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The impact of future summer temperature on public health in Barcelona and Catalonia, Spain

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Abstract Several epidemiological studies have reported associations between increases in summer temperatures and risks of premature mortality. The quantitative implications of predicted future increases in summer temperature, however, have not been extensively characterized. We have quantified these effects for the four main cities in Catalonia, Spain (Barcelona, Tarragona, Lleida, Girona). We first used case-crossover analysis to estimate the association between temperature and mortality for each of these cities for the period 1983 to 2006. These exposure–response (ER) functions were then combined with local measures of current and projected changes in population, mortality and temperature for the years 2025 and 2050. Predicted daily mean temperatures were based on the A1B greenhouse gas emission, "business-as-usual" scenario simulations derived from the ENSEMBLES project. Several different ER functions were examined and significant associations between temperature and mortality were observed for all four cities. For these four cities, the age-specific piecewise linear model predicts 520 (95%CI 340, 720) additional annual deaths attributable to the change in temperature in 2025 relative to the average from the baseline period of 1960–1990. For 2050, the estimate increases to 1,610 deaths per year during the warm season. For Catalonia as a whole, the point estimates for those two years are 720 and 2,330 deaths per year, respectively, or about 2 and 3% of the warm season. In comparing these predicted impacts with current causes of mortality, they clearly represent significant burdens to public health in Catalonia.

Keywords Climate change · Temperature · Heat waves · Mortality · Morbidity · Health · Impacts

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Introduction

Several epidemiological studies from Europe, North America and Asia have demonstrated statistical associations between higher summer temperatures and premature mortality (McMichael et al. 2008; Robine et al. 2008; Anderson and Bell 2009; Bell et al. 2008; Basagaña et al. 2011). These efforts correlate higher daily temperatures with increased risks of mortality on concurrent or subsequent days and control, via study design, for other factors that may impact day-to-day changes in mortality. At the same time, most global climate models are projecting important increases over the next few decades in average temperatures. For example, The United

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Nations Intergovernmental Panel on Climate Change (IPCC) has predicted that global surface temperature is likely to rise between +1.2 and +6.4°C during the 21st century (IPCC 2007). However, the predicted changes in temperature are not spatially homogenous and certain regions are likely to be especially impacted. Studies suggest that the Mediterranean region will be one of these regions (Giorgi 2006).

The likely changes in temperature over time are expected to impact health, both directly and indirectly, in many important ways. For example, in their review of the existing evidence, Ebi et al. (2006) list the following potential consequences of climate change: (1) mortality and morbidity due to higher temperatures; (2) air pollution (primarily ozone) related effects; (3) water and food-borne diseases due to extreme precipitation events; (4) vector- and rodent-borne diseases due to warmer temperatures and (5) increases in the likelihood of floods and hurricanes. In this paper, we quantify the direct heat stress impacts of projected increases in temperature on mortality. We utilize a methodology similar to that used over the past two decades to quantify the effects of air pollution on mortality. Formal guidance for this methodology has been provided by the World Health Organization (2001) and by the National Research Council (2002).

Impact estimates of the direct effects of high temperatures have been generated for several locations including: 15 European cities (Baccini et al. 2011); the metropolitan New York City area (Knowlton et al. 2007); six U.S., European and Australian cities (Gosling et al. 2009a, b) and the U.S. as a whole (Voorhees et al. 2011). A more complete review of previous impact assessments can be found in Huang et al. (2011). The general methodology used in these studies, described in detail below, involves combining ER functions with population exposure and projected changes in temperature. However, each effort involves several different assumptions and sub-models.

Our efforts focus on the impact of future changes in warm season temperature on mortality for the capital cities of each of the four provinces of Catalonia, an autonomous region in the northeast of Spain. The direct impacts on residents of the cities of Barcelona, Tarragona, Lleida and Girona are calculated for the years 2025 and 2050. We first generate city-specific ER functions of the association between temperature and mortality. In order to assess the future public health impact, these estimates are then applied to global and regional climate models that project future warm season temperature changes in Catalonia. While there is considerable uncertainty associated with quantifying these impacts, there is merit in informing decision-makers and the public about the likely magnitude of effects. With this information, the appropriate level of resources can be allocated to policies for mitigation and intervention.

General methodology

For a given study area, five components are necessary to quantify the mortality impact of increases in temperature:

1. An estimate of the baseline temperatures to which the population is or was exposed. Preferably several years of daily data should be used to construct an average to reduce the likelihood of a single anomalous year being used to represent baseline temperatures.
2. An estimate of future daily temperatures for several target years in the future. As in the baseline estimates, several years of data should be used.
3. An estimate of the size and profile demographics of the population exposed to these temperatures, and a projection of these values in future years.
4. The baseline incidence of the health effect being estimated (e.g. the underlying mortality rate in the population, in deaths per thousand people).
5. Risk estimates from ER functions relating ambient temperatures to mortality developed for the study area or adapted from the epidemiological literature.

Then, the predicted number of attributable cases of mortality (AM) associated to temperature is calculated as:

$$AM(T) = P * B * (1 - 1/RR(T)) \quad (1)$$

where:

P	Exposed population
B	Baseline population incidence of the given health effect (i.e., deaths per 1000 people)
$RR(T) = \exp(\beta * T)$	Relative risk from temperature T where β is obtained from the ER functions

Ultimately, the predicted increase of attributable deaths associated with an increase from baseline temperatures (Tb) to projected temperature (Tp) is calculated as:

$$Impact = AM(Tp) - AM(Tb) \quad (2)$$

Data and methods

Study setting

Catalonia is an autonomous region in the northeast of Spain with an area of about 32,000 km^2 and a population of approximately 7.5 million people in 2008 (Idescat 2011) with its capital in Barcelona (1.6 million people). Catalonia is the richest and most highly industrialized part of Spain with a GDP per capita higher than the European Union average. As all four study cities are relatively close to the Mediterranean (Barcelona and Tarragona are located on the sea, Girona is within 35 km and Lleida is within 75 km), their climate is characterized by warm to hot, dry summers and relatively mild and wet winters. Also, the rest of the population of Catalonia is heavily concentrated along the Mediterranean.

Temperature data

Baseline and projected daily mean model temperatures were derived from an ensemble of state-of-the-art high-resolution (25×25 km^2 grid) A1B greenhouse gas emission scenario simulations derived from the ENSEMBLES project (Fischer and Schär 2010; Haylock et al. 2008; see the description below). The A1B scenario is a "business-as-usual" emissions path, resulting in atmospheric CO_2 concentrations reaching 700 ppm in 2100 (i.e. two and a half times the pre-industrial concentration). The A1B scenario is defined by a balanced emphasis on both fossil and non-fossil energy sources in technological development, within the A1 family describing a future world of very rapid economic growth, a global population peaking in mid-century and declining thereafter, and the rapid introduction of new and more efficient technologies (Nakicenovic et al. 2000). According to this scenario, annual mean temperatures in the Mediterranean area are projected to rise in 2050 by around +2.5°C with respect to the 1901–1950 period, but the increase is even larger for the summer season (IPCC WGI 2007).

To determine city-specific temperatures, we used inverse-distance weighting restricted to continental grid-points to interpolate simulated gridded data (Daly et al. 2002). We used transient simulations (1950–2050) from eight different regional climate models, driven by four different general circulation models, including C4I, CNRM, DMI, ETHZ, ICTP, KNMI, MPI, SMHI C4I:RCA3 (driven by HadCM3Q16), CNRM:Aladin (ARPEGE-RM5.1), DMI: HIRHAM5 (ECHAM5-r3), ETHZ:CLM (HadCM3Q0), ICTP:RegCM3 (ECHAM5-r3), KNMI:RACMO2 (ECHAM5-r3), MPI:REMO (ECHAM5-r3) and SMHI: RCA (ECHAM5-r3 (Jacob et al. 2008). This combination of global and regional models thus covers a relatively large range of uncertainty derived from climate modeling and model nesting (Déqué et al. 2007).

Besides the projected temperature we also calculated the city-specific temperatures that corresponded to the historic (1960–1990) 95th percentile of the temperature distribution. The multi-model ensemble described above was used again for this purpose. Calendar days above this threshold were subsequently determined for 2010–2040 and 2035–2065 (herewith labeled as 2025 and 2050).

Calculating changes in temperature

Daily baseline temperatures were generated by averaging values from the eight climate models for each calendar day and city for the years 1960 through 1990. Thirty-one years were used to eliminate the possibility of a single anomalous year being used to characterize baseline temperatures. Based on the climate change model predictions, we calculated the projected temperature for each corresponding calendar day and grid point for 2025 and 2050. Again, 31 year averages centered at 2025 and 2050 were used to obtain a more robust projection. We used a similar method to calculate the number of days above the 95th percentile for the years 2025 and 2050. As described below, we explicitly incorporated climate model uncertainty into our estimates.

Since our ER functions (described below) examine the impact of temperature on mortality during the warm season (May 16 through October 15), only this period of calendar days was included in the predictions.

Estimating exposed population

Data for current and future population estimates were obtained from the Statistical Institute of Catalonia (IDESCAT 2011) which provides projections for Catalonia until the year 2041. We used simple linear projections to extend these projections to the year 2050. Future city growth was assumed to be proportional to projections for Catalonia as a whole. The Institute also provides projections assuming low, medium and high population growth rates. Since the medium growth scenario seeks to reflect the most likely changes in demographics in Catalonia, it was characterized with a higher weight for our estimates. We used the population projections for 2025 and 2050 to calculate the expected future exposed population. In additional sensitivity analyses, we also utilized age-specific projections in the population.

Determining baseline mortality rates

Daily mortality data were obtained from the Mortality Registry of Catalonia, and included the place, date and age of death. We extracted the total number of cases for each year for all non-accidental mortality (ICD-10 codes A through U). For the mortality rates for the full population, we used the mortality records from 2008 and obtained an annual rate of 8.15 per 1,000. For age-specific mortality rates, we first obtained counts of deaths and total population for those ages 65 and under and those over age 65 for the years for which these data were available: 1975, 1986, 1991 and 1996. For each of the years we calculated the age-specific mortality rates. Future annual age-specific baseline mortality rates were projected by fitting linear models to data and projecting rates for 2025 and 2050.

Developing exposure-response functions

For the analysis of the association between temperature and mortality, mortality data were obtained from the Mortality Registry of Catalonia, and included the date and age of death. The mortality analysis focused on all-cause mortality (excluding injuries, accidents, and homicides) for the full population, as well as separate analyses for those age 65 and under and those above 65. Only data for the warm season from May 16 to October 15 from 1983 to 2006 were included in the analysis. As in previous studies (Basu and Ostro 2008), we used a time-stratified case-crossover study design described by Levy et al (2001). In this method, temperature on the date of death (case) is compared to several control days (referent periods) occurring on the same day of the week within the same month and year. As a result, each individual in the study design serves as his or her own control, by matching on a wide range of individual-level confounders. Thus, by design, only factors that change on a daily basis—temperature and humidity—need to be included in the model specification. Conditional logistic regression analysis is used to obtain an effect estimate for each city. The subsequent results are relative risks that can be interpreted as the percent increase in mortality per 1°C change in temperature. Models using an unlagged temperature term (lag0) and one-day lag (lag1) were examined for each city to determine the best fit for the data. All models also included a lag0 term for humidity. The analysis was conducted using Stata version 10.1.

We first estimated a model for each city using a linear effect of temperature for the full population. Next, we re-estimated each city/specific model after stratifying by age to obtain separate ER functions for those aged 65 and under versus those above age 65. Individuals above age 65 are typically the most susceptible population (Basu 2009), as well as the group with the higher baseline death rate. We also examined a piecewise linear model using the city-specific historical (1960–1990) 95th percentile of temperature for the spline knot. This percentile has been used in the past to specify the more extreme temperature days (Basu 2009). This model generates a lower and upper line segment and provides a test for piecewise linearity in the ER function to determine whether the relative risk changes at higher temperatures. Next, we ran a regression model that explicitly modeled heat waves. Using a dichotomous variable, a heat wave day was defined as a day above the historic 95% percentile after the preceding day was also above that percentile. Finally, we examined age-specific functions for both the piecewise linear and heat wave models.

Quantifying the health impact

To quantify the impact of future temperatures on mortality, we examined the implications of the alternative models described above to test the sensitivity of the results. For the basic model, we used the city-specific linear ER function model for all ages with baseline temperature derived from actual recorded values. These results are presented for Barcelona, the four major cities together, and for all Catalonia.

Next, we repeated the analysis using the model stratified by age (those 65 and under and those above 65). We matched these estimated coefficients with the age-specific baseline mortality rates and age-specific projected population. Third, we used the piecewise linear model to account for the potential effects of more extreme temperatures and non-linearity in the ER function. Fourth, we incorporated the results of the age-specific piecewise linear model. Fifth, we used the results of the heat wave regression model and combined it with the projected and historic average number of heat wave days in each city. We also examined the impacts using the age-specific heat wave models. Finally, we also extrapolated the findings for the four cities to the entire population of Catalonia by applying the 4-city average expected heat-related mortality per 100,000 deaths to the whole population of Catalonia. In addition, when we extrapolated the age-specific estimates, we used the respective betas, mortality rates, and population sizes.

Note that in all of these impact assessments, temperature is the only parameter that changed. Specifically, we projected population and mortality rates for the years 2025 and 2050, and then calculated the additional mortality by only considering the change in temperature from the baseline to those years. However, it is also of interest to determine the full impact of projected future changes in temperature that also incorporates the changes in population and mortality rates over the period from baseline to 2025 and 2050. These impacts are also provided in the results.

We obtained point estimates and confidence intervals (CIs) by propagating the uncertainties in population growth, projected temperature, and the ER function using Monte Carlo simulations. Specifically, we modeled uncertainly assuming three population growth scenarios: "low", "medium", and "high" with sampling probabilities of 0.1, 0.8 and 0.1, respectively. Greater weight was placed on the central estimate since the Catalonia authorities indicated it was the best overall estimate of future population growth. For the parameters associated to the relative risk we drew values from a normal distribution using the estimated mean and standard error from the initial regressions. For projected temperature for each day, we first computed the daily mean and standard deviation provided by the eight climate models. The prediction for each day was then obtained by sampling from a normal distribution with that mean and standard deviation. Ultimately, the future climate time series was equal to the simulated mean future temperature from the climate model minus the simulated baseline temperature from the climate model plus the observed baseline temperature.

For the heat wave indicator, we drew values for each projected day as above and then calculated its corresponding value. Under these assumptions, for both 2025 and 2050 and for each city, we randomly drew a value with replacement for each of these parameters. The Monte Carlo sampling was repeated 100,000 times and was used to obtain both a point estimate (by the mean) and the confidence interval (using the 2.5th and 97.5th percentiles) in order to incorporate model uncertainty into the final results. In a sensitivity analysis for the number of Monte Carlo impact values, we obtained almost identical results, for both point and confidence interval estimation, for several numbers of computed values from 1000 to 100,000.

Results: quantifying the impacts for Catalonia

The parameters used in the impact assessment are summarized in Table 1. The first row summarizes the estimated population in 2009. The second and third rows summarize the mean city-specific observed and modeled temperature for 1960–1990, while the fourth and fifth rows display the modeled city-specific projected mean temperatures for 2025 and 2050. For example, for Barcelona, the measured and modeled baseline temperature were 19.87°C and 20.72°C, respectively. For the three other cities, the modeled was more similar to the measured temperature. For Barcelona, the projected temperatures for 2025 and 2050 are 22.16°C and 23.34°C, respectively, which are 1.4 and 2.6 degrees above the modeled baseline.

The next set of rows summarizes the city-specific results of the conditional logistic regressions in terms of percent change in mortality and 95% CI per 1°C. The results are provided for all ages, age ≤65, age >65, the lower and upper segments of the piecewise linear models, the heat wave model, and the age-specific results for Barcelona for the piecewise linear and heat-wave models. For the other three cities, the estimates for the age-specific piecewise linear and heat wave models were not used to calculate impacts since their goodness of fit statistics, based on the Akaike Information Criterion (AIC), were inferior to the all-age models, which were used instead.

For Girona, Tarragona and Lleida, an unlagged temperature term provided a better fit of the data than that including a one-day lag term, based on both the significance of the effect and the AIC. In Barcelona, the fit of the model using both lags 0 and 1 was only slightly better than the model with only lag0 alone. However, for consistency among cities, a lag0 for temperature adjusting for humidity was used for all of the models. For example, for Barcelona, for all ages taken together, mortality increases by 1.8% (95%CI 1.4, 2.1) per 1°C. This result as well as that of the other cities is statistically significant. The effect estimates for the other cities range from 2.0% in Tarragona to 1.3% in Girona, with Lleida at 1.6%. Considering the age-specific estimates, for Barcelona the effect estimate for the subset age 65 and younger versus those above age 65 was 0.8% and 2.1% per 1°C, respectively. The

Table 1 Parameters used in the impact assessment

Parameters	Barcelona	Tarragona	Lleida	Girona
2009 population (1,000 s)	1,622	140	136	96
Mean (1960–1990) baseline temperature (°C)	19.87	20.61	21.14	20.08
Mean (1960–1990) modeled temperature (°C)	20.72	20.80	21.64	20.44
Projected mean temperature, 2025 (°C)	22.16	22.23	23.22	21.95
Projected mean temperature, 2050 (°C)	23.34	23.38	24.47	23.21
Effect estimate (95% CI), full population[a]	1.8 (1.4, 2.1)	2.0 (0.9, 3.1)	1.6 (0.9, 2.3)	1.3 (0.4, 2.2)
Effect estimate (CI), ≤ age 65	0.8 (0.1, 1.4)	1.5 (−0.4, 3.5)	0.1 (−1.3, 1.6)	1.6 (−0.1, 3.3)
Effect estimate (CI), > age 65	2.1 (1.7, 2.5)	2.2 (0.9, 3.4)	2.1 (1.3, 3.0)	1.11 (0.1, 2.2)
Effect estimate (CI), lower spline	1.4 (1.1, 1.8)	1.8 (0.7, 2.9)	1.6 (0.9, 2.4)	1.2 (0.3, 2.1)
Effect estimate (CI), upper spline	9.7 (7.0, 12.5)	7.6 (−1.5, 17.1)	1.4 (−6.9, 10.4)	2.5 (−5.1, 10.6)
Effect estimate (CI), lower spline ≤ age 65	0.5 (−0.2, 1.2)	NA	NA	NA
Effect estimate (CI), upper spline ≤ age 65	8.2 (2.4, 14.2)	NA	NA	NA
Effect estimate (CI), lower spline > age 65	1.8 (1.4, 2.2)	NA	NA	NA
Effect estimate (CI), upper spline > age 65	10.2 (7.0, 13.4)	NA	NA	NA
Effect estimate (CI), heat wave	19.8 (15.6, 24.3)	9.4 (−4.7, 25.5)	15.8 (2.9, 30.3)	9.07 (−4.0, 23.7)
Effect estimate (CI), heat wave ≤ age 65	11.6 (3.4, 20.5)	NA	NA	NA
Effect estimate (CI), heat wave > age 65	22.5 (17.5, 27.7)	NA	NA	NA

NA not applicable

[a] Effect estimates are the percent change in mortality and 95% CI per 1°C

piecewise linear estimates for Barcelona are 1.4% for the lower segment and 9.7% for the upper segment per 1°C. The latter estimate increased to 10.2% for those greater than age 65 in the piecewise linear model. Finally, for Barcelona, the estimated mortality increased to 19.8% for a heat wave day and to 22.5% for a heat wave day for those above age 65. Based on the AIC, the age-specific piecewise linear model for Barcelona combined with the age-specific linear model for the other three cities were the best fitting models.

Table 2 summarizes the estimated mortality impacts for Barcelona, the four capital cities and for all Catalonia for 2025 and 2050. We began with the simple linear ER model and then examined the implications of the other ER functions summarized in Table 1. These estimates incorporate the uncertainties in the ER functions, population growth and climate models, but hold the population and mortality rate constant at either the 2025 or 2050 level. Using the simple linear model results in an increase of 90 attributable annual deaths for Barcelona in 2025, 110 for the four capital cities, and 420 for all of Catalonia. For Barcelona and the other capital cities, all of the other models generated larger mortality estimates. For example, for Barcelona the mortality estimates were higher by 30%, 45% and 100%, respectively, for the age-stratified model, heat wave model and age-stratified heat wave model. Much larger estimates, however, were derived from the piecewise linear and the age-stratified piecewise linear models. For example, using a piecewise linear model increases the Barcelona estimates by about three-fold over the simple linear function of temperature to 300 deaths (95%CI 180, 430) with an increase to 520 attributable deaths (95%CI 340, 720) using the age-specific piecewise linear estimates. Finally, allowing for changes in population growth and mortality rates from baseline (1960–1990) levels generates 1,430 excess deaths above the baseline.

For Catalonia, the age-stratified piecewise linear model also generates the highest estimate in 2025 of 720 excess deaths. Again allowing for changes in population growth and mortality rates from baseline (1960–1990) levels generates about 4,300 excess deaths relative to the baseline average. It is of note that the ER models that best fit the data (age-specific piecewise linear model for Barcelona and age-specific linear model for the other three cities) also generate the largest impact estimates.

Based on the age-stratified piecewise linear models for 2050, the excess deaths attributed to temperature increases in Barcelona and Catalonia as a whole are 1,610 and 2,330, respectively. Incorporating the changes in population to 2050 generates 4,300 and 12,010 excess deaths over the 1960–1990 baseline average.

Discussion

Using city-specific ER functions, we have provided estimates of the mortality impacts due to projected future increases in temperature in the four major cities of Catalonia. The best estimates are generated from an ER function that is both age-specific and piecewise linear. This function captures both the increased susceptibility of the older population and the greater relative risks per degree at the higher temperatures. Using this model and holding population and mortality rates constant at the 2025 level, the projected change in temperature generates

Table 2 Estimated attributable mortality impacts using alternative exposure-response models (point estimates and 95% confidence interval)

Models	Barcelona	Four cities	Catalonia
2025			
Basic linear	90 (60, 120)	110 (80, 150)	420 (320, 520)
Age-stratified	120 (80, 160)	140 (100, 180)	380 (280, 470)
Piecewise linear	300 (180, 430)	320 (200, 450)	660 (490, 840)
Age-stratified piecewise linear	520 (340, 720)	530 (350, 740)	720 (540, 920)
Heat wave	130 (80, 200)	150 (90, 220)	450 (210, 680)
Age-stratified heat wave	180 (100, 270)	190 (110, 280)	410 (180, 630)
Age-stratified piecewise linear, full impact[a]	1430 (1200, 1690)	1630 (1380, 1880)	4300 (3410, 5130)
2050			
Basic linear	190 (140, 250)	240 (180, 300)	880 (670, 1100)
Age-stratified	420 (330, 510)	480 (380, 570)	1310 (1010, 1560)
Piecewise linear	600 (400, 830)	650 (440, 880)	1350 (990, 1700)
Age-stratified piecewise linear	1610 (1160, 2140)	1670 (1210, 2200)	2330 (1810, 2880)
Heat wave	250 (150, 360)	290 (190, 410)	830 (420, 1250)
Age-stratified heat wave	550 (350, 760)	600 (400, 820)	1250 (600, 1900)
Age-stratified piecewise linear, full impact[a]	4300 (3420, 5200)	4820 (3840, 5790)	12010 (9030, 14640)

Estimates hold population and mortality rates constant at either the 2025 or 2050 level and only consider changes in temperature. All estimates incorporate uncertainty from climate models, population growth, and exposure-response function

[a] These estimates incorporate changes in population and mortality rates from baseline (1960–1990) to the future years

an increase of about 520 attributable deaths (about 2% of total mortality) in Barcelona, 530 for the four major cities in Catalonia (about 0.9% of total mortality) and 720 for Catalonia as a whole (about 0.8% of total mortality). For the year 2050, these estimates increase to 1610, 1670 and 2330, respectively. This corresponds to about 3.4, 1.5 and 1.4% of all deaths in 2050, respectively. The proportions decrease as we move from Barcelona to the four cities and Catalonia since the age-specific piecewise model was not significant for the non-Barcelona cities (maybe due to sample size and low number of deaths) and we relied instead on the linear age-specific model for them. If we assume the same proportion of heat-related total mortality for Catalonia as that in Barcelona, this would amount to 1,800 heat-related deaths in 2025 and 3,910 in 2050 in Catalonia.

The above estimates assume a constant population held at either 2025 or 2050 and only reflect changes in temperature form baseline. If we include the growth in population, we project 4,300 more deaths from temperature increases in Catalonia will occur in 2025 relative to the number of heat-related death occurring during the 1960–1990 period and that 12,000 more will occur in 2050.

Our analyses indicated that the results were fairly robust to a few of the model assumptions. For example, models using the ERs from the age-stratified or heat wave models generated mortality estimates that were within 50% of those from the simple linear model. However, for 2025 the estimates from the piecewise linear and age-specific piecewise linear models were three to five times greater than those of the linear model. In 2050, these two models were three to eight time higher than the linear model reflecting both the significant increase in the older population in the future and the greater risk estimates at the higher temperatures. The resultant functional form between temperature and mortality generated in this case by a piecewise linear model has been reported in many previous studies (Curriero et al. 2002; Baccini et al. 2008; Anderson and Bell 2009).

It is useful to compare the ER functions for our four Catalonia cities with those of previous studies. For example, Baccini et al. (2008) analyzed the association between maximum temperature mortality in 15 European cities from 1990 to 2000 using generalized estimating equations. For the seven "Mediterranean" cities in the sample, an all-cause mortality effect of 3.1% (95% credibility interval of 0.6, 5.7) per 1°C increase was reported, while for Barcelona alone the effect was 1.56% (95%CI 1.04, 2.08). A study of 13 Spanish cities using data from 1990 to 1996 and minimum temperature reported a statistically significant (standard error not reported) effect for Barcelona of 2.52% per 1°C increase (Iniguez et al. 2010). In a study of Lisbon and Oporto, Portugal, Almeida et al. (2010) reported a 2.1% (95%CI 1.6, 2.5) and 1.5% (95%CI 1.0, 1.9) effect, respectively, associated with a 1°C increase in mean apparent temperature. The latter is a general measure of discomfort that incorporates both temperature and humidity (Almeida et al. 2010). Studies of Italian cities by Michelozzi et al. (2006) and Stafoggia et al. (2006) indicated effect estimates of between 2.6 and 5.4% per 1°C increase. In addition, several studies have shown similar effect estimates regardless of the temperature measure used (i.e., mean, maximum, minimum, apparent temperature) given their high correlation (Barnett et al. 2010).

There are also several studies that examine the effects of extreme temperatures or heat waves in Barcelona and the Mediterranean region, in general. For example, Tobias et al. (2010) found that one day after an extreme heat day in Barcelona, defined as a day with temperature over 30.5°C, resulted in a 5% (95%CI 2, 8) increase in daily mortality. D'Ippoliti et al. (2010) analyzed the association between heat waves and mortality for those above age 65 in nine European cities, including Barcelona. A heat wave was generally defined as a two or more days above the historic 90th percentile of apparent temperatures. The authors reported that in Barcelona, mortality for this subgroup increased by 15.6% (95%CI 11, 20.4) on heat wave days and by 22% for the five analyzed Mediterranean sites as a whole. Thus, the ER functions used in our impact assessment appear to be reasonable in light of previous studies.

In support of our higher estimates for those over age 65, similar findings for elderly populations have been reported in several previous studies. For example, greater risks for elderly populations (either over age 65 or over age 75) were observed in studies conducted in Holland (Huymen et al. 2001), Ireland (Goodman et al. 2004), France (Fouillet et al. 2006), England and Wales (Hagat et al. 2007), the United States (Basu and Ostro 2008), Spain (Iñiguez et al. 2010), Portugal (Almeida et al. 2010) and in several other European cities (D'Ippoliti et al. 2010; Baccini et al. 2008).

We have estimated that for Barcelona, projected changes in temperature alone (i.e., holding population and mortality rates constant at the 2025 level) generate excess mortality that is approximately 2% of total annual mortality and about 5% of the warm season mortality. For 2050, the temperature-related mortality in Barcelona is about 3.4% of annual mortality and 8.8% of the warm season mortality. Direct comparisons with previous studies are difficult, however, because of the use of different methods (time series models using Poisson regression, case-crossover or generalized estimating equations), function forms, temperature lags used in the ER functions, temperature metrics (mean, maximum or minimum temperature), temperature ranges (full distribution, summer only, above a certain threshold or heat wave events), time periods, and endpoints (all ages, elderly, cardiovascular). Nevertheless, we can provide a crude idea of how the estimates for Barcelona compare to previous estimates for it and other Mediterranean cities.

Direct comparisons with previous impact estimates are difficult due to differences in the climate model used, baseline and projection years chosen, and ER functions. However, a few other studies used the A1B scenario and make the assessments comparable. For example, Baccini et al. (2011) generated mortality estimates for 15 European cities using the A1B emission scenario. Comparisons were made between a baseline of 1990–2000 and 2030. The attributable fraction varied from 0.6% in Helsinki to 5.4% in Rome. In an analysis of projected temperature changes for the United States for 2050 relative to a baseline of 2001, Voorhees et al. (2011) derived an attributable fraction of approximately 0.65%.

Clearly, there are important uncertainties in this analysis, besides the choice of the appropriate ER function. For example, our estimates would change with different assumptions about how the baseline mortality rates and population would vary over time. In our impact assessment, we used currently available mortality data for Catalonia and projected future mortality rates using linear models of data covering the last 35 years. This rate could change in either direction over time depending on changes in health habits, utilization and effectiveness of medical care, and competing risks. In addition, we assumed that the population of the four major cities would grow over time in proportion with that of Catalonia as a whole. In doing so, we examined the impacts of three different growth scenarios. However, it is possible that the growth of the four major cities will differ from that of the region as a whole, with some affect on the estimated mortality impact.

A third and significant uncertainty is derived from downscaled estimates of future IPCC-based predictions in temperature changes. Gosling et al. (2011) emphasized the importance of incorporating the distribution of different climate models. We attempted to develop a reasonable range for our impact assessment by using Monte Carlo sampling from the eight different regional climate models, driven by four different general circulation models. We also used a Monte Carlo simulation that propagated the uncertainties in our assumptions. We can also obtain a sense of the uncertainty due to the emissions models by examining the results of the analysis by Baccini et al. (2011). In one of their sensitivity analyses, they examined the impact of three different emissions scenarios from the IPCC Special Report (IPCC 2007). Temperature changes for the year 2030 were derived from low, medium and high scenarios (i.e., scenario B1, A1B and A2, respectively). Combining this information with a linear ER function for temperature and mortality (above a threshold of 22.4°C), a central estimate for Barcelona of 338 deaths was obtained. The low and high emissions scenarios altered this estimate by −5.6% and +3.5%, respectively. The mortality estimate was higher than our Barcelona estimate using the basic linear model for 2025. This is likely due to different estimates of future temperatures and different procedures for estimating population growth and baseline mortality.

A fourth uncertainty related to possible confounding of the temperature-mortality ER functions by air pollution, particularly ozone, a summertime pollutant. However, the analysis by Basagaña et al. (2011) indicated that inclusion of ozone in the temperature-mortality regression model did not alter the estimated effect estimate. Fifth, we only considered changes in temperature and assumed humidity would remain constant in the future. However, future changes in humidity would alter apparent temperature and could subsequently impact health.

A final uncertainty relates to our assumption about adaptation and mitigation of the population over time. Other researchers have used or suggested methods to estimate the potential impact of mitigation as well as biological adaptation (Ebi et al. 2006; Knowlton et al. 2007; Kinney et al. 2008; Gosling et al. 2009a, b). We have chosen to present our impacts without any assumptions about biological adaptation or behavioral mitigation over time. We note that an analysis of the association between temperature and mortality in Barcelona for 1983 to 2006, a period long enough to show the effects of adaptation and mitigation, failed to demonstrate a reduction in the effect estimate over time (Basagaña et al. 2011). Therefore, based on the best available evidence, adaptation appears to be minimal for the relevant population. This could change over time and thereby reduce the estimated mortality impacts. Regarding mitigation, analysis of air conditioner use in the United States suggests a subsequent reduction of the effects of temperature (Ostro et al. 2010). Specifically, the authors reported that a 10% increase in the proportion of exposed households using central air conditioners was associated with a 16% reduction in the all-cause mortality. Therefore, if residents of Catalonia were to adopt similar mitigation measures, some reductions in mortality estimates would be likely.

To provide some context for our impact estimates, we compare our projected heat-attributed mortality impacts with current mortality from other causes. For example, using the age-stratified piecewise linear model, we projected 530 additional deaths in 2025 in the four cities (about 520 in Barcelona), and 720 additional deaths in Catalonia due to higher temperatures relative to average temperatures from 1960 to 1990. We related this to the following cause-specific deaths in Barcelona and Catalonia, respectively, for the year 2007: flu (4, 11), accidents (28, 524), HIV (44, 153), diabetes (359, 1442), and chronic obstructive pulmonary disease (COPD) (431, 1886). Thus, based on our findings using reasonable assumptions about projected increases in temperature, empirically-derived effects of temperature on mortality, and simple assumptions about population growth, the future increases in temperature are likely to generate significant impacts on public health. As such, the health impact from heat exposure could become an important motivation for climate change mitigation.

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