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Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios

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ABSTRACT

Background: There is an established U-shaped association between daily temperature and mortality. Temperature changes projected through the end of century are expected to lead to higher rates of heat-related mortality but also lower rates of cold-related mortality, such that the net change in temperature-related mortality will depend on location.

Objectives: We quantified the change in heat-, cold-, and temperature-related mortality rates through the end of the century across 10 large US metropolitan areas.

Methods: We applied location-specific projections of future temperature from over 40 downscaled climate models to exposure-response functions relating daily temperature and mortality in 10 US metropolitan areas to estimate the change in temperature-related mortality rates in 2045–2055 and 2085–2095 compared to 1992–2002, under two greenhouse gas emissions scenarios (RCP 4.5 and 8.5). We further calculated the total number of deaths attributable to temperature in 1997, 2050, and 2090 in each metropolitan area, either assuming constant population or accounting for projected population growth.

Results: In each of the 10 metropolitan areas, projected future temperatures were associated with lower rates of cold-related deaths and higher rates of heat-related deaths. Under the higher-emission RCP 8.5 scenario, 8 of the 10 metropolitan areas are projected to experience a net increase in annual temperature-related deaths per million people by 2086–2095, ranging from a net increase of 627 (95% empirical confidence interval [eCI]: 239, 1018) deaths per million in Los Angeles to a net decrease of 59 (95% eCI: − 485, 314) deaths per million in Boston. Applying these projected temperature-related mortality rates to projected population size underscores the large public health burden of temperature.

Conclusions: Increases in the heat-related death rate are projected to outweigh decreases in the cold-related death rate in 8 out of 10 cities studied under a high emissions scenario. Adhering to a lower greenhouse gas emissions scenario has the potential to substantially reduce future temperature-related mortality.

1. Introduction

The relationship between ambient temperature and risk of death is well established and in evidence around the world (Gasparrini et al., 2015a; Guo et al., 2014; Hajat et al., 2014; Medina-Ramon and Schwartz, 2007). Specifically, there is an established U-shaped association between mean daily temperature and mortality, such that deviations from the temperature of minimum mortality (MMT) in either direction (i.e., hotter or colder) are associated with higher rates of mortality. The shape and magnitude of this U-shaped exposure-response function, as well as the MMT, vary considerably from location to location.

Continued climate change is projected to lead to higher average ambient temperatures across most of the globe (IPCC, 2013). Accordingly, several studies project substantial increases in heat-related morbidity and mortality if today's population were exposed to the higher temperatures projected through the end of the century, holding all other factors constant (Kingsley et al., 2016; Knowlton et al., 2007; Ostro et al., 2012; Peng et al., 2011). However, given the generally U-shaped exposure-response function between daily temperature and

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mortality, changes in temperature projected through the end of century may simultaneously lead to lower rates of cold-related mortality (Guo et al., 2016, Huynen and Martens, 2015, Li et al., 2013, Vardoulakis et al., 2014). The relative magnitude of these changes, as well as the sign of the net change in temperature-related mortality under temperatures projected for the future, will depend on many factors that vary by location. Specifically, it is possible that expected increases in heat-related mortality will be offset, partially or entirely, by expected decreases in cold-related mortality in a manner that depends on: 1) the shape of the exposure-response function between daily temperature and mortality, 2) the distribution of present-day daily temperatures, and 3) projected temperature changes going forward in each location.

A few previous studies have considered the impact of temperature changes across the calendar year through the end of the century in various locations within the United States (US) (Li et al., 2013; Mills et al., 2015; Schwartz et al., 2015). For example, Schwartz et al. (2015) estimated that most US regions would experience a net increase in temperature-related mortality due to projected temperature changes. Such analyses have also been carried out in the United Kingdom, Australia, Canada, and the Netherlands (Guo et al., 2016; Hajat et al., 2014; Huynen and Martens, 2015; Martin et al., 2012; Vardoulakis et al., 2014). However, building resilience against climatic effects (i.e., adaptation) depends on action by local policymakers and government officials, and prior studies have typically provided an incomplete description of the potential burden of mortality attributable to temperature changes needed for action at the local level. For example, prior studies have typically relied on future temperature projections from one or a few climate models rather than the full set of coupled ocean-atmosphere circulation models comprising the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012), the state-of-the-art model ensemble used in the most recent Intergovernmental Panel on Climate Change (IPCC) assessment (IPCC, 2013). Incorporating the full range of future temperature projections is important in order to better capture the uncertainty associated with these projections. Additionally, few studies have incorporated future population growth scenarios into projections of temperature-related mortality, potentially a key driver of the future public health burden of temperature-related deaths. Accordingly, with the goal of providing local municipalities with actionable evidence, we quantified the expected change in heat-related, cold-related, and total temperature-related mortality rates per million people if the current populations of 10 large US metropolitan areas were to experience the temperatures projected through the end of the century by the CMIP5 model ensemble under two representative concentrations pathways (RCPs), assuming all other factors are held constant. In addition, we estimated the total number of deaths attributable to temperature in 1997, 2050, and 2090, both assuming that population size remains constant and accounting for projected population growth.

2. Materials and methods

2.1. Overview

We conducted this analysis in ten large US metropolitan areas: Atlanta, Boston, Chicago, Dallas, Houston, Los Angeles, Miami, New York, Philadelphia, and Washington, D.C. (see Supplementary data, Table S1 for a list of counties included in each metropolitan area). In 1997, the temporal midpoint of the baseline period used in our analysis, these metropolitan areas ranged in size from 2.2 million (Miami) to 11.9 million (Los Angeles), collectively encompassing 58.7 million people or 22% of the 1997 US population (U.S. Census Bureau, 2002). We carried out the analysis of these 10 metropolitan areas in three stages. First, we developed exposure-response curves describing the present-day (1985–2006) relationship between mean daily temperature and mortality in the major city around which each metropolitan area is defined. Second, we combined these exposure-response curves with projections of future temperatures to estimate the change in the temperature-related mortality rate per million people in two future decades (2045–2055 and 2085–2095) in the metropolitan area around each city. Finally, we calculated the total number of deaths attributable to temperature in each metropolitan area at three time points: 1997, 2050, 2090, assuming either constant population size or that populations in each city would change according to available projections. A detailed description of our analytic approach is provided below.

2.2. Data sources

2.2.1. Present-day temperature and mortality

We acquired daily counts of all-ages mortality (excluding external causes) from the National Center for Health Statistics for a 20-year period centered around 1997 (1985–2006) for the major city contained within each of the 10 metropolitan areas. In this dataset, each city is defined as the county or set of counties in which that city is located (see Supplementary data, Table S1) (Schwartz et al., 2015; Lee et al., 2014). We obtained daily mean temperature values for each city from the National Oceanic and Atmospheric Administration (NOAA), as measured at the same set of airport weather stations used in previous work (Gasparrini et al., 2015a, 2015b). To characterize the impact of temperature on mortality in the larger metropolitan areas around each of the 10 cities, we obtained the number of all-ages, all-cause deaths occurring in 1997 for each county in each metropolitan area from CDC WONDER (US CDC 2000/2003) and summed them to yield annual metropolitan area death counts.

2.2.2. Temperature projections

We obtained projections of historical and future daily temperature for each metropolitan area from the CMIP5 ensemble of coupled ocean-atmosphere circulation models (Maurer et al., 2007) for time periods centered around 1997 (1992–2002), 2050 (2045–2055), and 2090 (2085–2095) (see Supplementary data, Table S2). Specifically, we obtained daily minimum and maximum temperature projections for the most central 1/8° grid square in each metropolitan area from each of approximately 40 models from the CMIP5 ensemble. These projections were downscaled using the bias-correction and constructed analogues approach (Brekke et al., 2013). We averaged the projected minimum and maximum temperature values to generate projected values of daily mean temperature.

CMIP5 temperature projections are available for four Representative Concentration Pathways (RCPs), which describe potential alternative standardized radiative forcing trajectories across the 21st century due to anticipated greenhouse gas emissions and other factors. This paper follows the convention of basing analyses on RCPs 4.5 and 8.5, because they represent relatively “better case” and “worse case” scenarios for future greenhouse gas emissions, respectively (Kingsley et al., 2016). RCP 4.5 assumes that future policies and technologies will reduce greenhouse gas emissions, resulting in a 1.8 °C increase in the global average temperature by 2100, relative to 1986–2005 (Thomson et al., 2011). On the other hand, RCP 8.5 is characterized by steadily increasing emissions over time, resulting in a 3.7 °C increase in global temperatures by 2100 (van Vuuren et al., 2011; IPCC, 2013).

2.2.3. Population data

For each county contained within the 10 metropolitan areas, we obtained baseline population estimates for the year 1997 (U.S. Census Bureau, 2002) as well as projected future population estimates for 2050 and 2090 from the U.S. Environmental Protection Agency's Integrated Climate and Land-Use (ICLUS) project (U.S. EPA, 2010). ICLUS provides projections based on four different land use scenarios that assume varying degrees of economic development, fertility, migration, social development, and population density. We chose the B2 scenario, which is characterized by moderate population growth over the 21st century

(Nakicenovic et al., 2000). We developed population change factors for each county for both 2050 and 2090, defined as the ratio of projected future county population to 1997 county population.

2.3. Statistical analysis

2.3.1. Present-day association between temperature and mortality

We characterized the present-day relationship between mean daily temperature and mortality in each city using distributed lag non-linear models with an overdispersed Poisson distribution and a 21-day lag function, as previously described (Gasparrini et al., 2015a). Briefly, we modeled mean daily temperature with a quadratic B-spline with three internal knots placed at the 10th, 75th and 90th percentiles of mean temperature observed in each city, centering the spline at the city-specific MMT. We modeled the lag-response curve for temperature with a natural cubic B-spline with three knots placed at equally spaced values on the log scale. We controlled for day of week, federal holidays, and seasonal and long-term time trends (natural cubic spline with 8 degrees of freedom per calendar year). Finally, we used the 10 city-specific exposure-response curves to fit a meta-analytic model, from which we obtained the best linear unbiased prediction (BLUP) of the association between temperature and mortality for each city. This approach is consistent with a previous large, international analysis of temperature and mortality (Gasparrini et al., 2015a).

2.3.2. Calculation of future temperature-related mortality rate

We estimated the change in the annual temperature-related mortality rate per million people in 2045–2055 and 2085–2095 in each metropolitan area and under each RCP. Specifically, we used the city-specific exposure-response curves in combination with projected temperatures from the CMIP5 climate models to calculate the fraction of deaths attributable to temperature (Gasparrini and Leone, 2014) in three time periods: a baseline time period (1992–2002, hereafter referred to simply as "1997") and two future time periods (2045–2055 and 2085–2095, hereafter referred to as "2050" and "2090"). As we have no information on the association between temperature and mortality at temperatures higher than the maximum temperature observed in each city between 1985 and 2006, we conservatively applied the relative risk of death for those location-specific maximum temperatures to days on which future temperatures are projected to be even hotter.

Next, we multiplied the city-specific attributable fraction for each time period by the 1997 mortality rate in its associated metropolitan area. This yields the annual temperature-related mortality rate in each metropolitan area in 1997, 2050, and 2090. Finally, we subtracted the temperature-related mortality rate for 1997 from the analogous quantities for 2050 and 2090 to estimate the change in the temperature-related death rate comparing 2050 and 2090 to 1997 under each of the two RCPs, assuming all other factors are held constant. As we used climate model-projected temperatures to calculate the attributable fraction for all three time periods, our estimates are corrected for any potential differences between climate model projections and observed temperatures during the baseline period.

In order to account for uncertainty in both the present-day exposure-response curves and in the projections of future temperature across different climate models, we calculated the change in the temperature-related mortality rate 5000 times for each future decade and RCP, each time using temperature projections from one climate model randomly selected from the CMIP5 ensemble and one randomly sampled set of the parameters describing the lagged, nonlinear relationship between temperature and mortality from each city-specific distributed lag model, assuming a multivariate normal distribution of those parameters. This latter portion of the calculation, which allows us to estimate uncertainty in the attributable fraction, has been described more thoroughly elsewhere (Gasparrini and Leone, 2014). This approach generated a distribution from which we estimated 95% empirical confidence intervals (eCIs) for the change in the temperature-related mortality rate in each metropolitan area.

We further partitioned these results into the change in the heat-related mortality rate (i.e., deaths due to temperatures above the location-specific MMT) and the change in the cold-related mortality rate (i.e., deaths due to temperatures below the location-specific MMT) (Gasparrini and Leone, 2014).

2.3.3. Calculation of future number of temperature-related deaths

We used the city-specific attributable fractions described above in combination with the 1997 metropolitan area population sizes to calculate the annual total number of deaths attributable to temperature in 1997, 2050, and 2090. This approach assumes that no population growth occurs over the 21st century; thus, any change in the number of temperature-related deaths in 2050 and 2090 compared to 1997 are due solely to changes in daily temperatures. We then performed this calculation a second time, incorporating the population sizes projected by the ICLUS B2 scenario for each metropolitan area in 2050 and 2090. In this second approach, changes in the number of temperature-related deaths in 2050 and 2090 relative to 1997 arise from a combination of projected changes in temperatures and projected changes in population size.

We conducted all analyses in the R programming language version 3.2.1 (R Development Core Team, 2013), using packages 'dlnm' (Gasparrini, 2011) and 'mvmeta' (Gasparrini et al., 2012).

3. Results

3.1. Present-day association between temperature and mortality

The association between mean daily temperature and mortality (1985–2006) in each city was U-shaped, with MMTs ranging from 22.8 °C in New York to 29.7 °C in Houston (see Supplementary data, Fig. S1). The shape of the city-specific exposure-response curves were similar to those previously reported for these cities by Gasparrini et al. (2015a) using identical temperature and mortality datasets, with small differences versus those previously published arising from the smaller number of cities contributing to the BLUP in our analysis.

3.2. Projected increase in temperature and population size

In each of the 10 metropolitan areas, mean temperatures are projected to increase by 2050, and to increase further by 2090, with the largest increase in temperature projected for Chicago and smallest for Miami. For example, in 2090 under RCP 8.5, the mean projected change in temperature is 5.8 °C (range: 2.5, 8.0 °C) in Chicago and 3.4 °C (range: 1.9, 4.7 °C) in Miami. Increases in projected temperatures under the higher greenhouse gas emissions RCP 8.5 scenario are larger than under RCP 4.5 in all metropolitan areas. This difference is more pronounced in 2090 than in 2050 (see Supplementary data, Table S3). Under the ICLUS B2 scenario, the population size of each metropolitan area is projected to increase over the 21st century (see Supplementary data, Table S3).

3.3. Projected temperature-related mortality rates

Projected changes in temperature through the end of the century are expected to lead to higher heat-related mortality rates which may be offset, in whole or in part, by lower rates of cold-related mortality. However, the sign, magnitude, and degree of uncertainty of the net change in the temperature-related mortality rate is expected to vary by location. To illustrate this point, Fig. 1 shows the projected change in heat-, cold-, and temperature-related mortality rates in Los Angeles and Boston in both decades and under both RCPs. These quantities are a function of each metropolitan area's exposure-response curve, present-day daily mean temperature distribution, and projected change in

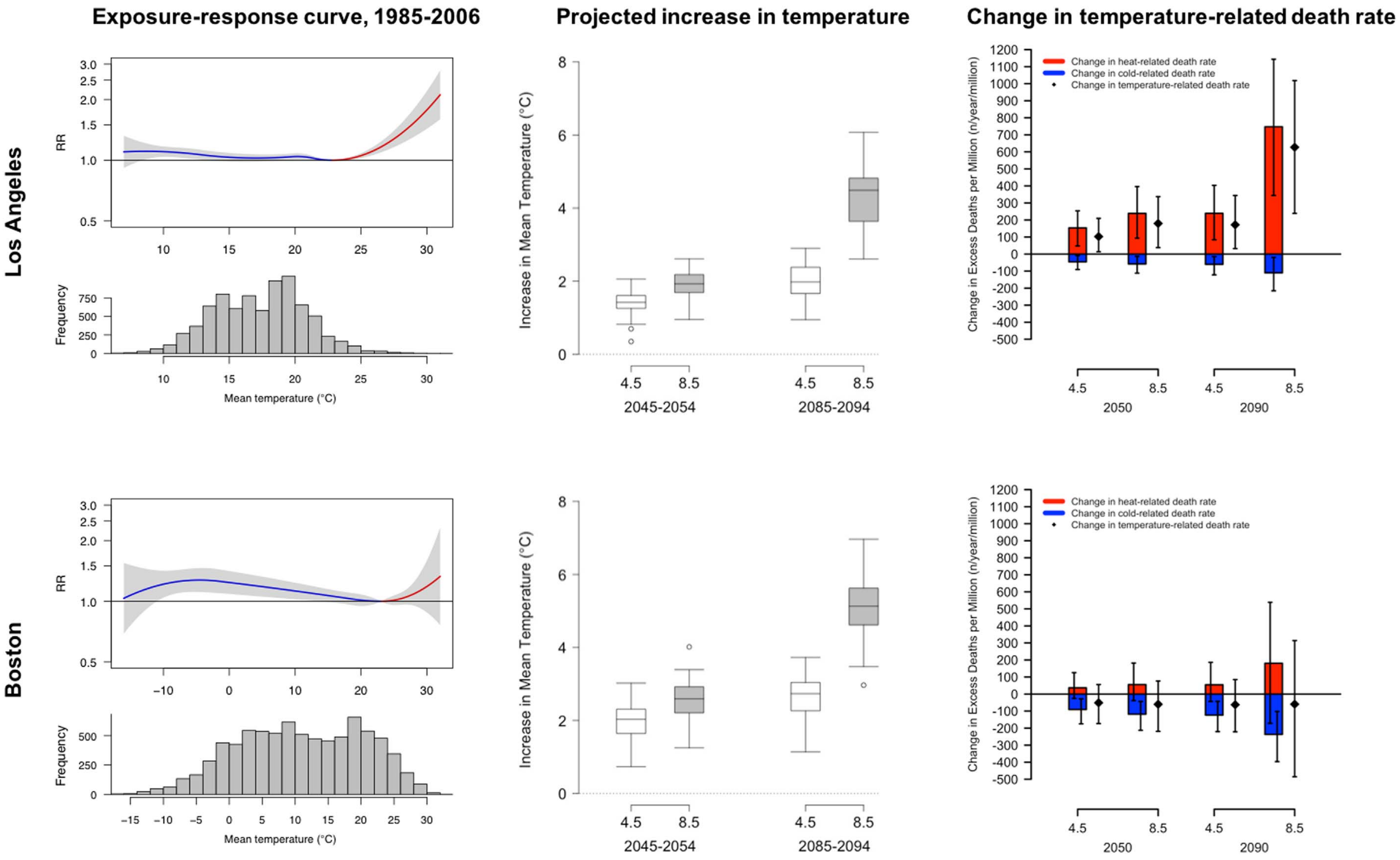

Fig. 1. Exposure-response curves characterizing the present-day relationship between mean daily temperature and mortality (left), increase in mean daily temperature projected by the CMIP5 model ensemble (middle), and projected change in the annual heat-related, cold-related, and total temperature-related mortality rate per million people in the Los Angeles and Boston metropolitan areas in 2050 and 2090 and under two representative concentration pathways (RCP 4.5 and RCP 8.5, right).

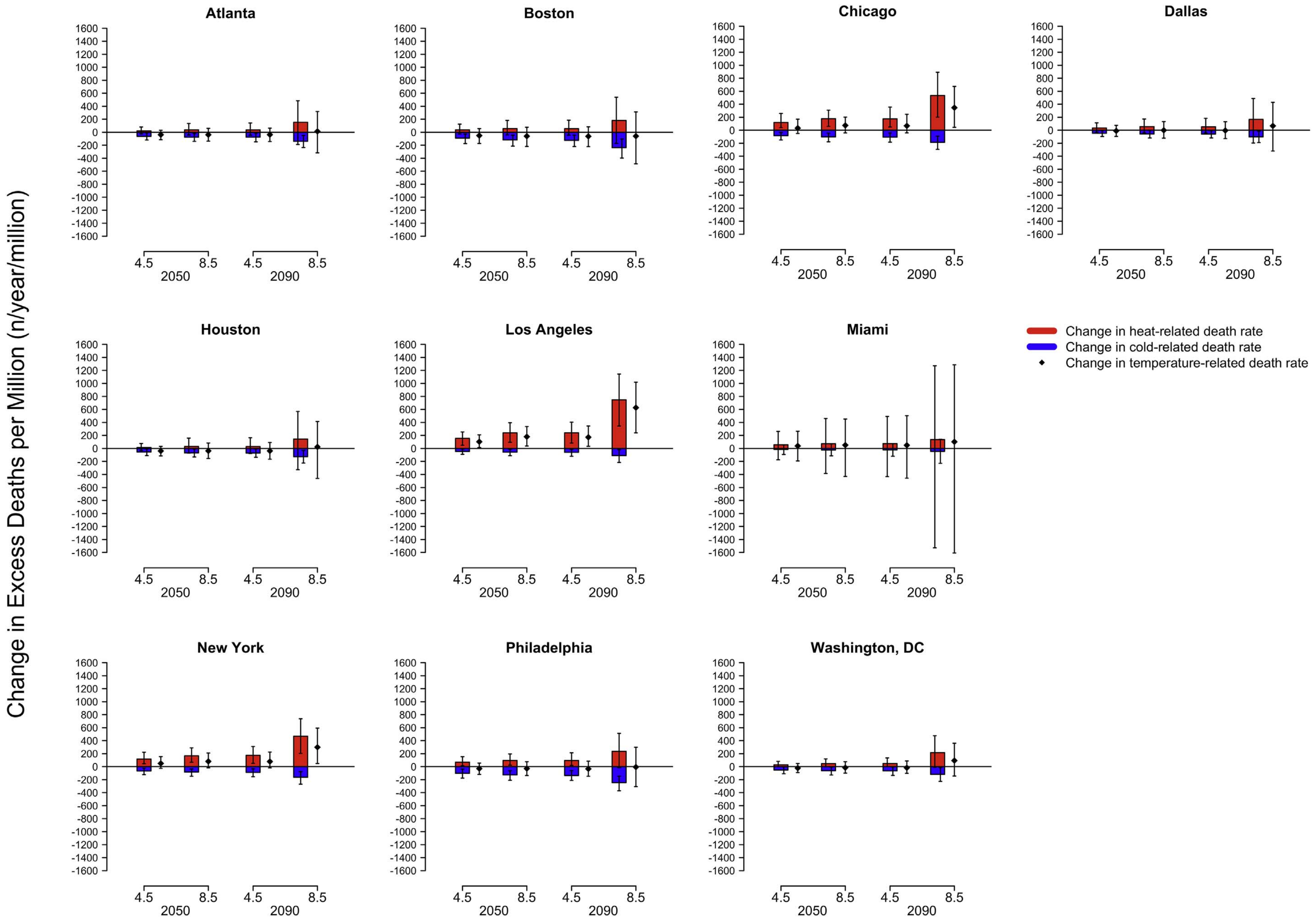

Fig. 2. Projected change in the annual heat-related, cold-related, and total temperature-related mortality rate in each of 10 metropolitan areas in two future decades (centered at 2050 and 2090) and under two representative concentration pathways (RCP 4.5 and 8.5).

temperature through the end of the 21st century, all of which are also shown in Fig. 1. If the 1997 population of Los Angeles were exposed to the temperatures projected for 2090 under RCP 8.5, we estimate that there would be 747 (95% eCI: 342, 1144) more heat-related deaths/million and 110 (95% eCI: − 216, − 19) fewer cold-related deaths/million each year, resulting in an annual net increase of 627 (95% eCI: 239, 1018) temperature-related deaths/million. In contrast, if the 1997 population of Boston were exposed to the temperatures projected for 2090 under RCP 8.5, we estimate that there would be 181 (95% eCI: − 172, 539) more heat-related deaths/million but 237 (95% eCI: − 396, − 102) fewer cold-related deaths/million each year, resulting in an annual net *decrease* of 59 (95% eCI: − 485, 314) temperature-related deaths/million. However, while the point estimate for the net change in Boston is negative, the 95% empirical confidence intervals include both positive and negative values.

Across the study area, we found that if the 1997 population of each metropolitan area were exposed to the higher temperatures projected for 2050 and 2090, rates of heat-related mortality would be higher while rates of cold-related mortality would be lower in each location (Fig. 2). By 2090 under RCP 8.5, we estimate that the projected increase in heat-related mortality rates will outweigh the projected decreases in cold-related mortality rates in 8 of the 10 metropolitan areas, leading to net increases in temperature-related mortality. However, the uncertainty varies across metropolitan areas, and in some locations the 95% empirical confidence intervals for this change are wide and include the null hypothesis of no change. The most precise projections of future change in temperature-related mortality rates are evident in the cities with the largest populations (and hence the most data for estimating the exposure-response functions): New York, Los Angeles, and Chicago.

The net change in temperature-related mortality rates in each metropolitan area is projected to be larger and/or more positive under RCP 8.5 than RCP 4.5 (Fig. 2). For example, in New York, the projected change in the annual temperature-related mortality rate is 299 (95% eCI: 48, 593) deaths/million under RCP 8.5, but only 79 (95% eCI: − 19, 225) deaths/million under RCP 4.5. In Atlanta, we estimate that the temperature-related mortality rate will decrease slightly by 2090 under RCP 4.5, but increase slightly under the hotter temperatures projected by 2090 under RCP 8.5. Additionally, projected changes in temperature-related mortality rates in all 10 metropolitan areas are projected to be smaller in 2050 than in 2090. In Miami, the 95% empirical confidence intervals around estimates for both 2050 and 2090 were wide, due to the large number of days projected to exceed the maximum daily temperature recorded during 1985–2006, where the exposure-response curve has high uncertainty.

3.4. Projected number of temperature-related deaths

During the baseline period there were an estimated 58.7 million people living in these 10 metropolitan areas, with an estimated 29,115 (95% eCI: 21,957, 36,112) deaths per year attributable to deviations in daily temperature from the MMT (Table 1). Considering heat-related and cold-related deaths separately, we found that a substantially larger number of deaths are attributable to cold than to heat in each city (see Supplementary data, Table S4).

Assuming that the population size of each metropolitan area remains at 1997 levels (i.e., holding all other factors constant), we project that the total number of temperature-related deaths across these 10 metropolitan areas will increase to 32,285 (95% eCI: 25,315, 39,050) in 2050 and 43,709 (95% eCI: 34,136, 53,242)) in 2090 under RCP 8.5 (Table 1). This net increase across the 10 metropolitan areas considered together occurs as the projected increase in the number of heat-related deaths outweighs the projected decrease in the number of cold-related deaths when comparing future years to the baseline period (see Supplementary data, Table S4). Substantially fewer total temperature-related deaths are projected under the lower greenhouse gas emissions RCP 4.5 scenario versus RCP 8.5.

The above analysis implausibly assumes that the population size in each metropolitan area will remain constant at 1997 levels. Accordingly, we next estimated the number of temperature-related deaths in each metropolitan region due to a combination of projected population growth and projected changes in daily temperature through the end of the century (Table 2). The combination of population growth and temperature changes are projected to lead to substantially more heat-related deaths, cold-related deaths, and total temperature-related deaths. Specifically, we estimate that across these 10 metropolitan areas with a projected combined population size of 128.0 million people in 2090, there will be 63,111 (95% eCI: 48,036, 77,874) deaths annually attributable to temperature under RCP4.5 and 86,152 (95% eCI: 63,431, 107,419) under RCP 8.5. Compared to 1997, we project that both heat- and cold-related deaths will increase in future decades (see Supplementary data, Table S5). The increase in cold-related mortality occurs as population growth leads to an increase in the number of people exposed to cold temperatures, even as the frequency of cold days declines due to climate change.

4. Discussion

Local officials are best equipped to implement policies that promote resilience against the effects of climate change projected for their communities. The development of effective adaptation strategies requires detailed, local information about potential future climate impacts. To provide evidence to inform local adaptation plans, we estimated the change in heat-related, cold-related, and total temperature-related mortality rates over the 21st century in each of 10 large US metropolitan areas under differing assumptions about future greenhouse gas emissions. In addition, to assist public health planning efforts, we estimated the total number of deaths attributable to temperature in 1997, 2050, and 2090, first assuming that the population size of each metropolitan area remains constant at 1997 levels throughout the 21st century, and then accounting for projected population growth.

Looking at results from across all 10 metropolitan areas, several patterns emerge. First, we found that rates of heat-related deaths will increase in all 10 metropolitan areas in 2050 and increase further in 2090, as compared to 1997. We estimate that the metropolitan area with the largest increase in heat-related mortality will be Los Angeles, with an additional 747 (95% eCI: 344, 144) heat-related deaths per million people per year, under the high emissions RCP 8.5 scenario in 2090. In the absence of population change and holding all other factors constant, we estimate that the total annual number of heat-related deaths in Los Angeles will increase substantially from 645 (95% eCI: 283, 1068) in 1997 to 9535 (95% eCI: 4720, 14,347) in 2090 under RCP 8.5. Across all 10 cities and again holding population and all other factors constant, we project that heat-related deaths will increase from approximately 2300 annual deaths in 1997 to 10,304 annual deaths in 2050 and 26,050 annual deaths in 2090 under RCP 8.5. In all metropolitan areas, estimates for the future number of heat-related deaths were substantially larger after allowing for projected population changes, due to a large increase in the number of people expected to be exposed to high ambient temperatures.

While future heat-related mortality has the potential to be large, there is evidence that the implementation of heat warning systems, heat response plans, and perhaps other adaptation measures is beginning to mitigate some of the effects of extreme heat. For example, in Montreal, the 2004 implementation of a heat action plan that included a warning component was associated with a decrease in heat-related mortality, especially among the elderly (Benmarhnia et al., 2016). The implementation of heat warning systems may have also played a role in reducing heat-related mortality in other locations, including France (Fouillet et al., 2008) and the United States (Weisskopf et al., 2002). However, while heat warning systems are typically focused on reducing mortality on extremely hot days, the public health burden of moderate

Table 1

Projected number of annual deaths (95% eCI) attributable to temperature in 1997, 2050, and 2090 under two representative concentration pathways (RCP) in 10 metropolitan areas assuming population size in each metropolitan remains constant at 1997 levels.

Metropolitan area	1997 population	RCP	Number of temperature-related deaths per year assuming 1997 population remains constant		
			1997	2050	2090
Atlanta	3,888,398	4.5	1541 (224, 2753)	1402 (164, 2493)	1410 (151, 2536)
		8.5	1548 (231, 2757)	1408 (158, 2529)	1616 (− 369, 3323)
Boston	4,302,696	4.5	3696 (1243, 5943)	3445 (1216, 5548)	3389 (1192, 5471)
		8.5	3690 (1242, 5943)	3399 (1173, 5505)	3408 (754, 5842)
Chicago	8,862,719	4.5	6134 (2446, 9634)	6479 (2920, 9908)	6816 (3275, 10,328)
		8.5	6126 (2358, 9653)	6813 (3180, 10,196)	9170 (4746, 13,488)
Dallas	2,800,670	4.5	649 (− 263, 1501)	622 (− 252, 1436)	643 (− 229, 1450)
		8.5	654 (− 267, 1504)	658 (− 227, 1454)	831 (− 255, 1811)
Houston	4,407,210	4.5	1288 (− 126, 2587)	1110 (− 185, 2282)	1129 (− 252, 2413)
		8.5	1293 (− 124, 2598)	1141 (− 202, 2394)	1391 (− 1363, 3699)
Los Angeles	11,915,815	4.5	3493 (940, 5860)	4746 (2132, 7307)	5565 (2715, 8529)
		8.5	3494 (942, 5888)	5630 (2727, 8497)	10,988 (5774, 16,030)
Miami	2,158,352	4.5	235 (− 773, 1164)	317 (− 664, 1247)	338 (− 868, 1479)
		8.5	238 (− 775, 1161)	337 (− 842, 1405)	415 (− 3044, 2846)
New York	11,737,563	4.5	7132 (2976, 11,060)	7754 (3770, 11,634)	8172 (4132, 12,002)
		8.5	7133 (2865, 11,000)	8145 (4123, 11,871)	10,725 (6410, 14,808)
Philadelphia	4,018,958	4.5	3199 (1811, 4606)	3079 (1689, 4430)	3064 (1701, 4390)
		8.5	3206 (1812, 4593)	3086 (1728, 4415)	3198 (1732, 4586)
Washington, DC	4,602,056	4.5	1877 (− 100, 3703)	1781 (− 25, 3415)	1813 (29, 3429)
		8.5	1877 (− 121, 3680)	1806 (20, 3426)	2336 (217, 4324)
Combined	58,694,437	4.5	29,144 (21,967, 36,155)	30,688 (23,759, 37,447)	32,208 (25,202, 39,367)
		8.5	29,115 (21,959, 36,112)	32,285 (25,315, 39,050)	43,709 (34,136, 53,242)

Table 2

Projected annual number of deaths (95% eCI) attributable to temperature in 2050 and 2090 under two representative concentration pathways (RCP) in 10 metropolitan areas accounting for projected changes in population size.

Metropolitan area	RCP	2050		2090	
		Projected population	Number of annual temperature-related deaths	Projected population	Number of annual temperature-related deaths
Atlanta	4.5	8,919,560	3059 (359, 5441)	12,412,232	4188 (447, 7534)
	8.5		3072 (345, 5520)		4800 (− 1097, 9871)
Boston	4.5	5,055,378	4042 (1427, 6509)	5,450,975	4289 (1509, 6923)
	8.5		3987 (1376, 6459)		4313 (954, 7393)
Chicago	4.5	12,341,415	8697 (3920, 13,300)	14,549,152	10,627 (5106, 16,102)
	8.5		9146 (4270, 13,688)		14,296 (7400, 21,029)
Dallas	4.5	5,985,909	1260 (− 511, 2909)	8,205,568	1760 (− 627, 3967)
	8.5		1332 (− 459, 2945)		2273 (− 699, 4955)
Houston	4.5	7,570,969	1887 (− 316, 3882)	9,315,607	2356 (− 526, 5037)
	8.5		1941 (− 344, 4072)		2903 (− 2847, 7722)
Los Angeles	4.5	18,333,105	7311 (3284, 11,254)	22,938,867	10,736 (5237, 16,453)
	8.5		8672 (4200, 13,088)		21,199 (11,139, 30,925)
Miami	4.5	5,615,565	825 (− 1728, 3245)	8,921,801	1397 (− 3588, 6115)
	8.5		877 (− 2191, 3655)		1714 (− 12,584, 11,766)
New York	4.5	20,932,311	13,809 (6713, 20,717)	28,383,887	19,734 (9977, 28,984)
	8.5		14,505 (7342, 21,139)		25,898 (15,479, 35,760)
Philadelphia	4.5	4,907,115	3716 (2039, 5348)	5,567,612	4174 (2318, 5982)
	8.5		3725 (2086, 5329)		4358 (2359, 6248)
Washington, DC	4.5	10,459,279	3462 (− 49, 6637)	12,285,684	4087 (65, 7728)
	8.5		3510 (40, 6659)		5264 (488, 9744)
Combined	4.5	100,120,606	47,940 (36,547, 59,108)	128,031,385	63,111 (48,036, 77,874)
	8.5		50,506 (39,144, 61,778)		86,152 (63,431, 107,419)

warm temperatures is likely larger than that of extreme hot temperatures in regions across the globe, including Australia, the United Kingdom, and the United States (Gasparrini et al., 2015a; Wellenius et al., 2017). Additional research is needed to identify strategies that are effective in preventing the burden of disease attributable to frequent days with moderate rather than extreme heat.

As average temperatures are projected to rise over the course of the century, it is plausible that many areas could see fewer cold-related deaths. Our analysis confirms this hypothesis: we found that the cold-related death rate per million people is projected to decrease in each of the 10 metropolitan areas. For example, we estimate that if the 1997 population of Atlanta experienced the warmer temperatures projected for 2090, there would be 110 fewer (95% eCI: − 215, − 19) deaths per million residents under RCP 8.5, partially offsetting the projected increase in heat-related deaths. Despite this reduction in the cold-related mortality rate, there will still be a substantial number of preventable deaths due to cold in future decades. For example, even assuming no change in population size from 1997 levels, we estimate that there would still be 977 (95% eCI: − 21, 1880) cold-related deaths per year in Atlanta in 2090 under RCP 8.5, down from an estimated 1543 (95% eCI: 191, 2731) in 1997, but still a substantial number. In addition, when accounting for future population growth, we project that the absolute number of cold-related deaths will *increase* sharply in all study sites in 2050 and 2090, as the number of people exposed to sub-optimal temperature on either side of the MMT outweighs the decrease in the cold-related death rate per million people. Thus, preventing cold-related deaths should remain an important public health goal both now and in the future.

Considering hot and cold temperatures simultaneously, our results indicate that most metropolitan areas are expected to experience an increase in temperature-related mortality rates, as well as a concomitant increase in the annual total number of temperature-related deaths, even assuming population size remains at 1997 levels. After accounting for projected population change, we estimate that all 10 metropolitan areas will see an increase in the annual total number of temperature-related deaths, highlighting the importance of developing and implementing prevention and response strategies now.

In each metropolitan area, our results further suggest that adhering to a lower versus a higher greenhouse gas emissions scenario (i.e., RCP 4.5 rather than RCP 8.5) would result in smaller elevations in average annual temperatures, smaller increases in the heat-related death rate, fewer heat-related deaths, and smaller increases in the total temperature-related death rate and temperature-related deaths. This pattern was observed in each metropolitan area in both 2050 and 2090. Looking across all 10 metropolitan areas, assuming that population size remains at 1997 levels, we project that temperature-related deaths will increase from around 29,100 deaths in 1997 to 43,709 deaths in 2090 under RCP 8.5, but a more modest 32,208 temperature-related deaths under RCP 4.5. If causal, these observations suggest that investments in climate change mitigation strategies that lead to lower greenhouse gas emissions could result in substantial health benefits.

Our results should be interpreted in light of some important limitations. First, while our analysis is intended to be relevant on a national scale, we did not provide estimates of the change in temperature-related mortality for every US metropolitan area. However, the 10 metropolitan areas we selected for inclusion in this study collectively contain almost a quarter of the US population (U.S. Census Bureau, 2002) and encompass both geographic and climatic diversity. Second, we did not account for changes in population age structure over time, as our mortality data and population projections were not broken down by age or other demographic characteristics. Third, we assumed that the rate ratio for the maximum temperature observed during the baseline period in each metropolitan area would apply to even higher temperatures projected for the future. This conservative assumption may lead to an underestimate of future heat-related mortality; however, we believe it this is a reasonable approach in the absence of information about the relative risk of mortality at very high temperatures. Fourth, we assumed that the shape of the exposure-response curve for the relationship between temperature and mortality stays constant in future decades, equivalent to assuming that there will be no further adaptation to changes in temperature. However, results from studies examining temperature-mortality relationships over long periods of time reveal an attenuation of the impact of heat on health in recent years, possibly reflecting adaptation (Åström et al., 2016; Bobb et al., 2014; Gasparrini et al., 2015b). Thus, future adaptation could result in smaller increases in heat-related mortality than estimated here. However, it remains uncertain the degree to which adaptation to heat will continue in the US, where air conditioning prevalence is already very high in much of the country, especially in urban areas.

On the other hand, this study also has a number of novel strengths. For example, we incorporated two key sources of uncertainty into our analysis: variability in projected future temperatures across the full set of CMIP5 climate models, and uncertainty in the present-day exposure-response curves for the relationship between temperature and mortality. This allows us to more completely capture the uncertainty in estimates of temperature-related deaths than has been previously done. Additionally, we provided a detailed assessment of the projected future risk associated with exposure to both hot and cold temperatures in each of the 10 metropolitan areas. Previous work examining the impact of a shifting temperature distribution on both heat-related and cold-related mortality focused on regional trends by clustering large groups of climatologically similar cities together for analysis (Schwartz et al., 2015). By carrying out our analysis at a finer scale (i.e., individual metropolitan areas), we provide evidence of direct relevance to local officials, yet still with a national scope in order to highlight the importance of this issue across the US.

5. Conclusions

Using city-specific exposure-response curves, temperature projections from over 40 climate models, and two greenhouse gas emissions scenarios, we found that rates and absolute numbers of heat-related deaths are projected to increase in each of the 10 largest US metropolitan areas. These increases may be partially offset by reductions in rates of cold-related deaths, but the net change in temperature-related mortality rates is projected to increase in 8 out of the 10 metropolitan areas considered by 2090. Our results further suggest that many excess temperature-related deaths may be avoided by transitioning to a lower greenhouse gas emissions trajectory and highlight the importance of investing in strategies to both mitigate and adapt to rising temperatures projected through the end of the century. Future studies would benefit from incorporating a range of assumptions about future adaptation into these estimates, considering analogous estimates of the change in future temperature-related morbidity (e.g., emergency department visits, hospitalizations), and calculating the change in disability-adjusted life years (DALYs) associated with increases in temperature in order to better quantify the health burden of climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2017.07.006.

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