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Projections of Temperature-Related Suicide under Climate Change Scenarios in Japan

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Background: The impact of climate change on mental health largely remains to be evaluated. Although growing evidence has reported a short-term association between suicide and temperature, future projections of temperature-attributable suicide have not been thoroughly examined.

Objectives: We aimed to project the excess temperature-related suicide mortality in Japan under three climate change scenarios until the 2090s.

Methods: Daily time series of mean temperature and the number of suicide deaths in 1973–2015 were collected for 47 prefectures in Japan. A two-stage time-stratified case-crossover analysis was used to estimate the temperature–suicide association. We obtained the modeled daily temperature series using five general circulation models under three climate change scenarios from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathways scenarios (SSPs): SSP1-2.6, SSP2-4.5, and SSP5-8.5. We projected the excess temperature-related suicide mortality until 2099 for each scenario and evaluated the net relative changes compared with the 2010s.

Results: During 1973–2015, there was a total of 1,049,592 suicides in Japan. Net increases in temperature-related excess suicide mortality were estimated under all scenarios. The net change in 2090–2099 compared with 2010–2019 was 1.3% [95% empirical confidence interval (eCI): 0.6, 2.4] for the intermediate-emission scenario (SSP2-4.5), 0.6% (95% eCI: 0.1, 1.6) for a low-emission scenario (SSP1-2.6), and 2.4% (95% eCI: 0.7, 3.9) for the extreme scenario (SSP5-8.5). The increases were greater the more extreme the scenarios were, with the highest increase under the most extreme scenario (SSP5-8.5).

Discussion: This study indicates that Japan may experience a net increase in excess temperature-related suicide mortality, especially under the intermediate and extreme scenarios. The findings underscore the importance of mitigation policies. Further investigations of the future impacts of climate change on mental health including suicide are warranted. https://doi.org/10.1289/EHP11246

Introduction

Climate change is one of the most important global challenges of the 21st century[1] affecting human health. A growing number of studies have investigated the impacts of climate change on mental health.[2,3] A systematic review[3] has found strong evidence of adverse impacts of climate change on mental health, including psychological distress symptoms[4,5] and sleep disturbances,[6] as well as mood disorders, such as depression[7–9] and anxiety,[7,9–12] and posttraumatic stress disorder[7,9,11–13] via both direct or indirect and short- and long-term effects. A recent scoping review also found evidence supporting the adverse impacts of climate change on mental health; climate change-related exposures such as heat, humidity, rainfall, drought, wildfires, and floods were associated with worse mental health, psychological distress, and increased suicide rates.[2] Heat is the most commonly studied climate-related exposure related to human health risk, and most studies found a rise in temperature was positively associated with worse mental health outcomes.[2] For instance, a systematic review found a positive association between elevated ambient temperatures and adverse mental health outcomes, with a meta-analysis showing that mental health-related mortality and morbidity increased with a relative risk (RR) of 1.022 [95% confidence interval (CI): 1.015, 1.029] and 1.009 (95% CI: 1.007, 1.015), respectively for each 1°C rise in temperature.[14] Increased ambient temperature was associated with elevated risks across most cause-specific mental health-related morbidity outcomes, including mood disorders, organic mental disorders, schizophrenia, and anxiety disorders, as well as across some mortality outcomes, such as organic mental disorders, and suicides and self-harm.[14]

Suicide is one of the heat-associated mental health outcomes.[2] Previous studies have found that ambient temperature may play a role in triggering suicides.[15–19] In 2019, suicide was the fourth leading cause of death globally among people 15–29 years of age, and with an estimated 703,000 suicide deaths globally for all ages, the age-standardized mortality rate was 9.0 per 100,000.[20] A recent systematic review reported that the RR of daily suicide per 7.1°C increase in daily temperature was 1.09 (95% CI: 1.06, 1.13).[16] Similarly, another systematic review and meta-analysis that examined short-term changes in meteorological conditions and suicide found a positive association between suicides and an increase in ambient temperature, with the RR for suicide deaths per 1°C rise in temperature of 1.016 (95% CI: 1.013, 1.019).[21] The strongest associations were found in the Pacific area and East Asia.[21] Although higher ambient temperature was generally associated with an increased suicide risk, the associations were inverted J shaped in East Asian countries, such as Japan and South Korea, whereas in Western countries, the associations were more linear.[17,19]

Despite the growing number of studies on climate change and mental health, the focus on the climate change impacts on mental health remains secondary to physical health, and the area of research is limited.[2,3] This is detrimental to the effort of improving the mental health of populations. For instance, there has been an increasing number of future projection studies investigating the temperature-related excess all-cause or nonexternal cause mortality under climate change scenarios.[22] However, evidence of such impacts on mental health, including suicide, is limited, and few quantitative future projection studies have investigated future climate change impacts on mental health outcomes.[23–25] For specific mental disorders, insufficient studies have been conducted assessing projected future health risks under climate change.[26] To our knowledge, only limited quantitative future projection studies

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have investigated suicide. The current evidence on this area is largely from North America.[24,25] One study used linear assumption to project the future suicide rates across the United States and Mexico under one climate change scenario, the high-emission Representative Concentration Pathway (RCP) 8.5 from the previous-generation Coupled Model Intercomparison Project Phase 5 (CMIP5), and projected 21,770 (95% CI: 8,950, 39,260) total additional suicides by 2050.[24] Another study suggested 3.0% annual increases in suicides by the end of the century, based on a simple projection under RCP8.5 scenario in the United States.[25] The association was again approximately linear, although the authors allowed for potential nonlinearities.[25] In the current phase of the CMIP (CMIP6), scenarios have been improved: CMIP6 models have better performance in simulating global surface air temperatures.[27] Projecting until the end of the century using multiple CMIP6 scenarios will provide a better and more nuanced picture of the future impacts and allow for comparison of late-century suicide outcomes of climate change between different warming levels, facilitating better development of future mitigation policies.

Furthermore, the impact of rising future temperatures on suicides in the presence of a nonlinear temperature–suicide association is unknown. Suicide remains one of the leading causes of death in Japan, with 20,169 suicides in 2019,[28] and it was the top cause of death for people 10–39 years of age in 2018.[29] The temperature–suicide association is nonlinear in Japan,[19] and the evidence of the impact of rising temperatures on suicide in Japan is scarce. To date, only limited studies have projected suicide in the presence of a nonlinear temperature-suicide association that projected until the end of the century under multiple latest climate change scenarios. Quantifying the link between climate change and mental health outcomes, such as suicide, is vital for facilitating more attention on mental health in the face of climate change. Therefore, the objective of this study was to project the future impact of climate change on temperature-attributable suicide mortality in all 47 prefectures in Japan under the three latest climate change scenarios from CMIP6 using a nonlinear assumption until 2099.

Methods

Data

Observed temperature and mortality data. Daily time-series data for observed daily temperature and suicide counts were collected for all 47 prefectures in Japan in the period 1973–2015. The daily mean ambient temperature was collected from the Japan Meteorological Agency, averaging hourly data captured by a single weather station in each capital city of the prefectures. Daily mean relative humidity (in percentage), daily precipitation (in millimeters), and daily mean wind speed (in meters per second) were also collected from the Japan Meteorological Agency. Cloud cover data (in percentage) was extracted from the European Centre for Medium-Range Weather Forecasts Re-Analysis 5 (ERA5), which is a gridded data set with a spatial resolution of $0.25^\circ \times 0.25^\circ$ and an hourly resolution.[30] The hourly cloud cover data was extracted by linking the coordinates to the nearest grid (Table S1). The 24-h cloud cover data was averaged to obtain daily mean cloud cover data.

Daily time-series data for suicide counts were obtained from the Ministry of Health, Labour and Welfare of Japan. Suicide was defined as intentional self-harm and self-poisoning using the 8th, 9th, and 10th revisions of the *International Statistical Classification of Diseases and Related Health Problems*[31–33] (ICD): codes E950.0–E958.9 for ICD-8 and ICD-9, and X60–X84 for ICD-10.

Modeled temperature and mortality data. We obtained the modeled daily mean temperature series for historical (1971–2014) and future simulation periods (2015–2099) from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) database (https://www.isimip.org/).[34] The ISIMIP provides a framework for consistently comparing the climate change impact projections across various factors, along with bias-adjusted climate input data.[34] Prefecture-specific time series of daily mean temperature were extracted through linkage of the coordinates to the nearest grid (Table S1). The modeled daily temperature series were corrected by a bias-correction approach that preserves long-term trends, such as absolute changes in monthly temperature.[35] The projected daily series of suicide mortality was calculated as the average suicide counts for each day of the year from the observed daily suicide counts, repeated along the projection period and assuming no population changes.

The modeled temperature series have been projected under climate change scenarios, according to five general circulation models (GCMs) of CMIP6: Geophysical Fluid Dynamics Laboratory Earth System Model Version 4 (GFDL-ESM4), Institut Pierre-Simon Laplace Climate Model 6A–Low Resolution (IPSL-CM6A-LR), Max Planck Institute Earth System Model 1.2–High Resolution (MPI-ESM1-2-HR), Meteorological Research Institute Earth System Model Version 2.0 (MRI-ESM2-0), and UK Earth System Model Version 1.0-LL (UKESM1-0-LL).[36] The CMIP6 model outputs have been bias-adjusted and statistically downscaled to a $0.5^\circ \times 0.5^\circ$ spatial resolution.

We used the latest ISIMIP3b simulation rounds for the historical climate simulations (available up to 2014 on the ISIMIP database) of mean daily temperature and future projections under three tier 1 climate change scenarios, SSP1-2.6, SSP2-4.5, and SSP5-8.5.[37] These scenarios were selected because they represent a broad range of future climate forcing and socioeconomic pathways. SSP1-2.6 is a low greenhouse gas (GHG)–emission scenario with a low 2,100 radiative forcing level of $2.6\,W/m^2$ and low societal vulnerability and low challenges for mitigation, whereas SSP2-4.5 is a middle-of-the-road scenario, which couples intermediate societal vulnerability with a medium $4.5\,W/m^2$ radiative forcing.[38] SSP2-4.5 is currently considered the most plausible scenario, whereas SSP5-8.5 is a worst-case scenario, with a high radiative forcing of $8.5\,W/m^2$ and very high GHG emissions[37] and is less plausible given the current decarbonization trajectories, including policy responses, and falling prices of renewable energy.[39–41]

Statistical Analyses

We used a modeling framework for health impact projections of climate change, described in detail in a methodology paper[42] and a previous study.[43] This framework has a well-structured and flexible approach, employing cutting-edge statistical techniques and clear assumptions.[42]

Estimation of the exposure–response association. We estimated the association between temperature and suicide based on the observed daily mean temperature series and suicide counts from the period 1973–2015, using a two-stage approach. In the first stage, to estimate prefecture-specific temperature–suicide associations, we applied a time-stratified case-crossover design that used a conditional Poisson regression model allowing for overdispersion.[44] The case-crossover approach, by design, adjusted for the long-term trend, season, and day of the week, with the assumption that time-varying confounders were constant within the reference window.[45] We defined a stratum as the reference window with a three-way interaction of the calendar year, month, and day of the week, which allowed for comparing exposure levels between the case and control days matched in each stratum. We modeled the temperature–suicide association using distributed-lag nonlinear models (DLNMs).[46] Specifically, a cross-basis function with a natural cubic B-spline basis of 4 degrees of freedom for both the temperature and the lag was used. The maximum lag of three previous days was applied. These specifications were motivated by a previous study.[19] The natural cubic spline allows for the log-linear extrapolation of the exposure–response curve beyond the boundaries of the observed temperature series, which is necessary for projecting risk using the modeled temperature series.[42] The bidimensional set of coefficients from each prefecture was reduced into an overall cumulative exposure–response curve across the lags to be used for the second stage.

In the second stage, the prefecture-specific estimates were pooled using a multivariate meta-regression model.[47] We used the best linear unbiased prediction (BLUP) for the overall cumulative temperature–suicide association for each prefecture. BLUPs allow prefectures with a smaller number of daily suicide counts to use information from larger populations with similar characteristics. We included the prefecture-level average temperature and range of daily mean temperature for 1973–2015 in the model as meta-predictors.

Projections of impacts on suicide mortality. The excess suicide mortality attributable to temperature was projected using the modeled daily temperature series and suicide mortality under the assumption of no adaptation or population changes, in line with previous studies.[43,48–50] For each combination of prefecture, scenario, GCM, and day, we computed the number of temperature-related suicide deaths (attributable deaths) by using the modeled temperature series, modeled suicide mortality series, and the prefecture-specific BLUPs for the estimated temperature–suicide association. The 25th percentile of the observed prefecture-specific temperature distribution was used as a reference for the prefecture-specific RR estimation (Table S1). First, the suicide deaths attributable to temperatures below and above the reference were computed separately, as the sum of the subsets corresponding to days with temperatures lower or higher than the reference. Then, the total attributable number of suicides was calculated by summing the contributions from all days of the temperature series.

The excess suicide mortality was calculated for each prefecture and combinations of GCMs and scenarios. Then, attributable fractions were calculated as GCM-ensemble averages, aggregated nationally and by decade and scenario, with the corresponding total number of suicide deaths as the denominator.[42,43] The attributable deaths and the attributable fractions were therefore computed using a baseline suicide mortality averaged from the observed suicide counts series.

The uncertainty of the estimates was quantified by generating 1,000 samples of the coefficients of the BLUPs through Monte Carlo simulations, calculating the 95% empirical confidence intervals (eCIs). The eCIs accounted for both the uncertainty in exposure–response association and the climate projections across the different GCMs.

Sensitivity analyses. A sensitivity analysis was performed by adjusting for daily mean relative humidity (in percentage), daily precipitation (in millimeters), daily mean wind speed (in meters per second), and daily mean cloud cover (in percentage). Furthermore, to explore whether adaptation has occurred compared with historical data, the period 1973–2015 for observed data was divided into nine subperiods, and the nationwide mean temperature, the 25th percentile temperature, and the nationwide RRs for the maximum suicide temperature vs. the reference (25th percentile of observed temperature) for the subperiods were computed. As a sensitivity analysis, we projected the future impacts using the BLUPs (i.e., the observed association between temperature and suicide) only for 1986–2015, given that that period was more recent and had a relatively stable mean temperature, and the 25th percentile temperature, which was used as reference for estimating the associations.

All analyses were conducted using R (version 4.0.3). The packages used included *gnm*, *dlnm*, and *mvmeta*.

Results

A total of 1,049,592 suicides were reported in the 47 prefectures of Japan between 1 January 1973 and 31 December 2015. The observed average daily mean temperature across the prefectures was 15.1°C (Table S2). The descriptive data for other meteorological variables, including daily mean relative humidity, daily precipitation, daily mean wind speed, and daily mean cloud cover are presented in Table S2. The daily mean temperature in each prefecture ranged from 8.9°C in Hokkaido to 22.9°C in Okinawa Prefecture (Table S3). On average, 66.8 suicide cases per day were reported during the study period in Japan. Descriptive data on the prefecture-specific suicide deaths are presented in Table S3.

Figure 1 shows the temporal trends in historical (1971–2014) and future (2015–2099) modeled temperature in Japan under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The summary data for Figure 1 are shown in Excel Table S1. The mean annual temperature will increase 2.8°C (range: 1.5–4.5°C) under the most plausible SSP2-4.5 scenario, 1.6°C (range: 1.3–2.3°C) under SSP1-2.6, and 5.7°C (range: 3.9–8.1°C) under SSP5-8.5 at 2099 compared with the historical average (1971–2014). Under the high-end, less plausible SSP5-8.5 scenario, there is a steeper rise in the modeled temperature, compared with the SSP1-2.6, where there is a more gradual and slight increase with a slight decline toward the end of the century. The temporal trends in modeled temperature for each prefecture are shown in Figure S1. The numeric data for Figure S1 can be found in Excel Tables S2a and S2b.

Figure 2 shows the overall cumulative exposure–response curve for temperature and suicide mortality in Japan, pooled by the multivariate meta-regression model. Summary data for Figure 2 are shown in Excel Table S3. There was an inverted J-shaped nonlinear association between temperature and suicide, with the suicide risk rising with temperature but leveling off at temperatures >23.1°C. Figure S2 shows the overall cumulative temperature–suicide association curves for each prefecture. The numeric data for Figure S2 can be found in Excel Table S4. The associations were generally inverted J shaped.

Temperature-related excess suicide mortality in Japan projected under the three climate change scenarios are summarized as estimated attributable fractions in Figure 3A. The summary data are shown in Excel Table S5a. For all scenarios, there is a projected rise in temperature-related excess suicide mortality, with a continuous increase under the most plausible SSP2-4.5 scenario and the steepest increase under the extreme, but less plausible, SSP5-8.5 scenario. In contrast, the projected trends slightly increase until the 2070s, then dip toward the end of the century under the SSP1-2.6 scenario with mitigation policies. Figure 3B shows the temporal changes in total temperature-related excess suicide mortality under the scenarios. The net changes in excess suicide mortality compared with 2010–2019 continue to increase under the most plausible SSP2-4.5 scenario and the less plausible SSP5-8.5 scenario, whereas the net changes gradually increase before slightly dropping toward the end of the century under SSP1-2.6. The summary data can be found in Excel Table S5b.

The temperature-related excess suicide mortality is projected to rise from 4.2% (95% eCI: 2.3, 5.9) in 2010–2019 to 5.5% (95% eCI: 3.0, 7.8) in 2090–2099 under the most plausible SSP2-4.5 scenario (Table 1). The temperature-related excess suicide mortality is projected to rise most steeply, from 4.1% (95% eCI: 2.2, 5.9) to 6.5% (95% eCI: 3.2, 9.6) under the extreme SSP5-8.5 scenario during the same period. For the period 2090–2099, the net increase in temperature-related excess suicide mortality is 1.3% (95% eCI: 0.6, 2.4) for the most plausible SSP2-4.5 scenario, 0.6% (95% eCI: 0.1, 1.6) for SSP1-2.6, and 2.4% (95% eCI: 0.7,

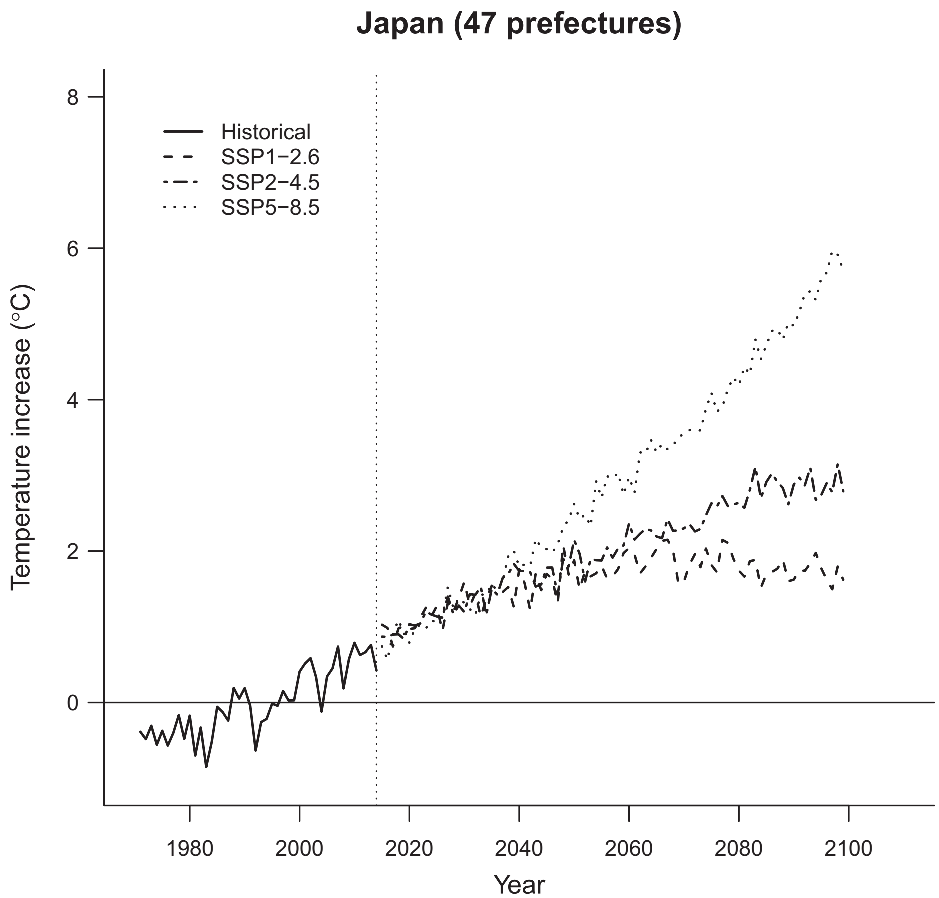

Figure 1. Temporal trends in projected temperature in Japan by climate change scenario. The lines show the mean annual temperature estimated across the five general circulation models, expressed as increase in annual mean temperature from the historical average temperature (1971–2014). The summary data for this figure can be found in Excel Table S1.

3.9) for SSP5-8.5. eCIs of the net difference in excess suicide mortality are significant for all scenarios and periods, except for the 2030s under the SSP1-2.6 scenario (Figure 3B). The attributable numbers of temperature-related suicide deaths are 10,208 (95% eCI: 5,543, 14,371) in the 2010s and 13,392 (95% eCI: 7,298, 19,109) in the 2090s under the most plausible SSP2-4.5 scenario (Table S4). The attributable numbers of temperature-related suicide deaths are 10,307 (95% eCI: 5,559, 14,516) and 10,083 (95% eCI: 5,379, 14,391) in the 2010s, and 11,829 (95% eCI: 6,441, 16,965) and 15,810 (95% eCI: 7,690, 23,426) in the 2090s under the less plausible SSP1-2.6 and SSP5-8.5 scenarios, respectively.

Figures S3 and S4 and Table S5 show the suicide mortality and the net difference in suicide mortality in Japan with separate components for above and below the reference, which is the 25th percentile of the prefecture-specific temperature distribution. The numeric data for Figures S3 and S4 can be found in Excel Tables S6 and S7. Under all the scenarios, there was an increase in the excess suicide mortality attributable to temperatures both lower than and above the reference. The excess suicide mortality attributable to temperatures lower than the reference increased steadily from −1.3% (95% eCI: −1.8, −0.9) in the 2010s to −0.5 (−0.8, −0.2) in the 2090s under the most plausible SSP2-4.5 scenario (Figure S3 and Table S5). In contrast, the increase was steeper under the less plausible SSP5-8.5 scenario, increasing from −1.3% (95% eCI: −1.8, −0.9) to −0.1% (95% eCI: −0.3, 0.0) during the same period. The increase was more gradual under SSP1-2.6 compared with SSP2-4.5, increasing from −1.3% (95% eCI: −1.6, −0.9) to −0.9% (95% eCI: −1.5, −0.5). Temperature-related excess suicide mortality and the net difference for each prefecture are shown in Figures S5 and S6 and Table S6. The numeric data for Figures S5 and S6 can be found in Excel Tables S7 and S8.

Sensitivity analysis suggested that the results were robust (Table S7). The estimates remained similar after separately adjusting for additional meteorological variables, such as cloud cover, precipitation, wind speed, and relative humidity.

Table S8 shows the nationwide RRs for the maximum suicide temperature vs. the reference (25th percentile of observed temperature) for the subperiods. The RRs did not decrease in a straightforward manner during the observed period (1973–2015), suggesting there was no strong evidence of adaptation in temperature–suicide association in Japan. The observed mean temperature and the 25th percentile temperature for Japan during the subperiods are also shown in Table S8.

The results of projecting using the association from a subperiod of 1986–2015 are reported in Table S7, and the results and conclusions from the projections did not drastically change compared with the main model. Combined with the complexity of accounting for adaptation in the presence of nonlinear association,[51] we maintained the assumption of no adaptation in the main model.

Discussion and Conclusions

This study aimed to project the future temperature-attributable excess mortality due to suicide in Japan until the end of the century under multiple climate change scenarios from CMIP6. The

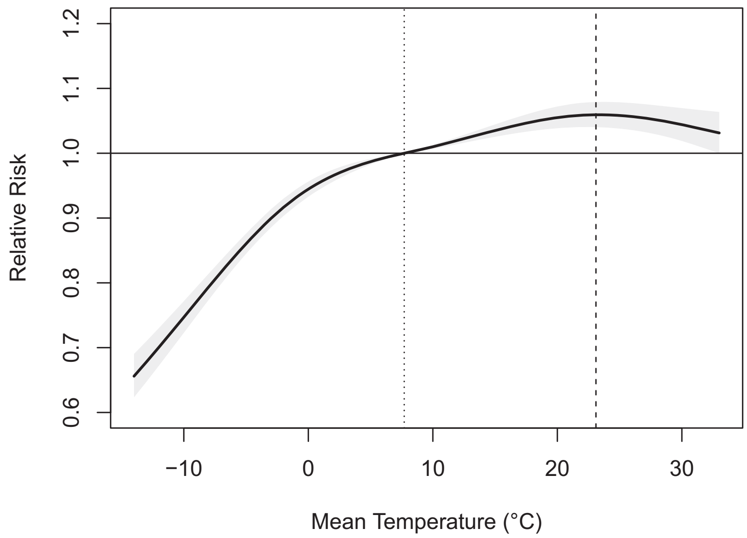

Figure 2. Overall cumulative exposure–response association between relative risk of suicide and temperatures across lag 0–3 d in Japan (1973–2015). A total of 1,049,592 suicides was reported during the study period. Exposure–response associations are the best linear unbiased prediction. The shaded areas indicate 95% CIs. The dashed vertical line represents the maximum suicide temperature. The dotted vertical line represents the reference, the 25th percentile of observed temperature (7.7°C for Japan). The summary data for this figure can be found in Excel Table S3. Note: CI, confidence interval.

assessment used a 40-y historical data set for observed daily temperature and suicide counts to estimate historical temperature–suicide association and projected the future impacts under three state-of-the-art, newly improved CMIP6 scenarios. Our analysis was based on advanced statistical methods and a structured analytical framework with well-defined assumptions.[42] Our study finds that the projected temperature-related suicide mortality increases in Japan under all the examined scenarios by the end of

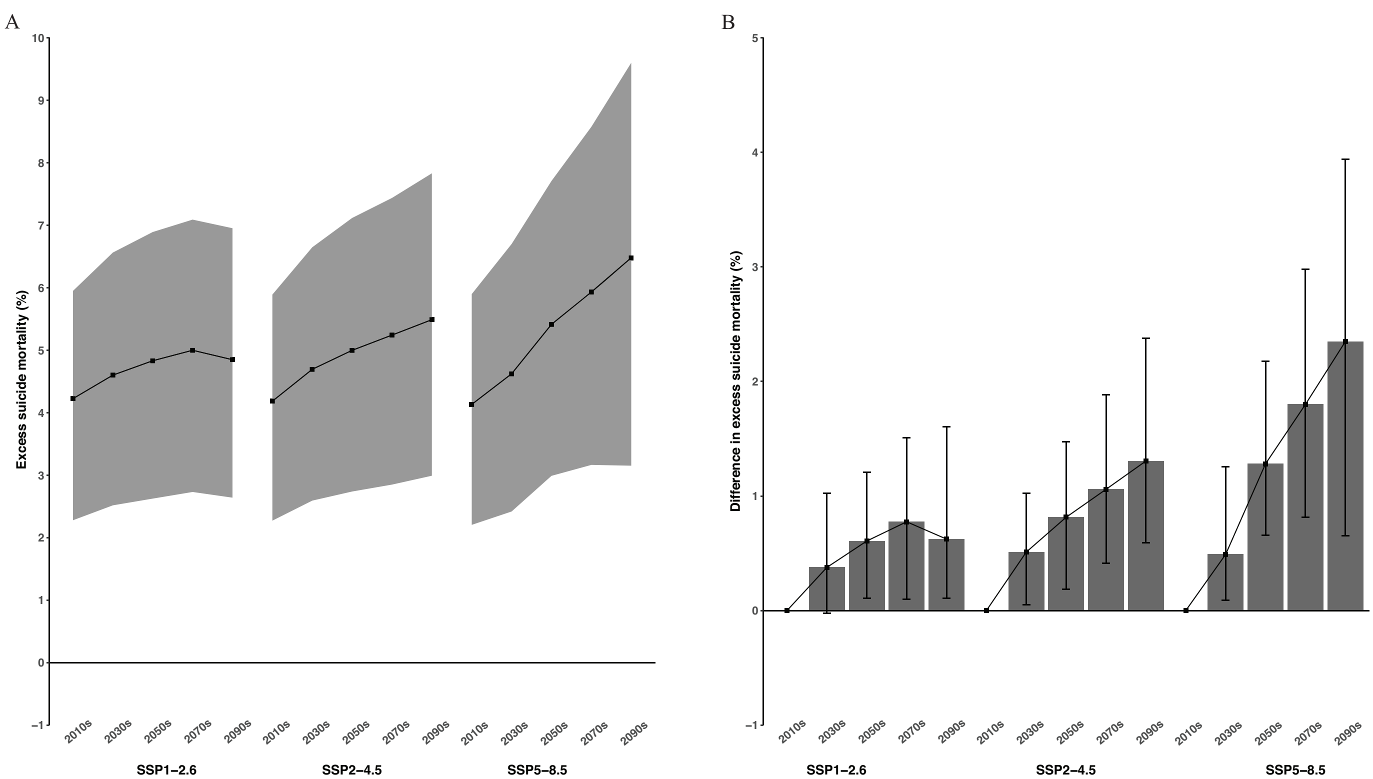

Figure 3. Projections of temperature-related excess suicide mortality in Japan. (A) Trends in temperature-related excess suicide mortality in Japan. The graph shows the excess suicide mortality by decade as a result of temperature (total attributable fractions for temperature) for three climate change scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5). Estimates are shown as GCM-ensemble average decadal fractions, computed using the 25th percentile of the observed prefecture-specific temperature distribution as the reference (Table S1). Shaded regions indicate 95% eCIs. The summary data can be found in Excel Table S5a. (B) Temporal change in excess suicide mortality in Japan. The graph shows the difference in total temperature-related excess suicide mortality by decade compared with 2010–2019 under three climate change scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5). Estimates are reported as GCM-ensemble averages. The black vertical segments denote 95% eCIs of the net change. The summary data can be found in Excel Table S5b. Note: eCI, empirical confidence interval; GCM, general circulation model; SSP, shared socioeconomic pathway.

Table 1. Total temperature-related excess suicide mortality and net change (%) with 95% eCI by period under three climate change scenarios in Japan.

Scenario	Average temperature (2010–2019)[a]	Projected increase in temperature (2090–2099 vs. 2010–2019)[b]	Excess suicide mortality [% (95% eCI)][c]		
			2010–2019	2050–2059	2090–2099
SSP1-2.6	15.9 (9.6–23.5)	0.9 (0.7–1.2)	4.2 (2.3, 5.9)	4.8 (2.6, 6.9)	4.8 (2.6, 7.0)
Net change[d]		—	—	0.6 (0.1, 1.2)	0.6 (0.1, 1.6)
SSP2-4.5		2.1 (1.6–2.6)	4.2 (2.3, 5.9)	5.0 (2.7, 7.1)	5.5 (3.0, 7.8)
Net change		—	—	0.8 (0.2, 1.5)	1.3 (0.6, 2.4)
SSP5-8.5		4.8 (3.4–5.7)	4.1 (2.2, 5.9)	5.4 (3.0, 7.7)	6.5 (3.2, 9.6)
Net change		—	—	1.3 (0.7, 2.2)	2.4 (0.7, 3.9)

Note: —, not applicable; eCI, empirical confidence interval; GCM, general circulation model; SSP, shared socioeconomic pathway.
[a]Current temperature is average daily mean temperature (°C, range) between 2010 and 2019 as GCM-ensemble average.
[b]Projected increases in temperature are GCM-ensemble average mean prefecture-specific temperature (range).
[c]Estimates are GCM-ensemble average decadal fractions. The reference is the 25th percentile of the observed prefecture-specific temperature distribution (Table S1). Total temperature-related excess suicide mortality was calculated by aggregating daily attributable numbers within periods and calculating the total attributable fraction as the ratio with the corresponding total number of suicide deaths.
[d]The net change is the difference in the total temperature-related excess suicide mortality compared with 2010–2019.

the 21st century, including the most plausible intermediate scenario (SSP2-4.5). The largest increase was projected for the high-emission SSP5-8.5 scenario and the lowest for the SSP1-2.6 scenario. Our findings suggest that climate change may increase the temperature-related risk of suicide in Japan.

Our study finds that the temperature-related excess suicide mortality and its net change continually increased, except for the SSP1-2.6 scenario. Future temperatures continuously rise under the most plausible intermediate scenario SSP2-4.5 and the less plausible extreme scenario SSP5-8.5 in which the carbon dioxide (CO_2) emissions remain around the current levels until around the 2050s and then gradually decline toward the end of the century in SSP2-4.5, whereas the emissions in the SSP5-8.5 scenario continue to increase, doubling from the current levels by 2050.[37,38] SSP5-8.5 is considered less plausible given the current emission trajectory and decarbonization efforts, such as policy responses, and decreasing prices of renewable energy[40]; for instance, a recent analysis found that SSP5-8.5 lies outside the plausible trajectories.[39] In contrast, for the SSP1-2.6 scenario, the temperature-related excess suicide mortality and the net change then gradually increased and experienced a peak in the 2070s, with a decline afterward. This is probably due to the decline in future temperatures resulting from net negative CO_2 emissions at the end of this century in the SSP1-2.6 scenario,[37] in which anthropogenic removals of CO_2 overtake anthropogenic emissions, limiting warming to $<2°C$. Both the decrease in excess suicide mortality above the reference after the 2070s and the decrease in excess suicide mortality below the reference appear to be contributing to the decline in total temperature-related excess suicide mortality in the SSP1-2.6 scenario (Figure S3).

Our results of a net increase in excess suicide mortality are broadly concordant with the findings of a previous projection study in the United States and Mexico, which also projected an increase in suicide under the high-emission scenario.[24] For instance, that study projected a rise in the suicide rates of 1.4% (95% CI: 0.6, 2.6) in the United States and 2.3% (95% CI: −0.3, 5.6) in Mexico by 2050 under the high-emission RCP8.5 scenario,[24] the predecessor of the SSP5-8.5. However, it is difficult to directly compare our estimates to that study because of the difference in projection periods, climate change scenarios, and projection approaches given that they used a linear approach and reported a change in suicide rates, whereas we used a nonlinear approach and estimated attributable fractions, which is a more common approach.[52] Another study also found an increase in suicides, suggesting 3.0% annual increases in suicides by the end of the century, under the high-end RCP8.5 scenario in the United States.[25] Neither of the previous U.S. studies projected the most plausible climate change scenario, namely SSP2-4.5 or its predecessor, RCP4.5.

We found the net increase in temperature-related excess suicide mortality appears to be considerably driven by the increase in excess suicide mortality attributable to temperatures below the reference temperature (Figure S3). In our study, the excess suicide mortality attributable to temperatures below the reference were calculated as negative values at all decades in the projection period, similar to those demonstrated by the Global Burden of Disease Study 2019.[53,54] However, as the projected future temperature rises, the expected absence of lower temperatures increased the negative attributable fractions over time for all scenarios, including under the most plausible SSP2-4.5 scenario. For the intermediate-emission scenario (SSP2-4.5) and the low-emission scenario (SSP1-2.6), the excess mortality attributable to temperatures below the reference appears to be contributing more to the net increase in temperature-related excess suicide mortality relative to the 2010s, compared with those attributable to temperatures above the reference (Figure S4). By contrast, the SSP5-8.5 scenario experienced the steepest increase, leading to the net increase in total temperature-related excess suicide mortality by the end of the century (Figure 3B). For SSP5-8.5, both components seem to be contributing more equally (Figure S4 and Table S5).

A growing body of literature suggests climate change has significant impacts on mental health, with research showing a relationship between increasing temperatures and more severe and frequent extreme weather events and worsened mental health.[2,3] Studies have investigated direct (including stress-related effects of acute events, such as floods and hurricanes) and indirect effects (including exposure to increased ambient temperature and air pollution) of climate change.[55] The existing literature demonstrates a positive association between increased temperatures and suicides from observed data.[2] Extreme temperatures are associated with various worsened societal outcomes, such as increased conflict[56] and poorer economic outputs,[57] and increased risk factors, such as disturbed sleep,[58] which may drive the adverse impacts on mental health.[59] Extreme heat may lead to physiological changes, impacting the central nervous system and blood flow, which may result in emotional and cognitive changes impacting mental health.[59] Although the definitive mechanism of the temperature–suicide association is still uncertain, the most plausible mechanism is the association of serotonin deficits with suicides and suicide attempts and the negative correlations between ambient temperatures and the biomarkers of serotonin.[16,17,60] Furthermore, people with preexisting mental illness may be more vulnerable to the mental health impacts of climate change.[55] For example, heat may worsen mental disorders among people with preexisting mental health conditions, leading to suicide.[59] Another potential mechanism linking ambient heat with worse mental health outcomes is sleep disruptions; sleep disruptions increase with higher temperatures, and sleep is associated with mental health outcomes.[61]

Recently, an increasing number of studies have evaluated the projected impacts of climate change on mental health, such as increasing extreme weather events, including droughts and hurricanes, and found that climate change directly worsened mental health.[26] However, there is a lack of studies that quantitatively project climate change impacts on future mental health outcomes.[23] Our study adds to the growing body of climate change and mental health research[25,61] and to the rarer quantitative future projection studies of climate change impacts on suicide, demonstrating that suicides are projected to increase and impact more people in the future if sufficient action is not taken.

Our study has implications for public health. Both climate change and mental health are two of the greatest global challenges society is facing.[59] Although climate change is increasingly being recognized by various groups, including governments, health professionals, and academia, as a public health emergency, the interplay between climate change and mental health is still largely neglected in favor of the focus on physical health.[59] Currently, there is a lack of awareness and response among health systems, policymakers, and communities about the threat of climate change to mental health.[59] This is perhaps due to that the extent of impacts of climate change on mental health is still largely unquantified in both practice and policy.[59] Our results quantitatively demonstrate that the higher the level of temperature rise, the higher the increases in temperature-related excess mortality due to suicide in Japan will be. Increased excess mortality due to suicide is projected even under the most plausible SSP2-4.5 scenario, whereas the highest excess mortality due to suicide is projected under the SSP5-8.5 scenario, which assumes fossil energy-based development, in which GHG emission continually increases. Our results indicate that limiting warming to $<2^{\circ}C$ may minimize the impacts of future high temperatures on suicide. These findings are similar to an existing study that found limiting the temperature rise in global mean temperature increases to $2^{\circ}C$ would prevent significant change in total temperature-related mortality compared with the current day.[49] Therefore, our findings underscore the importance of effective mitigation of climate change. Reducing GHG emissions is vital to minimize temperature rise and the impacts of climate change on mental health, together with building resilient infrastructure and anticipatory policies.[59]

Furthermore, increased recognition and awareness by the health systems, policymakers, and communities of the threats that climate change poses to mental health is needed to mitigate and adapt and respond to the impacts on mental health. This may be done through the establishment of effective programs to promote awareness that have the potential to reduce suicide rates despite rising temperatures. For instance, in Finland, increased suicides were associated with rising temperatures over a 100-y period until a national suicide prevention program was launched, which effectively reduced suicide rates despite the ongoing warming.[62] Government and health system programs, such as public health campaigns on heat vulnerability could be used to increase the public's ability to recognize and cope with these impacts.[59] Owing to the potential link between suicide and climate change, suicide prevention programs should consider the temperature–suicide association and consider raising the awareness of suicide and the mental health impacts of climate change among the public. Furthermore, preventing suicides among at-risk populations, such as people with preexisting mental health conditions, during events such as heatwaves may be needed by, for example, raising the community's awareness of suicide risks and awareness of community suicide prevention services,[63] training health care workers to identify and respond to temperature-related mental health symptoms, and raising awareness among mental health support organizations of climate change's role as a source of mental health distress.[59]

To develop specific policy recommendations, further investigations on the impacts of climate change on mental health-related outcomes, including suicide, are warranted. For instance, there is a need for further investigation of projections of climate change's impact on suicide in a more global context in different countries. Strengthening the evidence base on the impacts of climate change and mental health will inform decision-making and promote action among stakeholders, such as policymakers, health care systems, community organizations, and the public, alleviating the future mental health burden. Researchers should also raise awareness of the current evidence of mental health impacts by engaging with policymakers and health systems and the public, especially because the evidence of the impacts of climate change on mental health could be included as a part of the rationale for calling for climate action.[59] Further research on climate change and mental health could aid the development and implementation of climate adaptation plans and policies, including the identification of which climate mitigation policies should be prioritized, health systems planning to build resilience, and effective public mental health adaptation interventions to support people who experience mental health distress due to climate change. Adaptation plans may include, for instance, involving community mental health support in first response to extreme weather events such as heatwaves.[59] More work is also needed to identify at-risk groups and the contributions of climate change's mental health impacts to the worsening of inequalities.[55] Furthermore, understanding the largely unquantified economic burden caused by the impacts of climate change on mental health is needed to inform decision-making so that policymakers can better understand the benefits of climate action for mitigation and adaptation.[59]

Some limitations of this study should be noted. First, our projections did not consider factors such as future demographic changes and adaptation,[64,65] assuming that the population and the shape of the exposure–response curve will remain constant in the future. Although our approach enabled the isolation of the effects of climate change on temperature-related suicide mortality under different scenarios, the results should be interpreted as possible impacts under clearly defined hypothetical scenarios rather than as predictions of future excess mortality. However, a previous study found little adaptation in the temperature–suicide association in Japan.[19] Similarly, our RR estimates for the nine subperiods suggested that there was no strong evidence of adaptation in the temperature–suicide association in Japan during the observed period (1973–2015). However, owing to the overlapping CIs of the estimates, these results should be interpreted cautiously. Moreover, our sensitivity analysis in which we projected using only the historical association from 1986–2015, which experienced relatively stable mean temperature and 25th percentile temperature, showed that the results were robust. Further studies should account for future demographic changes and possible challenges to dealing with additional assumptions accordingly, which may result in more uncertainty.[42]

Second, we did not use minimum mortality risk (MMT) as the reference because MMT was the observed minimum temperature for all prefectures in our study. We instead presented the temperature-related excess suicide mortality above and below the reference, at the 25th percentile of the observed temperature in each prefecture. This may limit comparisons with other studies.

Third, given that we assumed a nonlinear association between temperature and suicide when estimating the historical temperature–suicide mortality relationship, the findings may not be generalizable to countries with different exposure–response curves, such as Western countries with more linear associations.[17] Another assumption of our study was that there was no spatial correlation between temperature and suicide in the prefectures. For example, although neighboring prefectures may have similar features in temperature and temperature–suicide association, our study did not consider them. Not accounting for spatial autocorrelation may lead to biases in the variances and may have affected the precision of the meta-regression estimates.[66,67] This omission may also cause an over- or underestimation of the temperature–suicide relationship in neighboring prefectures. However, few ecological studies using DLNM have implemented methods to deal with spatial heterogeneity given that incorporating spatial autocorrelation into the multivariate meta-analysis as used in the present study can greatly increase the model's complexity.[67,68] Likewise, considering the spatial autocorrelation in the projection steps would have been challenging.

Furthermore, although our model accounted for some seasonal and day-of-the-week variation, we did not account for calendar-date temporal shocks, such as shocks from natural disasters or societal events. This might have caused the temperature–suicide association to be over- or underestimated, depending on the events. Another potential limitation is that like previous projection studies,[43,48] we did not include other meteorological factors as climate inputs when projecting the future impacts of climate change on temperature-related suicide mortality owing to the complexity of such an approach. However, our sensitivity analyses showed that the historical temperature–suicide association was robust even after adjusting for these meteorological factors.

In conclusion, we project a net increase in temperature-related excess mortality due to suicide in Japan, especially under the most plausible intermediate scenario (SSP2-4.5), as well as under the very high scenario (SSP5-8.5). Future research is warranted to assess a more comprehensive picture of the impacts of climate change on mental health outcomes, including suicide.

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