Warming increases suicide rates in the United States and Mexico

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Linkages between climate and mental health are often theorized[1,2] but remain poorly quantified.[3] In particular, it is unknown whether suicide, a leading cause of death globally,[4] is systematically affected by climatic conditions. Using multiple decades of comprehensive data from both the US and Mexico, we find that suicide rates rise 0.7% in US counties and 2.1% in Mexican municipalities for a 1°C increase in monthly average temperature. This effect is similar in hotter versus cooler regions and has not diminished over time, indicating limited historical adaptation. Analysis of depressive language in >600 million social media updates further suggests that mental wellbeing deteriorates during warmer periods. We project that unmitigated climate change (RCP8.5) could result in a combined 9-40 thousand additional suicides (95% CI) across the US and Mexico by 2050, representing an change in suicide rates comparable to the estimated impact of economic recessions,[5] suicide prevention programs,[6] or gun restriction laws.[7]

Climate is increasingly understood to influence many dimensions of human health,[1,8,9] affecting health outcomes ranging from vector-borne disease mortality to rates of cardiac arrest.[9,10] These relationships have been shown to occur through direct physical stress or insults to the body (e.g. heat-stroke or cyclone-caused drowning), changes in disease ecology (e.g. seasonal flu or malaria), and/or changes in socio-economic conditions that support human health (e.g. drought-induced famine). Recent work has also demonstrated that social conflicts between individuals, which cause intentional injuries and mortality, are particularly responsive to changes in temperature, perhaps due to changes in underlying economic conditions or altered individual-level aggressiveness.[11]

Potential linkages between climatic conditions and mental health are also increasingly hypothesized.[3] However, unlike other key health outcomes, there remains limited quantitative evidence linking temperature to suicide and related mental health outcomes.[12,13] Determining whether or not suicide responds to climatic conditions is important, as suicide alone causes more deaths globally than all forms of interpersonal and intergroup violence combined,[4] is among the top 10-15 causes of death globally, among the top 5 causes of lost life-years in many wealthy regions,[14] and among the top 5 causes of death for individuals aged 10-54 in the US.[15] It is the only cause of death among the top 10 in the US for which age-adjusted mortality rates are not declining.[16] Thus even modest changes in suicide rates due to climate change could portend large changes in the associated global health burden, particularly in wealthier countries where current suicide rates are relatively high and/or on the rise.

Strong seasonal patterns in suicides (typically, an early summer "peak") were recognized in the 19th century, but it was unknown whether this pattern was caused by seasonally-varying temperature, by other seasonally varying meteorological factors such as daylight exposure, or by other social or economic factors that also vary seasonally.[17] More recent work has moved away from this seasonal focus, instead examining whether temperature and suicide are correlated in individual time-series for particular locations. This work has been inconclusive, with studies finding no effect,[18,19] positive effects,[20–22] and negative effects.[23] These discrepancies are likely due in part to limited sample sizes, difficulty in fully accounting for critical time-varying confounds (e.g. macroeconomic conditions[5]), and/or differences in baseline suicide rates across locations that may be correlated with baseline temperature levels or seasonality. Due to the large number of non-climate factors that may potentially contribute to suicide rates and the potential for complex interactions between different possible causes—similar to the challenge of inferring whether climate is a contributing factor to social conflict[24]—reliably inferring whether temperature is a contributing factor to suicide risk requires adequately accounting for these potential confounds.

Here we study the effect of local ambient temperature on rates of suicide across the US and Mexico – two countries that, based on current estimates,[25] account for roughly 7% of all global suicides. To eliminate sources of potential confounding and small sample biases, we analyze the relationship between temperature and suicide using monthly vital statistics data for thousands of US counties[26] and Mexican municipalities[27] over multiple decades (see Methods) – a drastically larger sample than has been available in past work ($N_{USA} = 851,088$; $N_{MEX} = 611,366$). By using longitudinal data on many geographic units over time, we plausibly isolate the effect of temperature on suicide from other seasonal, time-trending, and/or cross-sectional factors that might be correlated with both temperature and suicide.

We estimate the effect of random monthly temperature fluctuations on locality-level suicide using a fixed effects estimator, where the suicide rate in a given locality-month is modeled as a function of the temperature exposure during that month in that locality, accumulated precipitation over the same period, and a large number of flexible nonparametric controls that account for (i) all average differences between suicide rates across counties—such as those caused by regional poverty or gun-ownership rates; (ii) average monthly changes in suicide rates within each county, which allows seasonal patterns to differ across counties and accounts for factors such as location-specific effects of daylight exposure and holidays; and (iii) all time-varying confounds affecting all locations within each state simultaneously, including both gradual trends and abrupt shocks, which accounts for factors such as economic growth and recessions or news of celebrity suicides (see Methods). To ensure robustness of our findings, we measure temperature exposure during a given month using two different approaches: as the average daily temperature during the month or as the count of days during that month with average temperatures falling into different 3°C temperature bins (Methods). Because the data strongly indicate an essentially linear response in daily average temperature using the flexible non-parametric model, we focus here on the linear-in-monthly-average-temperature model as our baseline. We use an identical research design to analyze a geocoded dataset of over 600 million social media updates on the Twitter platform[28] ("tweets"), and evaluate whether warmer-than-normal monthly temperatures elevate the likelihood that social media users express abnormally depressive feelings in their language.

Intuitively, our estimates of temperature effects derive from comparing suicide rates or depressive tweets between an average January in a given county to a warmer-than-average January in the same county, after having accounted for any changes common to all counties in a given state in that year. Whether a particular location experienced a hotter January than normal is plausibly random and statistically independent from all covariates, indicating that our temperature coefficients can be interpreted as the average causal effect of hotter-than-average temperatures on suicide rates. We test for the possibility that abnormally high temperatures do not cause additional suicides but instead hasten suicides that would have otherwise happened by estimating distributed-lag models that allow for simultaneous influence of past, current, and future temperatures. If hot temperatures merely hasten suicides, then responses to current and lagged temperatures should have opposite signs and their effects should sum to zero.[29]

We then assess how responses differ across decades, by income level, sex, population level, and both air conditioning (AC) and gun ownership rates, as well as across regions with different long-run average temperatures. As is common in the literature[30,31] , stratifications by income, AC, time period, and baseline temperature allow us to evaluate whether economic development or experience with warmer conditions might have historically alleviated the burden of excess suicides via adaptation, a common theory in the broader climate-health literature[10] and putative cause of observed differences in suicide seasonality across countries,[32] but one which has received little direct empirical scrutiny.

Finally, under the assumption that future suicide rates will respond shifts in mean temperature as they have responded to past to temperature fluctuations in the recent past, we construct projections for the impact of future climate change on suicide in the US and Mexico. We utilize output from 30 global climate models run under a business-as-usual emissions scenario (RCP8.5) and compute a distribution of net changes in excess suicides by mid-century. We then compare the estimated effect sizes from other known determinants of suicide to the projected impact of climate change.

Results

Unlike all-cause mortality, which has been shown to increase at both hot and cold temperatures around the world,[29,33] we find in both the US and Mexico that the relationship between temperature and suicide is roughly linear: suicides decrease when a given location-month cools and increases when it warms (Figure 1). We find that a +1°C increase in average monthly temperature increases the monthly suicide rate by 0.68% (95% CI: 0.53% to 0.83%) in the US over the years 1968-2004, and increases the suicide rate in Mexico by 2.1% (95% CI: 1.2% to 3.0%; Figure 3, top panel) over the years 1990-2010. For comparison, the average standard deviation of temperature variation over time (after accounting for seasonality) is 1.7°C at the county level in the US, suggesting that monthly suicide rates rose $>2\%$ due to temperature in the hottest months on record. We confirm our US results using a second annually-resolved suicide dataset from the CDC,[34] finding slightly larger point estimates for these more recent data (1.3% per +1°C increase in annual average temperature). Our results contrast with past studies in the US, which have shown varied response.[18,19,35,36] To our knowledge, the only comparable studies of the temperature-suicide relationship conducted in developing or middle-income countries during this period is ref[[13]] in India, which finds larger effects than those we report here.

Results are robust to a large range of alternate models, including the use of more and less-restrictive fixed effects, inclusion of additional time controls, inclusion or exclusion of populations weights, more flexible functional forms for modeling the temperature/response relationship including higher order polynomials and splines, alternate codings for the outcome variable, and alternate methods for clustering the standard errors (Figure 1 and Tables S1-S3). A binned model that relates the monthly suicide rate to the distribution of daily temperatures within that month similarly uncovers a roughly linear relationship between daily temperatures and monthly suicide rates (Figures S1-S2).

Heterogeneous effects and adaptation

Earlier work highlights the potential for various adaptations to lessen the health-related impacts of climate over time. For example, the proliferation of AC in the US is likely to have mitigated the relationship between temperature and all-cause mortality.[30] Similarly, a broader literature highlights the potential for economic development to mitigate climate-health linkages, either because wealthier countries can better invest in health or because other aspects of development lessen environmental exposures.[10]

In contrast to this literature, we find little evidence of adaptation in the temperature-suicide relationship. First, we find no qualitatively or statistically significant decline in the suicide-temperature relationship over our study period in either the US or Mexico (Figure 2, top panel). Point estimates are roughly stable in Mexico, and if anything trend up over time in the US, and are robust to restricting the data to only those countries reporting data in all years (Figure S3). Second, we find no evidence that individuals more frequently exposed to hot temperatures are less sensitive to their effects: effects in locations with hotter average temperatures are statistically indistinguishable from effects in cooler regions (Figures 3 and S2b), and state-specific estimates in both the US and Mexico are largely statistically indistinguishable from national estimates (Figure 2, bottom panel). Third, income differences within countries do not mediate the temperature-suicide relationship: we find no significant difference in suicide response to temperature between rich and poor municipalities or counties. In the US, using data on county-level AC adoption from multiple waves of the US census[30] and one Mexican census, we similarly find no evidence that higher air-conditioning adoption is associated with reduced effects of temperature on suicide (Figure 3); this hold true for exposure to extremely hot ($>30°$C) days as well (Figure S2), although limited current exposure to these temperatures in counties with low air conditioning penetration makes estimates imprecise. Because average temperature, average income, and average AC penetration co-vary in the US, we estimate an additional model that interacts each covariate with temperature in a joint regression; we again find that none of these variables reduces the effect of temperature on suicide, with estimated interactions small in magnitude and not significant (Table S4).

We also find no clear evidence of different effects of temperature on suicide by sex in either country, no differential effects by method of suicide in the US (data on method of suicide are unavailable in Mexico), no difference by county population size and, using state-level data on self-reported gun ownership in 2002 in the US,[37] no evidence that states with higher gun ownership have larger suicide responses to temperature (Figure 3). While there could remain other unobserved covariates that modify the temperature/suicide relationship, the broadly uniform structure of the temperature effects across a range of observed populations in both countries and the absence of evidence that these effects change over time suggest that the underlying mechanism linking temperature to suicide is highly generalizable across contexts and individuals.

Temporal displacement

We evaluate whether hot temperatures hasten suicides that would have happened anyway or trigger "excess" suicides that would never have occurred in a cooler counterfactual scenario. Using a distributed lag model (Methods), we find evidence of temporal displacement in both the US and Mexico (Figure 3, bottom panel), with higher temperatures in a previous month having negative and statistically significant effects on suicide in the current month. Summing the contemporaneous and lagged effects provides an estimate of the total number of excess suicides generated by hot temperatures, net of any temporal displacement.[29,38] As expected, we find no evidence that temperatures one month in the future affect current suicide rates.

Depressive language on social media

Although the absence of heterogeneous effects across subpopulations and countries suggests that the mechanism(s) linking suicide to temperature are similar across contexts, isolating specific responsible mechanism(s) in our mortality data is difficult. Alternate data, however, allow us to indirectly explore certain potential mechanisms. One hypothesis is that high temperatures alter the mental wellbeing of individuals directly, perhaps due to side-effects of thermoregulation (e.g. altered brain perfusion[39]) or other neurological responses to temperature. Notably, this hypothesis is consistent with suicide responding to very short-run (e.g. daily or monthly) variation in temperature, as well as with the finding that depressive disorders are implicated in over half of all suicides.[40]

If exposure to high temperatures directly alters the mental wellbeing of individuals, then this relationship should be observable using non-suicide outcome measures across a broad population, including individuals not immediately at risk of suicide. We test for such a pattern by examining whether monthly temperature also correlates with patterns of language on social media that express declining mental wellbeing.[28] To do this, we collect and analyze 622,749,655 geolocated Twitter updates occurring in the US between May 22, 2014 and July 2, 2015, noting that previous work has shown that analysis of Twitter updates can be used to predict variation in suicide in the US.[41] Using a statistical approach directly comparable to the analysis of suicides above (see Methods), we find that the probability a tweet expresses “depressive" language increases with contemporaneous local monthly temperature (Figure 4), similar to our findings for suicide. While baseline estimates for the effects of contemporaneous temperature are only statistically significant for one coding ($p < 0.01$ for Coding 1, $p > 0.1$ for Coding 2), estimates for both codings are significant once lagged effects are also accounted for ($p < 0.05$, Figure S4). Accounting for lags, we find that each additional +1°C in monthly average temperature increases the likelihood an update is depressive by 0.79% [95% CI: 0.23% - 1.35%] and 0.36% [95% CI: 0.05% - 0.68%] for the two different coding procedures we use. As shown in Figure 4, we estimate statistically and qualitatively similar effects under a variety of fixed effects and time controls.

Projected excess suicides under future climate change

To project potential impacts of future climate change on suicide, we use projected changes in temperature under a “business-as-usual" scenario (RCP8.5) to 2050 from 30 global climate models used in the recent Intergovernmental Panel on Climate Change (IPCC) 5th Assessment.[42] Relative to the year 2000, the climate models project a population-weighted average temperature increase by 2050 of 2.5°C [95% range: 1.3°C -3.7°C] in the US and 2.1°C [95% range: 1.5°C -3.2°C] in Mexico. To calculate the change in the suicide rate due to climate change, holding other social and economic factors fixed, we multiply projected increases in temperature in each future year by our estimated effect of past warming on the suicide rate, accounting for uncertainty in both the historical suicide-temperature relationship (including temporal displacement) and future climate projections[43] (see Methods). Given that the effects of temperature on suicide in the US appear to be trending up over time (recall Figure 2), we re-estimate the historical effect of temperature on suicide in the US using post-1990 data, and use these estimates to define the temperature response in our projections; for models that include temporal displacement, effects for the more recent 1990-2004 period are somewhat higher than for the full 1968-2004 period (0.58% increase per 1°C versus 0.42%), as temperature impacts have trended up over time (recall Figure 2).

Assuming that future outcomes will respond to a given mean temperature increase in the same way as past outcomes have responded to temperature fluctuations is a common but untestable assumption in the climate impacts literature,[44–47] but it is an assumption perhaps partially supported by the observed stationarity (or increase) in the temperature/suicide relationship over our study period. Under this assumption, and absent unprecedented adaptation, we calculate an increase in suicide rate by 2050 of 1.4% [95% CI: 0.6%-2.6%] in the US and 2.3% [95% CI: -0.3%-5.6%] in Mexico (Figure 5, left panel). Larger uncertainty for the effect in Mexico is due to larger uncertainty in that country's regression estimates once temporal displacement is accounted for (recall Figure 3). Combining our estimated changes in the suicide rate with projections of future population change in the two countries, we estimate that by 2050, climate change will cause a total of 14,020 excess suicides in the US [95% CI: 5600-26,050] and 7,460 excess suicides in Mexico [95% CI:-890-18,300] (Figure 5). Accounting for the covariance in US and Mexico temperatures within each climate realization, this amounts to 21,770 [95% CI 8,950-39,260] total additional suicides when summed across both countries.

Discussion

We provide longitudinal and country-scale evidence that local suicide rates in both a developed and a middle-income country are robustly associated with local temperatures, findings which are consistent with recent work in both developed and developing countries.[13,22] The remarkable consistency of the measured association over time and across contexts suggests that any hypothesized mechanism explaining this relationship must be widespread, and provides some confidence in generalizing these findings to other contexts and into the future. While our social media results support the hypothesis that temperature induces changes in mental state that follow the same pattern as suicides, and the generality of the suicide responses to temperature across geographic and socioeconomic strata is consistent with a common biological response, we cannot decisively reject other non-biologic explanations, such as that changes in temperature could affect social mediators of suicide.

Nevertheless, our results do suggest that the mechanism through which temperature affects suicide is likely distinct from temperature's effects on many other causes of mortality. In contrast to all-cause mortality, suicide increases at hot temperatures and decreases at cold temperatures; also unlike all-cause mortality, the effect of temperature on suicide has not decreased over time and does not appear to decrease with rising income or the adoption of air conditioning. The linear and stable structure of the suicide response is more similar to previously recovered relationships between interpersonal/intergroup violence and temperature,[11] which may plausibly have related biological origins.

Linearity and intertemporal stability in the suicide response has important implications for climate change projections, as it leads to no projected reduction in suicide mortality from rising temperatures in cold regions and no clear indication that secular societal trends or adaptation will reduce climate sensitivities. Both of these conclusions contrast strongly with dominant themes in the existing climate-health literature,[10] and along with other recent studies[13] contribute needed empirical evidence on the effects of changes in climate on mental health.

Our calculations suggest that projected changes in suicide rates under future climate change could be as important as other well-studied societal or policy determinants of suicide rates (see Figure 5 left panel). In absolute value, the effect of climate change on the suicide rate in the US and Mexico by 2050 is roughly two to four times the estimated effect of a 1% increase in the unemployment rate in the EU,[5] half as large as the immediate effect of a celebrity suicide in Japan,[48] and roughly one-third as large in absolute magnitude (with opposite sign) as the estimated effect of gun restriction laws in the US[7] or the effect of national suicide prevention programs in OECD countries.[6] The large magnitude of our results add further impetus to better understand why temperature affects suicide and to implement policies to mitigate future temperature rise.

Methods

Data on US suicides come from the Multiple Cause-of-Death Mortality Data from the National Vital Statistics System (NVSS),[26] which report county location, month, and cause of death for all individuals (prior to 1989), or those individuals residing in counties with more than 100,000 people (post-1989), representing roughly 75% of the total US population. We calculate age-adjusted suicide rates in each county-month by combining cause-of-death data with US census data on age-specific populations. County-level data from NVSS are available beginning in the early 1960s, but data on cause-of-death using common re-codes do not begin until 1968. After 2004, county identifiers are no longer made available in the public use data. Our suicide data in the US thus span the years 1968-2004.

In the US, we combine county-level suicide data with temperature and precipitation data from PRISM, a high-resolution gridded climate dataset.[49] PRISM data contain 4km-by-4km gridded estimates of monthly temperature and precipitation for the contiguous US, with daily estimates beginning in 1981, constructed by interpolating data from more than 10,000 weather stations. We aggregate these grid cells to the county- or municipality-month level, weighting by estimated grid-cell population from LandScan,[50] following the procedure in[51] for our nonlinear models. We test robustness using alternate suicide statistics drawn from the CDC's Underlying Cause of Death database (available at the county-year level for the years 1999-2013).[34]

Data on monthly suicide rates in Mexican municipalities come from Mexico's Instituto Nacional de Estadística y Geografía,[27] which we match to gridded daily[52] and monthly[53] temperature and precipitation data (the available daily data from ref [[52]] do not contain precipitation data, thus we use the UDel data[53] as our source of precipitation data). Our Mexican dataset spans the years 1990-2010.

We estimate the following regression separately for our US and Mexican panels:

$$y_{ismt} = f(T_{ismt}) + \gamma P_{ismt} + \mu_{im} + \delta_{st} + \varepsilon_{ismt} \quad (1)$$

using ordinary least squares, where i indexes localities (county or municipality), s indexes the state that the locality falls in, m indexes month-of-year, and t indexes year. y_{ismt} is the monthly suicide rate and P_{ismt} is monthly precipitation. μ_{im} and δ_{st} are, respectively, vectors of county-by-month effects and state-by-year effects; the former account for other locally-seasonally-varying factors that could also be associated with suicide, such as day length, or seasonal cycles in other factors, such as the school year, and the latter account for shocks common to all counties in a given state in a given year, such as unemployment conditions. Regressions are weighted by average population in each county or municipality, with standard errors clustered at the i level to nonparameterically adjust[54] for arbitrary within-unit autocorrelation in the disturbance term ε_{ismt}. We test robustness to alternate clustering regimes, including clustering at the state level and two-way clustering at the county and year level, and find that standard errors are only modestly affected (Table S3.

For the temperature response function $f(T_{ismt})$ in Equation 1 we focus on models that are a function of average monthly temperature T_{ismt} (e.g. the average temperature in January of 1996 in Santa Clara County, California), including linear models and higher order polynomials and spines. Estimates in the linear fixed effects models can be equivalently interpreted as the impact of a +1°C deviation from normal temperature, or as the effect of an absolute +1°C temperature increase, as (e.g.) the impact of a temperature increase from 0°C to 1°C is estimated to be the same as an increase from 20°C to 21°C . While monthly data cannot easily resolve sub-monthly responses to even shorter-run temperature variation (e.g. daily, as documented in past studies[22]), it more easily captures potential multi-week displacement effects that have been demonstrated in other weather-violence studies;[55] indeed, we find displacement effects in both the US and Mexico that appear to last months (Fig 3). A further reason for monthly aggregation is suicide data in Mexico are only available at the monthly level, and our source for temperature data in the US does not provide daily temperature data before 1980.

We also estimate binned models where suicide is modeled as a function of accumulated exposure to different daily temperatures, $f(T_{ismt}) = \sum_j \beta_j T^j_{ismt}$, with $T^{j=1}_{ismt}$ indicating the number of days in location-month-year $ismt$ when the average temperature fell below -6°C , $T^{j=2}_{ismt}$ as the number of days with average temperature in the (-6°C ,-3°C] interval, $T^{j=3}_{ismt}$ as the number of days in the (-3°C ,0°C] interval, and so on in 3°C intervals up to a top bin of (30°C , ∞)—indexing these bins by j. The (15°C ,18°C] bin is the omitted category in our binned regressions, so the coefficients of interest shown in Figure S1 can be interpreted as the effect on the monthly suicide rate from an additional day spent in bin j, relative to a day spent in the (15°C ,18°C] bin. See ref. [[51]] for a derivation and complete discussion of this approach and its interpretation.

The outcome in each regression is the monthly suicide rate, and we divide the estimate of β by the baseline suicide rate (the average suicide rate over the study period) to calculate percentage changes. As migration is unobserved in our data, our approach cannot account for potential selective migration into or out of specific counties – although migrants would have to differ in their suicide response to temperature for this to bias our results. We also note that our approach using county- or municipal-level data is focused on making inferences about average effects within these aggregate areas, and we do not attempt to draw any inferences regarding the risk that any specific individual within an administrative unit will commit suicide in any particular month.

To estimate the heterogeneous responses reported in Figure 3, we estimate versions of equation 1 that contain interactions:

$$y_{ismt} = \beta_1 T_{ismt} + \beta_2 (T_{ismt} * D_i) + \gamma_1 P_{ismt} + \gamma_2 (P_{ismt} * D_i) + \mu_{im} + \delta_{st} + \varepsilon_{ismt} \tag{2}$$

where D_i is equal to one if location i has a specified value for a the mediating variable of interest (e.g. above median income) and is zero otherwise. To estimate the year- or state-specific effects in Figure 2, we estimate a version of Equation 2 where temperature and precipitation are interacted with either year dummies or state dummies, and coefficients on these interactions are reported separately for each year or each state.

Because looking at heterogeneity in a linear model (Equation 2 might not directly reveal adaptation to temperature extremes, we also estimate heterogeneous responses using the binned model, studying whether the effect of extreme heat exposure differs by the average frequency of this exposure or by access to air conditioning (Figure S2).

To estimate the potential displacement effects of hot temperatures on future suicides, we estimate distributed lag models that include lags of monthly temperature and precipitation:

$$y_{ismt} = \sum_{L=0}^{1} (\beta^L T_{is(m-L)t} + \gamma^L P_{is(m-L)t}) + \mu_{im} + \delta_{st} + \varepsilon_{ismt} \tag{3}$$

where $\beta^{L=0}$ indicates the effect of current month's temperature and $\beta^{L=1}$ the effect of previous month's temperature.A finding of $\beta^{L=0} > 0$ and $\beta^{L=1} < 0$ would be consistent with displacement (hot temperatures in a given month increase suicides in that month and decrease them in the following month), with the sum of coefficients $\beta^{L=0} + \beta^{L=1}$ giving the overall effect of a hot month, net of displacement. These estimates are shown in the bottom panels of Figure 3.

Depressive language in social media updates For the analysis of Twitter updates, we built on earlier work showing that certain keywords and phrases in tweets are predictive of local-level suicide.[41] We coded tweets as "depressive" using the keywords and phrases in this earlier work, but because this approach only coded 0.02% of tweets in our sample as depressive, we developed an alternate approach that used a simpler set of suicide-related keywords to code tweets. In this latter coding, we compiled an extensive list of words associated with depression from various electronic sources, including more formal sources such as Crisis Text Line website (*www.crisistextline.org*), as well as from a number of suicide-related blogs found through Google searches (not listed here for privacy reasons). We retained words that were common across these sources and removed words likely to generate false positives (for example, "mom" is frequently included in suicidal texts). The dictionary of keywords that result from this procedure is (listed alphabetically): *addictive, alone, anxiety, appetite, attacks, bleak, depress, depressed, depression, drowsiness, episodes, fatigue, frightened, lonely, nausea, nervousness, severe, sleep, suicidal, suicide, trapped*. Using this simpler dictionary, we code 1.4% of tweets in our sample as "depressive". We designate this approach "Coding 1" and the earlier-literature derived approach "Coding 2".

Using each of these two keyword dictionaries, we computed the total number of Twitter updates in each of 885 Core-Based Statistical Areas (CBSA) (roughly, metropolitan areas) that contained at least one keyword in each day as a fraction of all Twitter updates between May 2014 and July 2015, following the approach in ref [[28]]. To reduce noise and to make estimates comparable to the suicide results, we limit our sample to CBSAs in which at least one Twitter update was posted on 90% of the sampling frame, and we aggregate up to the monthly level. Our dataset thus contains 24,780 CBSA-month observations. We then estimate the effect of monthly temperature on the likelihood that a Twitter update contains a depressive keyword using the following fixed effects regression

$$y_{ismt} = \beta T_{ismt} + \gamma P_{ismt} + \mu_i + \lambda_{sm} + \delta_{st} + \varepsilon_{imst} \tag{4}$$

via ordinary least squares where i indexes CBSAs, s indexes state, m indexes month, and t indexes year. y_{ismt} is the proportion of tweets in a CBSA-month that contain a depressive word and T_{ismt} and P_{ismt} are the average temperature and total precipitation for that CBSA-month. μ_i is a vector of CBSA fixed effects, which we include to account for time-invariant local drivers of depressive social media use. To account for local seasonality in both depressive tweets and temperature, we include state-by-month fixed effects λ_{sm} (i.e. 12 dummy variables for each state), and to account for local changes over time in either tweeting behavior or temperature, we include state-by-year fixed effects δ_{st}. Regressions are weighted by the average number of tweets in each CBSA. As in the suicide results, we report estimates of β normalized by the baseline rate of depressive tweets (either 1.4% or 0.02% for the two codings), such that they can be interpreted as percentage changes in the rate of depressive tweeting.

We show robustness under a range of alternate fixed effects, time trends, and the inclusion or exclusion of weights (Figure 4, analogous to Figure 1 for suicide results), and show how depressive tweets in a current month respond to temperature variation in that month, earlier months, and later months (Figure S4, analogous to the bottom panel of Figure 3 for suicide). As in the suicide results, results are primarily driven by contemporaneous responses to temperature.

Calculating impacts of future climate change To calculate the potential impacts of future climate change on suicide rates, we use climate projections drawn from the Coupled Model Intercomparison Project 5 (CMIP5). We utilize projections run under the RCP8.5 emissions scenario, in which emissions continue to rise substantially through 2100. We obtain data from 30 global climate models[56] that publish RCP 8.5 projections for changes in mean temperature.

Climate projection data are processed as follows, repeated separately for each of the 30 climate models. Projected changes in monthly temperatures are calculated for each climate grid cell by averaging monthly projected temperature around 2050 (2046-2055) and monthly projected temperature around the baseline period (1986-2005), then differencing them. Model grids are then overlapped on the study administrative units (e.g. US counties) and locality-specific changes are calculated by averaging over grid cells that overlap the locality, weighting by the amount of the grid cell falling into the unit.

We then combine these locality-level projections with our historical estimates of the effect of temperature on suicide to estimate (1) the potential percentage change in the suicide rate due to warming by 2050 and (2) the total number of excess suicides that could occur by 2050. The percentage change in the rate for a given country is calculated by multiplying the historical effect of temperature on suicide reported in Figure 3 for that country (using the combined effects of current and lagged temperature, to account for possible displacement) by the population-weighted projected change in temperature between 2000 and 2050 from each of the 30 climate models. Excess cumulative suicides in country c due to warming between 2000 and 2050 is then

$$Y_c = \sum_{t=2000}^{2050} pop_{ct} * (\beta_c * \Delta T_{ct}) \tag{5}$$

where pop_{ct} is the projected population in year t in 100,000s (taken from UN population projections[57]), β_c is the estimated net change (lagged plus current) in the suicide rate per +1°C increase in temperature (measured in deaths per 100,000/yr), and ΔT_{ct} is the projected increase in temperature between 2000 and year t. Again, because temperature effects in the US appear to be trending up over time, for the US we estimate β_c by applying Equation 1 to data from 1990 onwards. The application of future changes in annual average temperature (ΔT_{ct}) to monthly temperature-suicide coefficients (β_c) is appropriate given the limited evidence over our study area that future climate change will lead to differential levels of warming across seasons.[58,59]

We quantify uncertainty in these projections by bootstrapping the historical estimates of the suicide-temperature relationship (1,000 times, sampling with replacement) and applying this distribution of estimated temperature sensitivities to projections from each of the 30 climate model projections to construct 30,000 possible projections.[43]

It is sometimes suggested that constructing climate change projections using coefficients from a within-location fixed-effects estimator is inappropriate because temporary changes in environmental conditions may trigger social responses that differ from the response to more permanent climate changes (see refs. [[31,51]] for a general discussion of this issue). The Marginal Treatment Comparability (MTC) assumption[51] required for such an extrapolation to be valid appears to be well-supported in this context, based on evidence that we recover. Our within-location estimator recovers the local slope of the temperature-suicide function in the vicinity of average local conditions observed in each locality, in the sense of a local first-order Taylor approximation. Our climate change projection then uses this local derivative to extrapolate local suicide rates as each locality warms and experiences the climate of locations slightly further south (or with slightly warmer temperatures). If the MTC assumption is violated, then once a county warms permanently, it will not necessarily experience a permanent change in its suicide rate that reflects our estimates. This could occur for two reasons.

First, the overall average suicide rate of counties could be determined exclusively by non-temperature factors, with temperature only determining the timing of when suicides occur within a given year. If this were true, then temporary warm events would only appear to increase the suicide rate because they cause a temporary surge in suicides that is offset later in the year by a reduction in suicides—a mathematical necessity required to keep to total suicide rate fixed at the level determined by non-temperature factors. This phenomena is known as "temporal displacement" or "harvesting" in the literature. As shown in Figure 3, we test for such behavior in the data and find some evidence of temporal displacement, but also that a portion of the suicide signal we observe is "additional" in the sense that they are not compensated for by delayed reductions in suicide rates. This causes the sum of contemporaneous and lagged effects of temperature to be positive, indicating that warming does lead to a net elevation of a locality's total cumulative suicides and that average suicide rates are not only determined by non-temperature factors. Importantly, we account only for this additional effect, netting out any temporal displacement, when constructing climate change projections so as to avoid over-estimating projected suicides.

A second case in which the application of the local derivative of the temperature-suicide relationship to future warming would be inappropriate is if the slope of the temperature-suicide relationship depends on average temperature, or similarly if the response of suicide to extreme heat days depends on the frequency of exposure to these extremes – i.e. because populations adapt to warming. Indeed, prior studies of electricity use[60] and tropical cyclone mortality[61] have shown that locations with more exposure to an environmental stressors respond differently than those with less exposure, indicating adaptation. Using the same test but in the suicide-temperature context, we check for evidence for adaptation by examining if locations that are warmer on average had a shallower slope in their temperature-suicide response, or if suicides in locations more frequently exposed to temperature extremes (e.g. days $>30°$C) were less affected by these extremes that locations less frequently exposed.

We test for such behavior by estimating the temperature-suicide relationship for localities above and below the median temperature in both the US and Mexico (Figure 3), by estimating the local derivative for the temperature-suicide function for every single state in the US and Mexico separately (Figure 2), and by estimating the differential effect of exposure to extreme absolute temperatures for countries with less- and more-frequent exposure to these extremes (Figure S2). In all cases we fail to find evidence that effects diminish at higher temperatures: we see similar responses to temperature deviations in warmer and cooler counties and between warmer and cooler states, and we do not find that counties more frequently exposed to extreme absolute temperatures have diminished suicide responses compared to less-frequently-exposed locations, although estimates are somewhat noisy for cooler regions given limited exposure to extremes (Fig S2b). This evidence, along evidence that adoption of air conditioning has not reduced temperature-suicide relationships (Fig S2c) and that temperature-suicide relationships have diminished over time (Fig 2), suggest limited historical adaptation to either warmer-than-average mean temperatures or extreme heat exposure in our context.

We note two important caveats to this adaptation analysis. First, average county-level temperature could be correlated with other unobserved factors that also affect suicide risk (e.g. culture), and so any comparison of temperature-suicide effects by climate zones risks confounding the effect of differences in average temperature with differences in these other unobserved factors. Although we do not find differential effects across climate zones or observable covariates that might plausibly matter (income, AC adoption, and population; Figure 3), suggesting a potentially limited role for the influence of correlated unobservables in our analysis, we cannot decisively rule out the hypothesis that the effect of unobservables could exactly offset any differential impact of average temperature. Second, we cannot rule out that unprecedented adaptations in the future could reduce the temperature-suicide link in ways not observed historically. If this were to occur, then our estimates of excess suicides due to future warming would be too high. However, we note that there is no downward trend in the sensitivity of suicide to temperature during the period we observe (Figure 2), indicating that the emergence of unprecedented adaptations would itself be without precedent.

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Author Contributions. M.B., P.B., S.B., and S.H. designed the study, M.B., C.B., F.G., S.HN, P.B analyzed data, M.B., P.B, S.HN, S.B, S.H. wrote the paper.

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Figure 1: **Effects of temperature on suicide rate.** Lines show the estimated relationship between monthly temperature and monthly suicide rate in the US (panel a; 1968-2004) or Mexico (panel b; 1990-2010), under different specifications of the fixed effects and increasingly flexible polynomials or splines as described in the legend. Blue shaded areas are the bootstrapped 95% CI on Model 1 for each country. Histograms at the bottom display the distribution of monthly temperatures in each sample. Fixed effects in Mexico are as in the US, except with municipality and state-month FE in place of county-month FE.

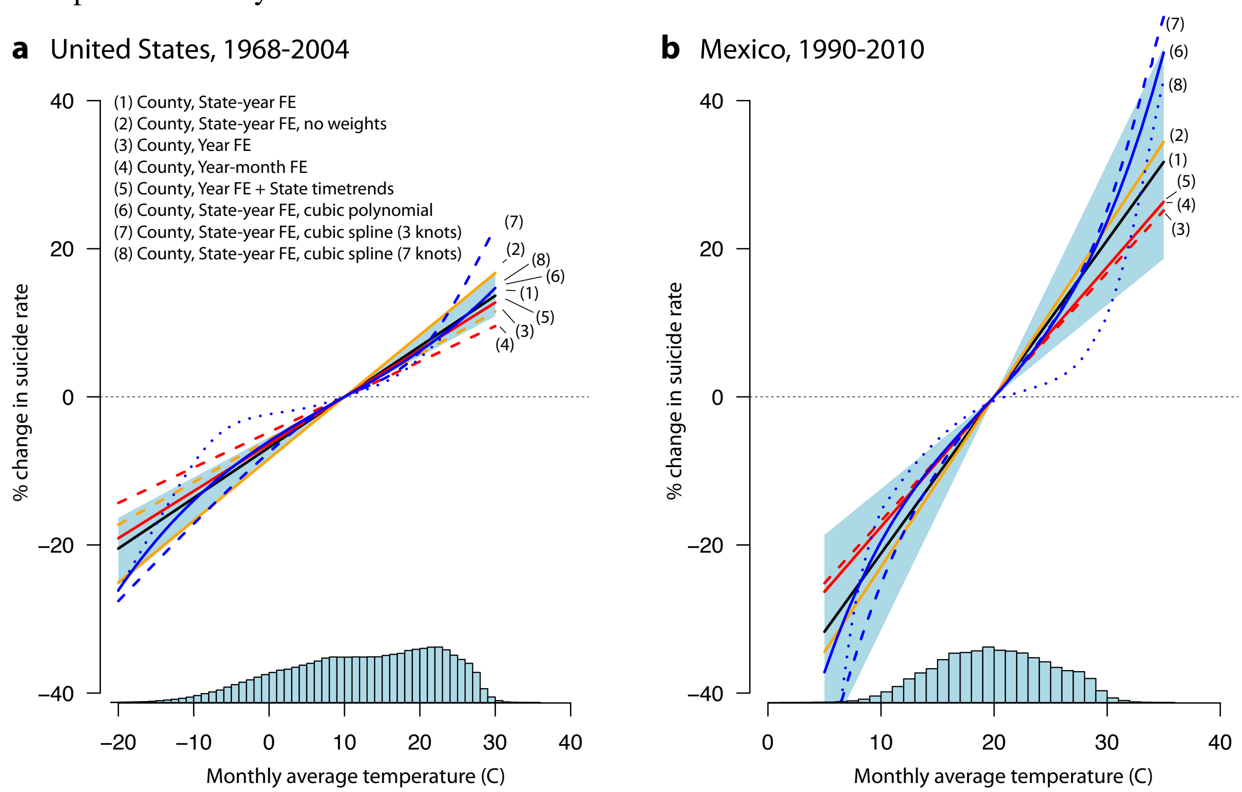


Figure 2: **Temperature effects on suicide over time and space.** **a-b**: Effects over time in US and Mexico. Each dot is the year-specific effect of temperature on suicide (line is 95% confidence interval), expressed as a percentage change above that year's average suicide rate. The red dotted line shows the average effect across the full sample in each country. **c** Effects by state. Colors show the percentage increase in the state-specific monthly suicide rate per 1°C increase in monthly temperature. Histograms show the distribution of estimates across states in US and Mexico. States outlined in black have estimates that are statistically distinguishable from the nation-wide average estimate.

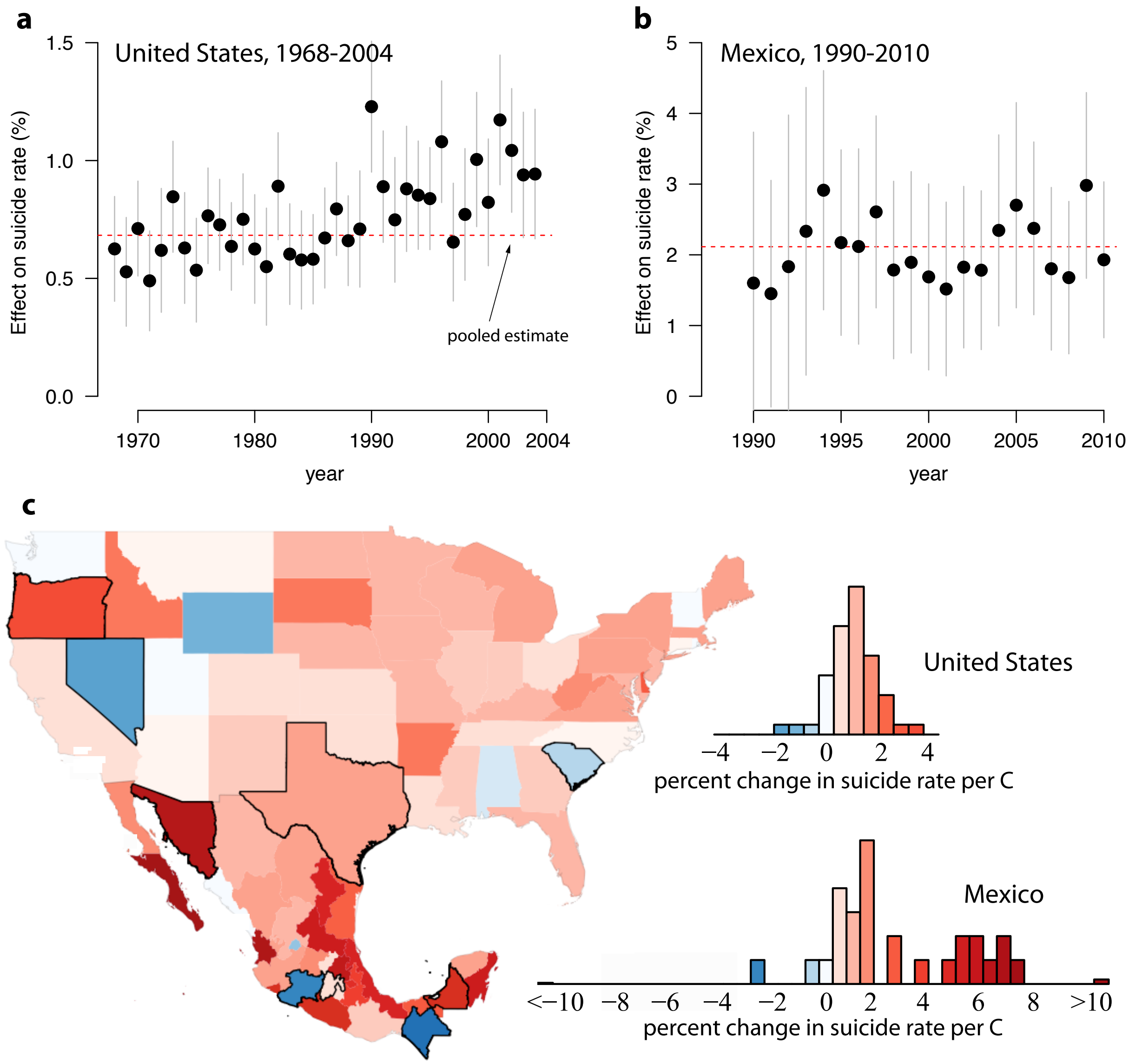


Figure 3: **Effect of variation in temperature on monthly suicide rate across the full sample in US (black circles), Mexico (white circles) and for sub-groups in those countries**. Dots are point estimates of the effect of monthly temperature on monthly suicide (from Equation 1 or 2), lines are 95% confidence intervals. Base rates are reported in deaths per 100,000 person-months.

	Sample	Obs.	Base rate	Effect size (95% CI)
Full sample	US, monthly 1968–2004 (NHCS)	851,088	0.97	0.68 (0.53,0.83)
	US, annual 1999–2013 (CDC)	5,725	0.91	1.28 (0.28,2.29)
	Mexico, 1990–2010	611,366	0.30	2.11 (1.17,3.06)
By average temperature	Below median temperature	425,544	0.90	0.67 (0.46,0.87)
	Above median temperature	425,544	1.04	0.71 (0.49,0.94)
	Below median temperature	305,683	0.28	2.21 (1.14,3.29)
	Above median temperature	305,683	0.33	1.93 (0.96,2.90)
By income	Below median income	403,224	0.96	0.46 (0.27,0.65)
	Above median income	403,224	0.98	0.72 (0.56,0.87)
	Below median income	300,258	0.19	2.87 (1.01,4.73)
	Above median income	300,258	0.32	2.10 (1.18,3.02)
By AC penetration	Below median penetration	425,544	0.99	0.63 (0.47,0.78)
	Above median penetration	425,544	0.96	0.75 (0.59,0.90)
	Below median penetration	74,904	0.21	2.82 (0.77,4.87)
	Above median penetration	74,904	0.39	2.29 (1.38,3.19)
By population	Below median population	425,544	1.03	0.71 (0.21,1.21)
	Above median population	425,544	0.97	0.68 (0.52,0.84)
	Below median population	305,683	0.20	3.01 (0.84,5.18)
	Above median population	305,683	0.30	2.08 (1.14,3.01)
By sex and suicide type	Male, nonviolent	454,764	0.21	0.51 (−0.13,1.14)
	Male, violent	454,764	1.17	0.70 (0.46,0.95)
	Female, nonviolent	454,764	0.16	1.22 (0.63,1.82)
	Female, violent	454,764	0.21	0.23 (−0.30,0.76)
	Male	611,366	0.50	2.36 (1.33,3.38)
	Female	611,366	0.10	0.89 (−1.20,2.98)
By gun ownership	Below median ownership	425,544	0.96	0.70 (0.52,0.88)
	Above median ownership	425,544	1.02	0.63 (0.35,0.90)
Displacement and placebo tests	next month temperature (m+1)	844,872	0.97	0.00 (−0.14,0.15)
	current month temperature (m)	844,872	0.97	0.72 (0.57,0.87)
	previous month temperature (m−1)	844,872	0.97	−0.30 (−0.45,−0.14)
	current + previous	844,872	0.97	0.42 (0.20,0.64)
	next month temperature (m+1)	606,521	0.30	0.03 (−0.87,0.93)
	current month temperature (m)	606,521	0.30	2.79 (1.78,3.79)
	previous month temperature (m−1)	606,521	0.30	−1.78 (−2.76,−0.81)
	current + previous	606,521	0.30	1.00 (−0.23,2.23)

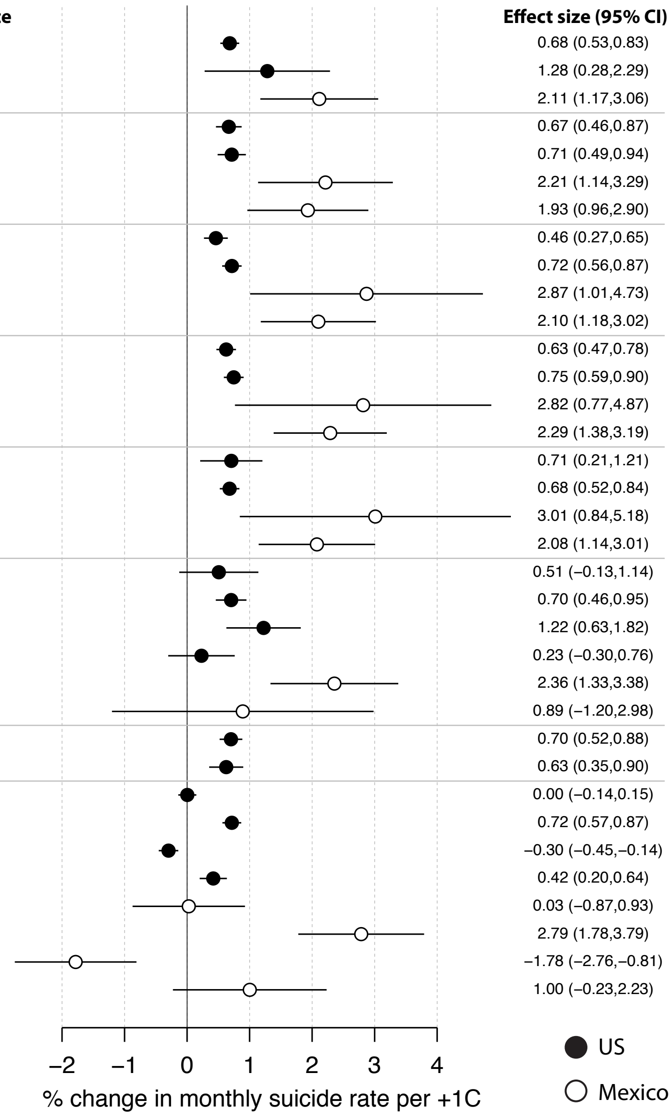


Figure 4: **Effect of monthly temperature on the likelihood that a Twitter update in US metropolitan areas contains depressive keywords.** Lines show the estimated relationship between monthly average temperature and the monthly share of Twitter updates ("tweets") that contain depressive language, under alternate fixed effects and time controls. (N=24,780 location-months). Blue shaded regions are bootstrapped 95% confidence intervals on the baseline model. Grey histograms display the distribution of monthly temperatures in the sample. The two plots show alternative coding approaches used to identify depressive language (see Methods).

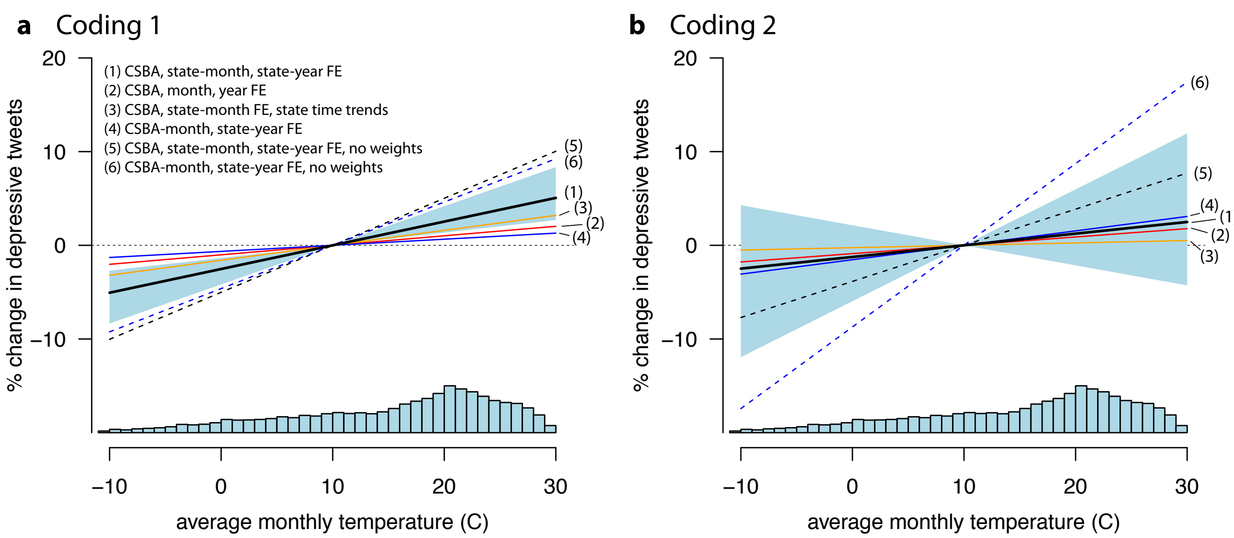
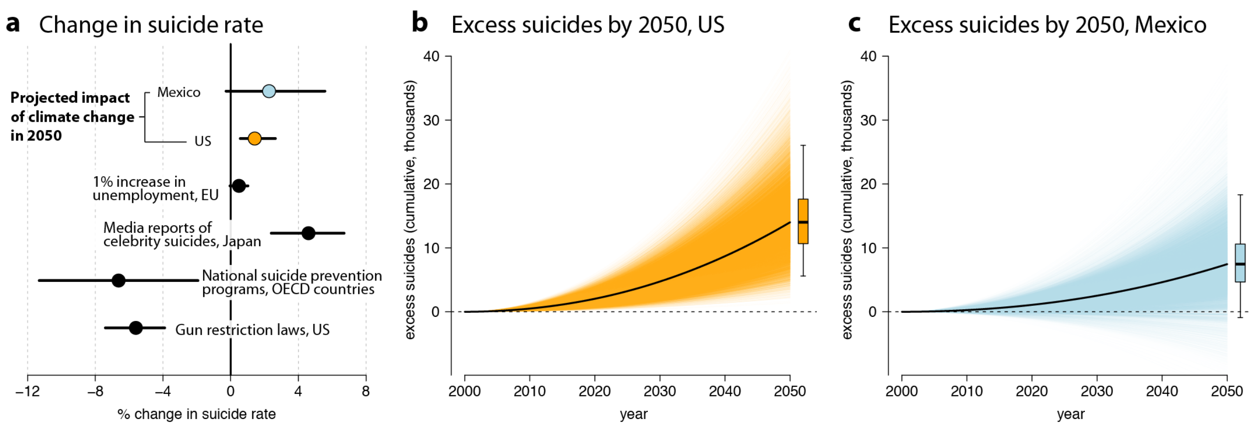


Figure 5: **Change in suicide rate, and cumulative excess suicides, by 2050 due to projected temperature change in RCP8.5**. **a**: projected change in the suicide rate by 2050 for US and Mexico, accounting for temporal displacement across months (*current* + *previous*) as shown in Figure 2. Whiskers are 95% CI that account for uncertainty in both future temperature change and in the historical response of suicide to temperature.[43] Black markers are published estimates for the impacts of other policies/events[5–7,48] displayed for comparison. **b-c**: distributions of total projected cumulative excess suicides in US and Mexico over time. Black lines are median projections with colored regions displaying the distribution of 30,000 Monte Carlo projections that resample parameter estimates and climate models. Boxplots show median, interquartile range, and 95% CI of projected cumulative excess suicides by 2050.



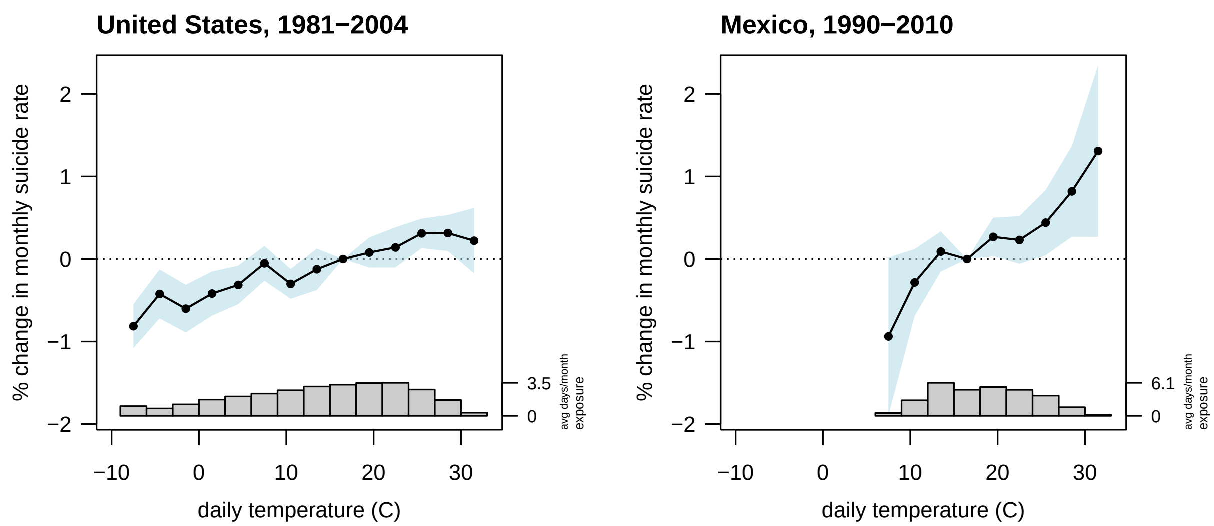


Figure S1: **Effects of daily temperature on monthly suicide rate.** Connected black markers are the change in monthly suicides rates in US (left) and Mexico (right) caused by altering the temperature of a single day in that month (blue shaded area is 95% CI). Effects are the relative change in monthly suicides due to changing a day's average temperature from 15-18°C to an alternative average temperature (left vertical axis). Estimates are net of all constant differences between locations, all within-location seasonal (monthly) variations, and all nationally coherent annual changes in rates. Grey histograms display the distribution of individual days in each sample (right vertical axis).

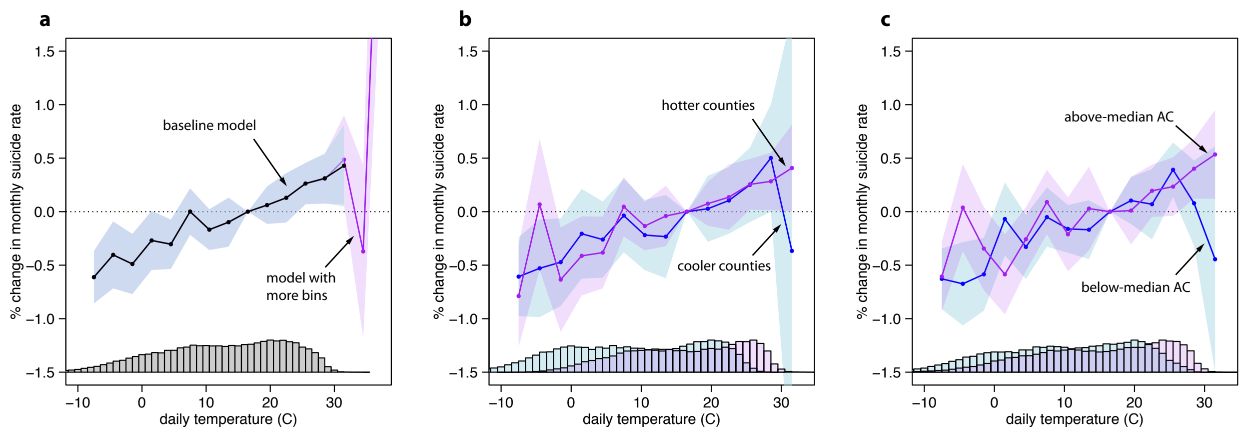


Figure S2: **Robustness and heterogeneity in the binned model for the US. a**, Baseline binned model (black, as in Figure S1A assigns all daily exposure >30°C into one bin. Estimates from a model that instead splits exposure above 30°C exposure into 30-33°C , 33-36C, and >36C bins has identical estimates below 30°C but noisy estimates above 33°C , given the very low number of days in our sample with daily average temperatures above 33°C (as shown in the histogram at bottom). **b**, the effect of daily temperature exposure on suicide as a function of county average temperatures, with blue (purple) showing counties with below (above) median temperature. Estimates in cooler counties are noisy in the >30°C bin given the minimal exposure in those counties to hot temperatures, as shown in the histograms at bottom. **c**, as in (b) but for above- and below-average air-conditioning (AC) penetration. Counties with lower AC penetration, which tend to be cooler in our sample and thus have low current exposure to extreme heat, again have noisy estimates for the >30°C bin. As in Figure S1, all estimates refer to the 1981-2004 period for which we have daily temperature data.

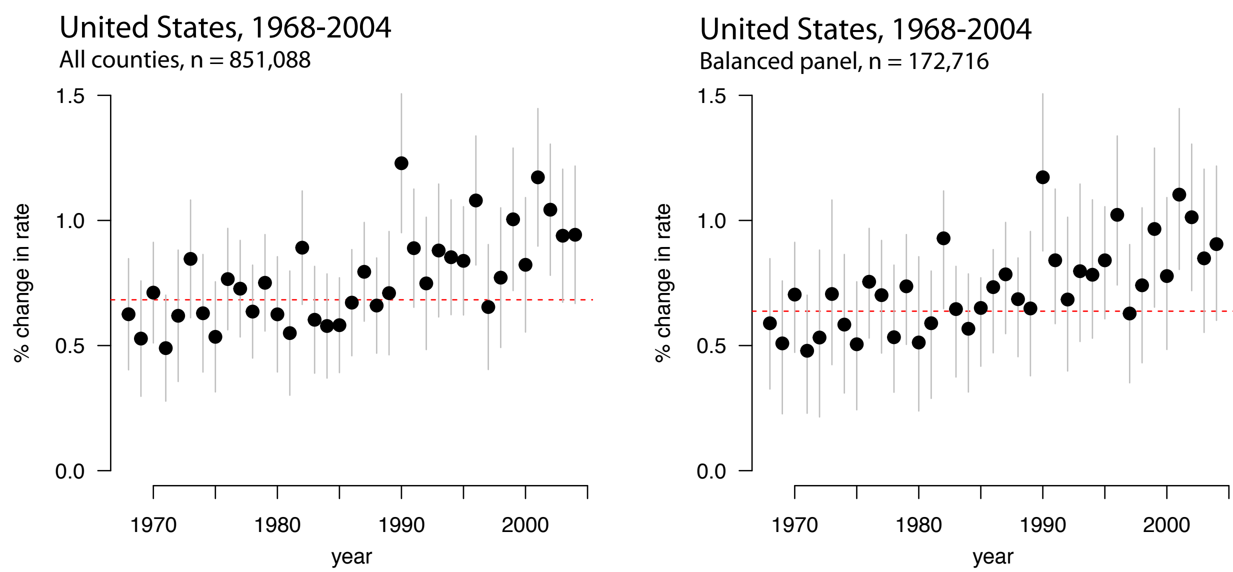


Figure S3: **Robustness of effects of temperature on monthly suicide rate over time in the US.** Left plot: As in Figure 2A. Right plot: sample restricted to a balanced panel of counties reporting data in every year.

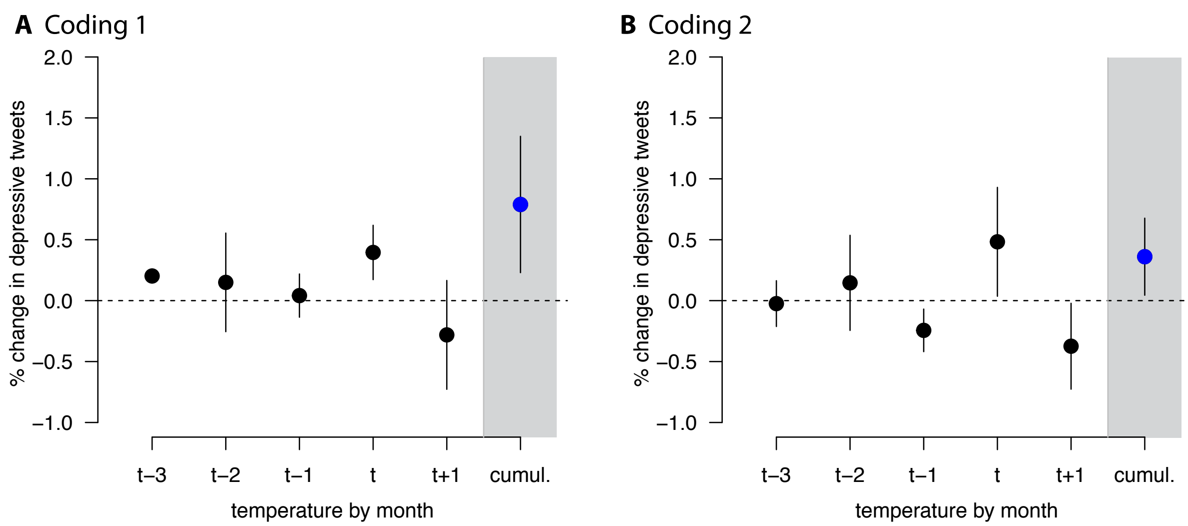


Figure S4: **Effect of temperature earlier and later months on depressive tweets in the current month.** Black markers are changes in the rate of depressive tweets in month t as a function of a 1°C increase in previous, current, and future months, for both codings of depressive tweets. Blue markers show the cumulative effect ($\sum_{t-3}^{t} \beta_t$) of current and previous-month temperature exposure. See Methods for full description.

Table S1: **Estimates of the linear effect of temperature on suicide rate in the US are robust to different statistical specifications.** All models include county-month fixed effects (i.e. 12 dummy variables for each county) as indicated in the FE1 row, and include time fixed effects as indicated in the FE2 row, with 'S'=state, 'Yr'=year, 'Mo'=month. Some models also contain linear time trends, and are weighted by county population, as indicated in the bottom rows. The outcome variable is the monthly suicide rate (models 1-5; mean = 1.03 suicides per 100,000 people), the log of the monthly suicide rate (model 6), or the inverse hyperbolic sine-transformed monthly suicide rate (model 7). Temperature is measured in °C , precip in meters. Standard errors are shown in parenthesis, clustered at the county level. Models 1-5 are analogous to lines 1-5 shown in Figure 1A.

	Dependent variable:						
	suicide rate					log(rate)	ihs(rate)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
temp. (°C)	0.007^{***}	0.008^{***}	0.006^{***}	0.006^{***}	0.005^{***}	0.005^{***}	0.004^{***}
	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	(0.001)	(0.0005)
prec. (m)	−0.035	0.014	-0.059^{**}	−0.038	−0.048	−0.011	−0.016
	(0.024)	(0.073)	(0.029)	(0.024)	(0.032)	(0.032)	(0.016)
FE1	C x Mo	C x Mo	C x Mo	C x Mo	C x Mo	C x Mo	C x Mo
FE2	S x Yr	S x Yr	Yr	Yr	Yr x Mo	S x Yr	S x Yr
Pop. weights	Y	N	Y	Y	Y	Y	Y
Observations	851,088	851,088	851,088	851,088	851,088	280,486	851,088
R^2	0.175	0.128	0.166	0.172	0.167	0.512	0.232

Note: *p<0.1; **p<0.05; ***p<0.01

Table S2: **Estimates of the linear effect of temperature on suicide rate in Mexico are robust to different statistical specifications.** All models include Municipality fixed effects as indicated in the FE1 row, state-month fixed effects (i.e. 12 dummies for each state) as indicated in the FE2 row, and include time fixed effects as indicated in the FE3 row, with 'S'=state, 'Yr'=year, 'Mo'=month. Some models also contain linear time trends, and are weighted by municipality population, as indicated in the bottom rows. The outcome variable is the monthly suicide rate (models 1-5; mean = 0.22 suicides per 100,000 people), the log of the monthly suicide rate (model 6), or the inverse hyperbolic sine-transformed monthly suicide rate (model 7). Temperature is measured in °C , precip in meters. Standard errors are shown in parenthesis, clustered at the county level. Models 1-5 are analogous to lines 1-5 shown in Figure 1B.

	Dependent variable:						
	suicide rate					log(rate)	ihs(rate)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
temp. (C)	0.006^{***}	0.007^{**}	0.005^{***}	0.005^{***}	0.005^{**}	0.008^{*}	0.005^{***}
	(0.001)	(0.003)	(0.002)	(0.002)	(0.002)	(0.004)	(0.001)
prec. (m)	0.011	0.009	−0.015	−0.010	−0.025	0.076	0.007
	(0.020)	(0.046)	(0.027)	(0.027)	(0.028)	(0.055)	(0.013)
FE1	Mun.	Mun.	Mun.	Mun.	Mun.	Mun.	Mun.
FE2	S x Mo	S x Mo	S x Mo	S x Mo	S x Mo	S x Mo	S x Mo
FE3	S x Yr	S x Yr	Yr	Yr	Yr x Mo	S x Yr	S x Yr
Pop. weights	Y	N	Y	Y	Y	Y	Y
Observations	611,366	611,366	611,366	611,366	611,366	40,701	611,366
R^2	0.168	0.018	0.164	0.166	0.164	0.736	0.298

Note: *p<0.1; **p<0.05; ***p<0.01

Table S3: **Estimates of the linear effect of temperature on suicide rate are robust to different ways of clustering the standard errors.** Top panel is United States, bottom panel is Mexico. Columns show estimates under different clustering schemes: (1) county, (2) county + state-by-year, (3) county + year, (4) state.

	United States:			
	(1)	(2)	(3)	(4)
temp. (C)	0.0067^{***}	0.0067^{***}	0.0067^{***}	0.0067^{***}
	(0.0008)	(0.0008)	(0.0011)	(0.0007)
prec. (m)	−0.0347	−0.0347	−0.0347	−0.0347
	(0.0242)	(0.0238)	(0.0236)	(0.0300)
Clustering	County	County + State-Yr	County + Yr	State
Observations	851,088	851,088	851,088	851,088
R^2	0.1754	0.1754	0.1754	0.1754

	Mexico:			
	(1)	(2)	(3)	(4)
temp. (C)	0.0063^{***}	0.0063^{***}	0.0063^{***}	0.0063^{***}
	(0.0014)	(0.0015)	(0.0014)	(0.0017)
prec. (m)	0.0108	0.0108	0.0108	0.0108
	(0.0203)	(0.0137)	(0.0172)	(0.0144)
Clustering	Mun.	Mun. + State-Yr	Mun. + Yr	State
Observations	611,366	611,366	611,366	611,366
R^2	0.1684	0.1684	0.1684	0.1684

Note: *p<0.1; **p<0.05; ***p<0.01

Table S4: **Heterogeneous effect of temperature on suicide rate in the US**. Covariates include county income in each year (in $1000 USD), county average temperature averaged across all years (in °C), and state-level AC penetration in each year (defined as percent of households with residential AC, derived from Barreca et al[30]). Covariates are all de-meaned to ease interpretation. All regressions include county-month FE and state-year FE and are weighted by county population.

	Dependent variable:			
	suicide rate			
	(1)	(2)	(3)	(4)
temp	0.0068***	0.0065***	0.0067***	0.0065***
	(0.0008)	(0.0008)	(0.0008)	(0.0008)
temp*income	0.0001***			−0.000003
	(0.00003)			(0.00004)
temp*avgtemp		−0.0001		−0.0002
		(0.0002)		(0.0002)
temp*AC			0.0037***	0.0037*
			(0.0012)	(0.0020)
Observations	806,448	806,448	806,448	806,448
R^2	0.1756	0.1755	0.1755	0.1756
Note:				*p<0.1; **p<0.05; ***p<0.01