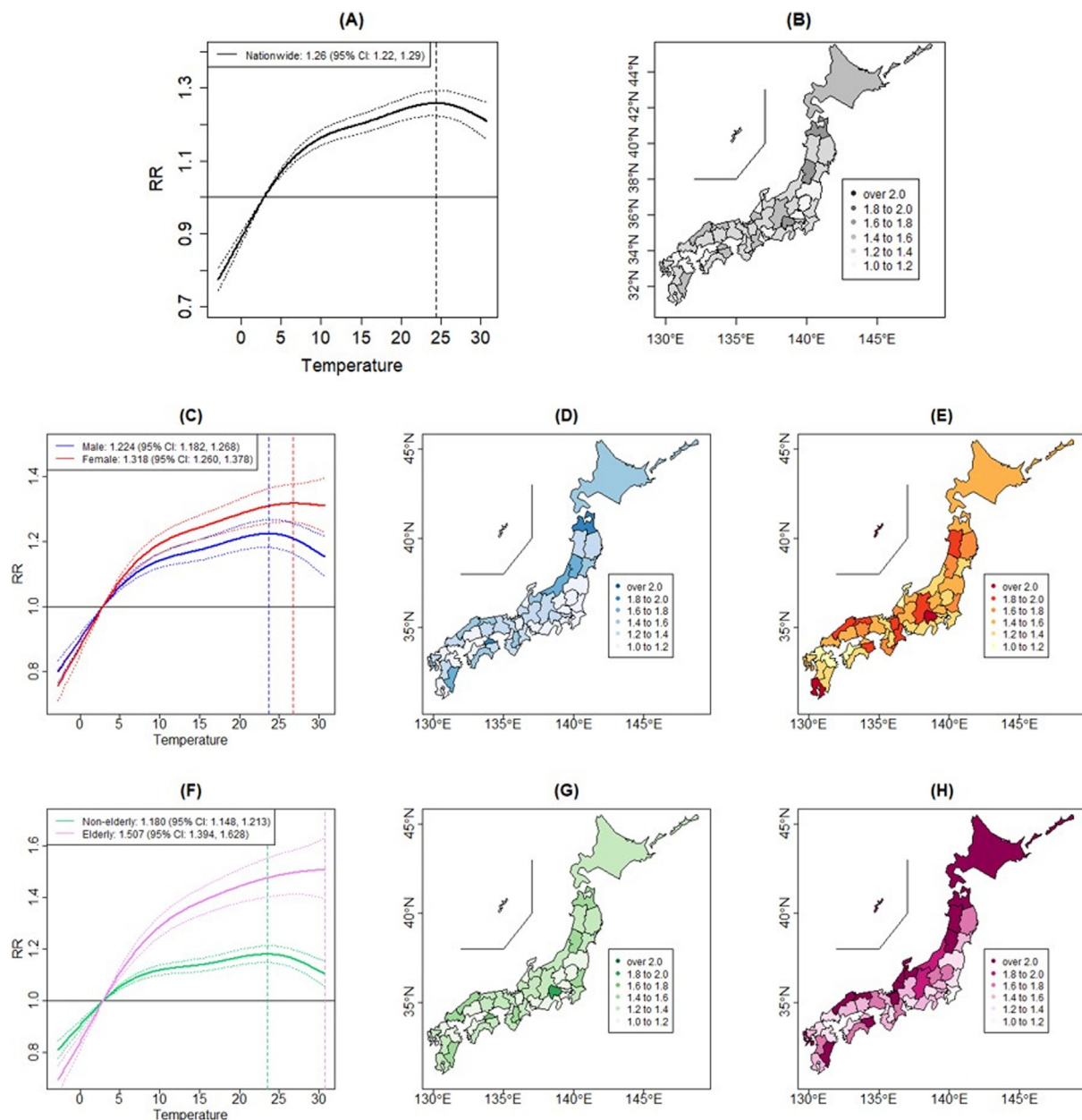
Fig. 1. Short-term association between temperature and suicide represented by the lag-cumulative relative risk (RR) curve and the spatial map of the prefecture-specific RR for the maximum suicide temperature versus the 5th percentile of observed temperature (2.9 °C); (A) RR curve for the total population; (B) spatial map of the RR in the total population; (C) RR curve for males and females; (D) spatial map of the RR in males; (E) spatial map of the RR in females; (F) RR curve for the non-elderly (15–64 y) and elderly (≥65 y) population; (G) spatial map of the RR for the non-elderly; and (H) spatial map of the RR for the elderly.

higher for the rural prefectures than for the urban ones with the RR of 1.32 (1.26, 1.38) and 1.20 (1.17, 1.24), respectively. However, the southern and northern prefectures exhibited similar RR curves with the RR of 1.30 (1.22, 1.37) and 1.25 (1.21, 1.29), respectively.

As a sensitivity analysis, we calculated the max/min RR, that is the relative risk for maximum suicide temperature versus minimum suicide temperature as a reference instead of the 5th percentile. Figures S4–S5 show that the conclusions drawn in Figs. 1 and 2 remain the same except that the RR curve shifted upwards overall. Figure S6 indicates that the conclusion in Fig. 3-(A) remains similar but the RR change derived by temperature and dewpoint temperature became statistically insignificant.

4. Discussion

This work represents the first nationwide study to investigate the heterogeneity in the temperature–suicide association and the role of the climatic, demographic, and socioeconomic factors in explaining the varying associations. An inverted J-shape nonlinear association between the temperature and suicide risk was observed: the risk of suicide increased as the temperature increased but leveled off above a threshold temperature. The magnitude of the association (represented by the RR) was larger for the females and elderly people. Furthermore, the RR was larger in rural prefectures characterized by a smaller population, higher proportions of females and the elderly, and lower levels of socioeconomic capacity and people's education. The association remained similar over the four decadal periods from 1972 to 2015 except for a significant attenuation in the 2000s.
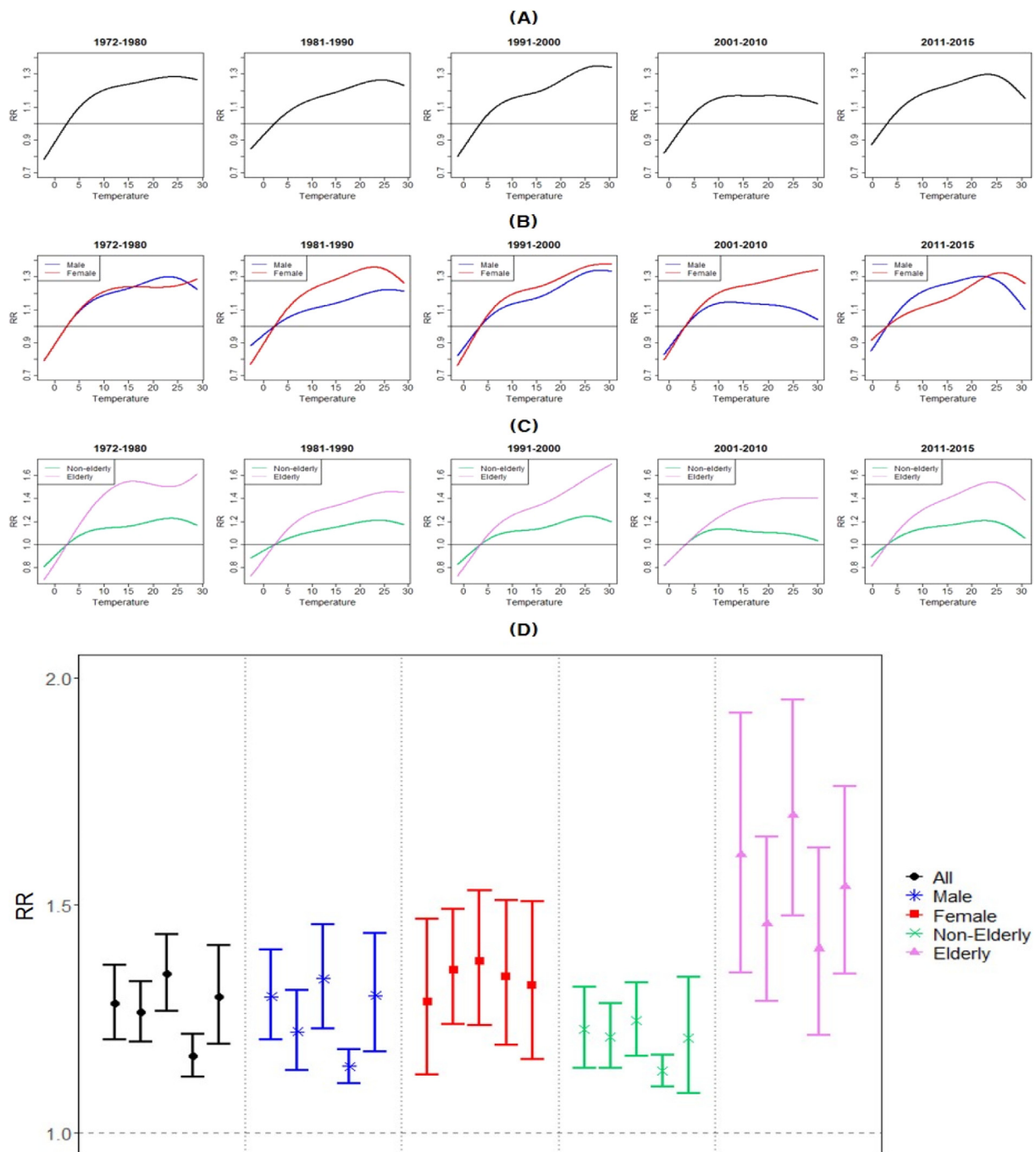
Fig. 2. Short-term association between the temperature and suicide represented by the lag-cumulative relative risk (RR) curve and the RR for the maximum suicide temperature versus the 5th percentile of observed temperature (2.9 °C) over different sub-periods; (A) RR curve over different periods for the total population; (B) RR curve over different periods for the males and females; (C) RR curve over different periods for the non-elderly (15–64 y) and the elderly (≥65 y) population; and (D) the RR over different periods by different subgroups.

The finding of a positive short-term association between the temperature and suicide is consistent with that of many previous studies (Page et al. 2007; Likhvar et al. 2011; Hanigan et al. 2012; Dixon et al. 2014; Williams et al. 2015; Kim et al. 2016; Bando et al. 2017; Carleton 2017; Burke et al. 2018; Dixon and Kalkstein 2018; Thompson et al. 2018; Kim et al. 2019; Gao et al. 2019). However, a recent multi-country study reported that, although this association is positive, it may be linear or nonlinear depending on the considered countries (Kim et al. 2019). Our result in Japan adds to the evidence of an inverted J-shape nonlinear association, implying that an extremely hot temperature may not increase the suicide risk compared with that corresponding to the moderately hot ones. This aspect is quite different from the temperature association with the general or cardiorespiratory mortality, which takes the U- or J-shape in general, indicating that the presence of extreme temperatures further increases the mortality risk (Anderson and Bell 2009; Gasparrini et al. 2015; Ban et al. 2017; Chung et al. 2017; Chung et al. 2018; Vicedo-Cabrera et al. 2018). This aspect implies that the potential mechanism of the temperature effect on suicide is different from that for the other causes of deaths. This finding also suggests that the nonlinear feature should be carefully considered in projecting the future risk of suicide under climate change, which was done in a previous study under the linearity assumption (Burke et al. 2018).
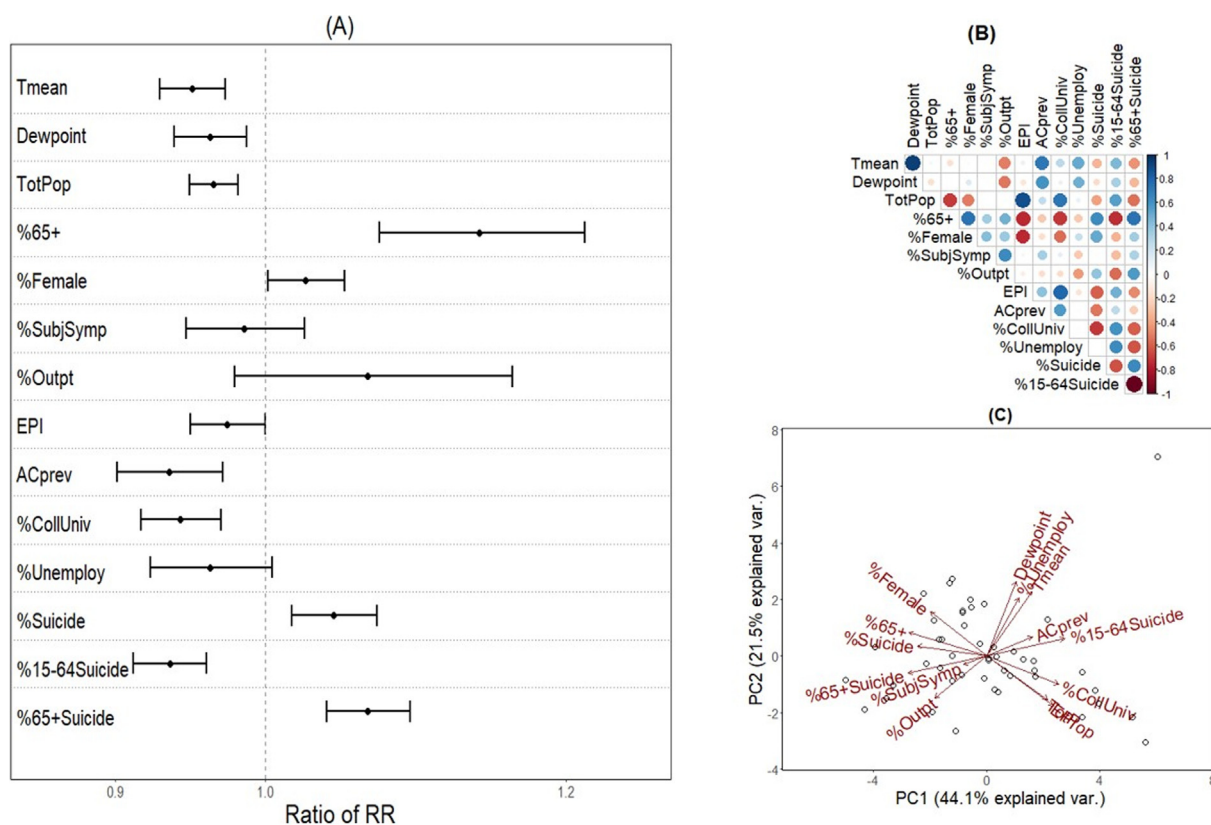
Fig. 3. Modification of the temperature–suicide association by each prefecture-level variable, and the correlation structure among all the prefecture-level variables; (A) ratio of the RR per 1-standard deviation change in each prefecture-level variable, where the dots exhibit point estimates, and the bars indicate the 95% confidence intervals; (B) Pearson's correlation coefficients among all the prefecture-level variables; and (C) the first and second principal component scores (PC1 & PC2) (dots) for each prefecture along with the loading vectors for each prefecture-level variable (arrows). [Abbreviations: temperature (Tmean), dewpoint temperature (Dewpoint), total population (TotPop), proportion of the elderly (%65 +), proportion of females (%Female), proportion of people who have subjective symptoms (%SubjSymp), proportion of outpatients (%Outpt), economic power index (EPI), air conditioning prevalence (ACprev), proportion of people educated up to college or university (%CollUniv), unemployment rate (%Unemply), suicide rate (%Suicide), proportion of 15–64 y individuals in the total suicide count (%15–64Suicide), the proportion of elderly individuals in the total suicide count (%65 + Suicide)]

Our results exhibited that the temperature–suicide association may differ by the gender and age group. In particular, our findings suggest that females and the elderly are more sensitive to the increase in the temperature with respect to the risk of committing suicide. However, a recent multi-country study reported that the gender and age group difference was not observed in countries except for Japan and South Korea (Kim et al. 2019). This may imply that there exist some country- or culture-specific factors that may underlie the observed difference by the gender and age group in Japan. For example, the status of women is less-regarded than that of men, and the social welfare and concern for the elderly is relatively weak in Asian countries, which may make the change in weather conditions such as the temperature more likely to trigger suicide events in these subgroups. Other explanations were proposed in previous studies; the elderly people may be less cared for in the days with warmer temperature as people enjoy outdoor activities (Kim et al. 2011), and the elderly people tend not to use the cooling appliances like air conditioning even in hot weather, which may help explain the age group difference in temperature-related suicide risk (Kondo et al. 2013).

We found that the temperature–suicide association quantified by the RR remained similar over the four decadal study periods, except for a significant reduction in the 2000s. This is partly consistent with the findings of previous studies (Hanigan et al. 2012; Burke et al. 2018) in which no temporal change in the association was observed in Mexico and Australia; however, these findings seem contradictory to the evidence that the temperature association with general or cardiorespiratory mortality has continuously attenuated over the last decades

(Chung et al. 2018; Vicedo-Cabrera et al. 2018). Our results suggest that little adaptation may have happened in the suicide related to temperature under changing climate. They may further imply that the adaptive mechanism in mental health may be different from that in physiological health. However, the RR in our study was calculated comparing the 5th temperature percentile and the maximum suicide temperature, both of which varied over the sub-periods. So, it is hard to quantify the amount of adaptation or lack of adaptation in the current study. Although no continuous change was observed, we found that there was a temporary attenuation in the association in the 2000s in Japan with the RR curve exhibiting wider plateaus. This implies that the temperature variation did not affect the suicide risk much unless the temperature decreased considerably. This may be explained by the long-term economic stagnation that Japan went through in the 2000s, when the suicide rate recorded the highest ever value, as shown in Figure S7-(A). During this time, the proportion of female and elderly suicides was lower compared with that in the other periods (Figure S7-(B) and (D)), which may have led to the temporary attenuation of the association in the 2000s.

It was also observed that the magnitude of the association was larger for the rural prefectures than for the urban ones. These results may be explained by the fact that public health infrastructure is better established and local government interventions for preventing suicide events occur more frequently in urban area. Alternatively, the urban/rural difference may be interpreted in a comparable way to the interpretation of the seasonal suicide pattern being greater for rural areas than for urban ones. Previous studies observed that the spring peak of

suicide events tends to be higher in rural areas and suggested that urban people appear to be more immune to seasonal changes compared to people who engage in agricultural activities in rural areas. Consequently, the intensity of social stress, which may trigger suicide, may not fluctuate following the seasonal cycle in urban areas (Durkheim 1897; Chew and McCleary 1995; Ajdacic-Gross et al. 2010). In a similar context, urban people may be less sensitive to the weather change in terms of the vulnerability to committing suicide.

In addition to the urban/rural difference, the magnitude of the temperature–suicide association (represented by the RR) was observed to be larger for the prefectures with colder climates (i.e., lower temperature). This may be related to people's acclimatization to climate, which corresponds to a phenomenon in which people living in colder regions are less adapted to hot temperatures and thus are more sensitive to the increase in the temperature. Such adaptation has been observed in the temperature association with the total or cardiorespiratory mortality in many of the previous studies (Gasparrini et al., 2012; Chung et al. 2015; Chung et al. 2017; Chung et al. 2018). In addition, our findings suggest that people living in drier regions (lower level of dewpoint temperature) are more sensitive to the temperature in terms of the suicide risk. However, high correlation was observed between ambient temperature and dewpoint temperature (Fig. 3-(B)) in our data, so the observed modification of the association by dewpoint temperature may simply reflect the effects of the ambient temperature.

The potential mechanism of the temperature–suicide association has been discussed in many previous studies; however, it still remains uncertain. The most plausible explanation is the biological mechanism explained in a previous study (Kim et al. 2019). In particular, the deficits of the neurotransmitter serotonin (5-HT) are associated with suicidal behaviors, and negative correlations exist between the ambient temperature and the biomarkers of serotonin. In addition, psychiatric interpretations were proposed in other previous studies (Hansen et al. 2008; Page et al. 2012), which reported that people with mental illness are more vulnerable to heat-related mortality. These studies discussed that heat may exacerbate the mental disorders that lead to death and suicide, which is the most common cause of death for mentally ill people. This aspect may explain the temperature–suicide association observed in many studies.

Finally, we acknowledge some limitations in this study. First, we divided the complete period into five sub-periods to investigate the temporal change, which may be insufficient to examine a more continuous temporal change. However, our results suggest that a significant attenuation occurred only in the 2000s, whereas before and after this time, the association remained similar. In such a case, the sub-period analysis would be more appropriate to identify the temporary change point and interpret the findings. Second, we examined the role of each prefecture-level variable separately in the mixed effects *meta*-regression. Multiple variables can be included in the *meta*-regression, using which the important variables controlling the other variables can be determined. However, given the strong correlation structure as in Fig. 3-(B), the multiple variable approach may not select the actually important variables due to multicollinearity. Therefore, we conducted the PC analysis to provide information regarding the correlation structure among the variables. Lastly, we did not examine other macroeconomic indicators to explain the large reduction in the association in the 2000s.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105829.

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