

1 **Title:** Projected Temperature-Related Deaths in Ten Large U.S. Metropolitan Areas Under
2 Different Climate Change Scenarios

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4 **Authors:** Kate R. Weinberger,^{a,b} Leah Haykin,^{a,b} Melissa N. Eliot,^b Joel D. Schwartz,^c Antonio
5 Gasparrini,^d Gregory A. Wellenius^b

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7 ^aInstitute at Brown for Environment and Society, Brown University, Providence, Rhode Island,
8 USA; ^bDepartment of Epidemiology, Brown University School of Public Health, Providence,
9 Rhode Island, USA; ^cT.H. Chan School of Public Health, Harvard University, Boston,
10 Massachusetts, USA; ^dDepartment of Social and Environmental Health Research, London
11 School of Hygiene & Tropical Medicine, Camden, London, UK

12

13 **Address correspondence to:** K.R. Weinberger, Brown University School of Public Health, Box
14 G-S121-2, Providence, RI 02912 USA. Telephone: (401) 863-5124. E-mail:

15 kate_weinberger@brown.edu

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18

19 **Abstract**

20

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

25

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

28

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

36

37 Results: In each of the 10 metropolitan areas, projected future temperatures were associated with
38 lower rates of cold-related deaths and higher rates of heat-related deaths. Under the higher-
39 emission RCP 8.5 scenario, 8 of the 10 metropolitan areas are projected to experience a net
40 increase in annual temperature-related deaths per million people by 2086-2095, ranging from a

41 net increase of 627 (95% empirical confidence intervals [eCI]: 239, 1018) deaths per million in
42 Los Angeles to a net decrease of 59 (95% eCI: -485, 314) deaths per million in Boston. Applying
43 these projected temperature-related mortality rates to projected population size underscores the
44 large public health burden of temperature.

45

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

50

51 **Keywords:** climate change, ambient temperature, health impacts, United States

52 **1) Introduction**

53

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

61

62 Continued climate change is projected to lead to higher average ambient temperatures across
63 most of the globe (IPCC 2013). Accordingly, several studies project substantial increases in heat-
64 related morbidity and mortality if today's population were exposed to the higher temperatures
65 projected through the end of the century, holding all other factors constant (Kingsley et al. 2016,
66 Knowlton et al. 2007, Ostro et al. 2012, Peng et al. 2011). However, given the generally U-
67 shaped exposure-response function between daily temperature and mortality, changes in
68 temperature projected through the end of century may simultaneously lead to lower rates of cold-
69 related mortality (Guo et al. 2016, Huynen and Martens 2015, Li et al. 2013, Vardoulakis et al.
70 2014,). The relative magnitude of these changes, as well as the sign of the net change in
71 temperature-related mortality under temperatures projected for the future, will depend on many
72 factors that vary by location. Specifically, it is possible that expected increases in heat-related
73 mortality will be offset, partially or entirely, by expected decreases in cold-related mortality in a
74 manner that depends on: 1) the shape of the exposure-response function between daily

75 temperature and mortality, 2) the distribution of present-day daily temperatures, and 3) projected
76 temperature changes going forward in each location.

77

78 A few previous studies have considered the impact of temperature changes across the calendar
79 year through the end of the century in various locations within the United States (US) (Li et al.
80 2013, Mills et al. 2015, Schwartz et al. 2015). For example, Schwartz et al. (2015) estimated that
81 most US regions would experience a net increase in temperature-related mortality due to
82 projected temperature changes. Such analyses have also been carried out in the United Kingdom,
83 Australia, Canada, and the Netherlands (Guo et al. 2016, Hajat et al. 2014, Huynen and Martens
84 2015, Martin et al. 2012, Vardoulakis et al. 2014). However, building resilience against climatic
85 effects (i.e., adaptation) depends on action by local policymakers and government officials, and
86 prior studies have typically provided an incomplete description of the potential burden of
87 mortality attributable to temperature changes needed for action at the local level. For example,
88 prior studies have typically relied on future temperature projections from one or a few climate
89 models rather than the full set of coupled ocean-atmosphere circulation models comprising the
90 Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012), the state-of-the-
91 art model ensemble used in the most recent Intergovernmental Panel on Climate Change (IPCC)
92 assessment (IPCC 2013). Incorporating the full range of future temperature projections is
93 important in order to better capture the uncertainty associated with these projections.

94 Additionally, few studies have incorporated future population growth scenarios into projections
95 of temperature-related mortality, potentially a key driver of the future public health burden of
96 temperature-related deaths. Accordingly, with the goal of providing local municipalities with
97 actionable evidence, we quantified the expected change in heat-related, cold-related, and total

98 temperature-related mortality rates per million people if the populations of 10 large US
99 metropolitan areas were to experience the temperatures projected through the end of the century
100 by the CMIP5 model ensemble under two representative concentrations pathways (RCPs),
101 assuming all other factors are held constant. In addition, we estimated the total number of deaths
102 attributable to temperature in 1997, 2050, and 2090, both assuming that population size remains
103 constant and accounting for projected population growth.

104

105

106 **2) Materials and Methods**

107

108 2.1) Overview:

109

110 We conducted this analysis in ten large US metropolitan areas: Atlanta, Boston, Chicago, Dallas,
111 Houston, Los Angeles, Miami, New York, Philadelphia, and Washington, D.C. (see
112 Supplemental Material, Table S1 for a list of counties included in each metropolitan area). In
113 1997, the temporal midpoint of the baseline period used in our analysis, these metropolitan areas
114 ranged in size from 2.2 million (Miami) to 11.9 million (Los Angeles), collectively
115 encompassing 58.7 million people or 22% of the 1997 US population (U.S. Census Bureau
116 2002). We carried out the analysis of these 10 metropolitan areas in three stages. First, we
117 developed exposure-response curves describing the present-day (1985-2006) relationship
118 between mean daily temperature and mortality in the major city around which each metropolitan
119 area is defined. Second, we combined these exposure-response curves with projections of future
120 temperatures to estimate the change in the temperature-related mortality rate per million people

121 in two future decades (2045-2055 and 2085-2095) in the metropolitan area around each city.
122 Finally, we calculated the total number of deaths attributable to temperature in each metropolitan
123 areas at three time points: 1997, 2050, 2090, assuming either constant population size or that
124 populations in each city would change according to available projections. A detailed description
125 of our analytic approach is provided below.

126

127

128 2.2) Data Sources:

129

130 ***2.2.1) Present-day temperature and mortality:***

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

142

143 **2.2.2) Temperature projections:**

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

153
154 CMIP5 temperature projections are available for four Representative Concentration Pathways
155 (RCPs), which describe potential alternative standardized radiative forcing trajectories across the
156 21st century due to anticipated greenhouse gas emissions and other factors. This paper follows
157 the convention of basing analyses on RCPs 4.5 and 8.5, because they represent relatively “better
158 case” and “worse case” scenarios for future greenhouse gas emissions, respectively (Kingsley et
159 al. 2016). RCP 4.5 assumes that future policies and technologies will reduce greenhouse gas
160 emissions, resulting in a 1.8°C increase in the global average temperature by 2100, relative to
161 1986-2005 (Thomson et al. 2011). On the other hand, RCP 8.5 is characterized by steadily
162 increasing emissions over time, resulting in a 3.7°C increase in global temperatures by 2100 (van
163 Vuuren et al. 2011; IPCC 2013).

164

165 **2.2.3) Population data:**

166 For each county contained within the 10 metropolitan areas, we obtained baseline population
167 estimates for the year 1997 (U.S. Census Bureau 2002) as well as projected future population
168 estimates for 2050 and 2090 from the U.S. Environmental Protection Agency's Integrated
169 Climate and Land-Use (ICLUS) project (U.S. EPA 2010). ICLUS provides projections based on
170 four different land use scenarios that assume varying degrees of economic development, fertility,
171 migration, social development, and population density. We chose the B2 scenario, which is
172 characterized by moderate population growth over the 21st century (Nakicenovic et al. 2000). We
173 developed population change factors for each county for both 2050 and 2090, defined as the ratio
174 of projected future county population to 1997 county population.

175

176

177 2.3) Statistical Analysis:

178

179 **2.3.1) Present-day association between temperature and mortality:**

180 We characterized the present-day relationship between mean daily temperature and mortality in
181 each city using distributed lag non-linear models with an overdispersed Poisson distribution and
182 a 21-day lag function, as previously described (Gasparrini et al. 2015a). Briefly, we modeled
183 mean daily temperature with a quadratic B-spline with three internal knots placed at the 10th, 75th
184 and 90th percentiles of mean temperature observed in each city, centering the spline at the city-
185 specific MMT. We modeled the lag-response curve for temperature with a natural cubic B-spline
186 with three knots placed at equally spaced values on the log scale. We controlled for day of week,
187 federal holidays, and seasonal and long-term time trends (natural cubic spline with 8 degrees of

188 freedom per calendar year). Finally, we used the 10 city-specific exposure-response curves to fit
189 a meta-analytic model, from which we obtained the best linear unbiased prediction (BLUP) of
190 the association between temperature and mortality for each city. This approach is consistent with
191 a previous large, international analysis of temperature and mortality (Gasparrini et al. 2015a).

192

193 ***2.3.2) Calculation of future temperature-related mortality rate:***

194 We estimated the change in the annual temperature-related mortality rate per million people in
195 2045-2055 and 2085-2095 in each metropolitan area under each RCP. Specifically, we used the
196 city-specific exposure-response curves in combination with projected temperatures from the
197 CMIP5 climate models to calculate the fraction of deaths attributable to temperature (Gasparrini
198 et al. 2014) in three time periods: a baseline time period (1992-2002, hereafter referred to simply
199 as “1997”) and two future time periods (2045-2055 and 2085-2095, hereafter referred to as
200 “2050” and “2090”). As we have no information on the association between temperature and
201 mortality at temperatures higher than the present-day maximum temperature observed in each
202 city between 1985-2006, we conservatively applied the relative risk of death for those location-
203 specific maximum temperatures to days on which future temperatures are projected to be even
204 hotter.

205

206 Next, we multiplied the city-specific attributable fraction for each time period by the 1997
207 mortality rate in its associated metropolitan area. This yields the annual temperature-related
208 mortality rate in each metropolitan area in 1997, 2050, and 2090. Finally, we subtracted the
209 temperature-related mortality rate for 1997 from the analogous quantities for 2050 and 2090 to
210 estimate the change in the temperature-related death rate comparing 2050 and 2090 to 1997

211 under each of the two RCPs, assuming all other factors are held constant. As we used climate
212 model-projected temperatures to calculate the attributable fraction for all three time periods, our
213 estimates are corrected for any potential differences between climate model projections and
214 observed temperatures during the baseline period.

215

216 In order to account for uncertainty in both the present-day exposure-response curves and in the
217 projections of future temperature across different climate models, we calculated the change in the
218 temperature-related mortality rate 5,000 times for each future decade and RCP, each time using
219 temperature projections from one climate model randomly selected from the CMIP5 ensemble
220 and one randomly sampled set of the parameters describing the lagged, nonlinear relationship
221 between temperature and mortality from each city-specific distributed lag model, assuming a
222 multivariate normal distribution of those parameters. This latter portion of the calculation, which
223 allows us to estimate uncertainty in the attributable fraction, has been described more thoroughly
224 elsewhere (Gasparrini et al. 2014). This approach generated a distribution from which we
225 estimated 95% empirical confidence intervals (eCIs) for the change in the temperature-related
226 mortality rate in each metropolitan area.

227

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

232

233 **2.3.3) Calculation of future number of temperature-related deaths:**

234 We used the city-specific attributable fractions described above in combination with the 1997
235 metropolitan area population sizes to calculate the annual total number of deaths attributable to
236 temperature in 1997, 2050, and 2090. This approach assumes that no population growth occurs
237 over the 21st century; thus, any change in the number of temperature-related deaths in 2050 and
238 2090 compared to 1997 are due solely to changes in daily temperatures. We then performed this
239 calculation a second time, incorporating the population sizes projected by the ICLUS B2
240 scenario in each metropolitan area for 2050 and 2090. In this second approach, changes in the
241 number of temperature-related deaths in 2050 and 2090 relative to 1997 arise from a
242 combination of projected changes in temperatures and projected changes in population size.

243

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

246

247

248 **3) Results**

249

250 3.1) Present-Day Association Between Temperature and Mortality:

251

252 The association between mean daily temperature and mortality (1985-2006) in each city was U-
253 shaped, with MMTs ranging from 22.8 °C in New York to 29.7 °C in Houston (see Supplemental
254 Material, Figure S1). The shape of the city-specific exposure-response curves were similar to
255 those previously reported for these cities by Gasparrini et al. (2015a) using identical temperature

256 and mortality datasets, with small differences versus those previously published arising from the
257 smaller number of cities contributing to the BLUP in our analysis.

258

259

260 3.2) Projected Increase in Temperature and Population Size:

261

262 In each of the 10 metropolitan areas, mean temperatures are projected to increase by 2050, and to
263 increase further by 2090, with the largest projected increase in temperature observed in Chicago
264 and smallest observed in Miami. For example, in 2090 under RCP 8.5, the mean projected
265 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
266 Miami. Increases in projected temperatures under the higher greenhouse gas emission RCP 8.5
267 scenario are larger than under RCP 4.5 in all metropolitan areas. This difference is more
268 pronounced in 2090 than in 2050 (see Supplemental Material, Table S3). Under the ICLUS B2
269 scenario, the population size of each metropolitan area is projected to increase over the 21st
270 century (see Supplemental Material, Table S3).

271

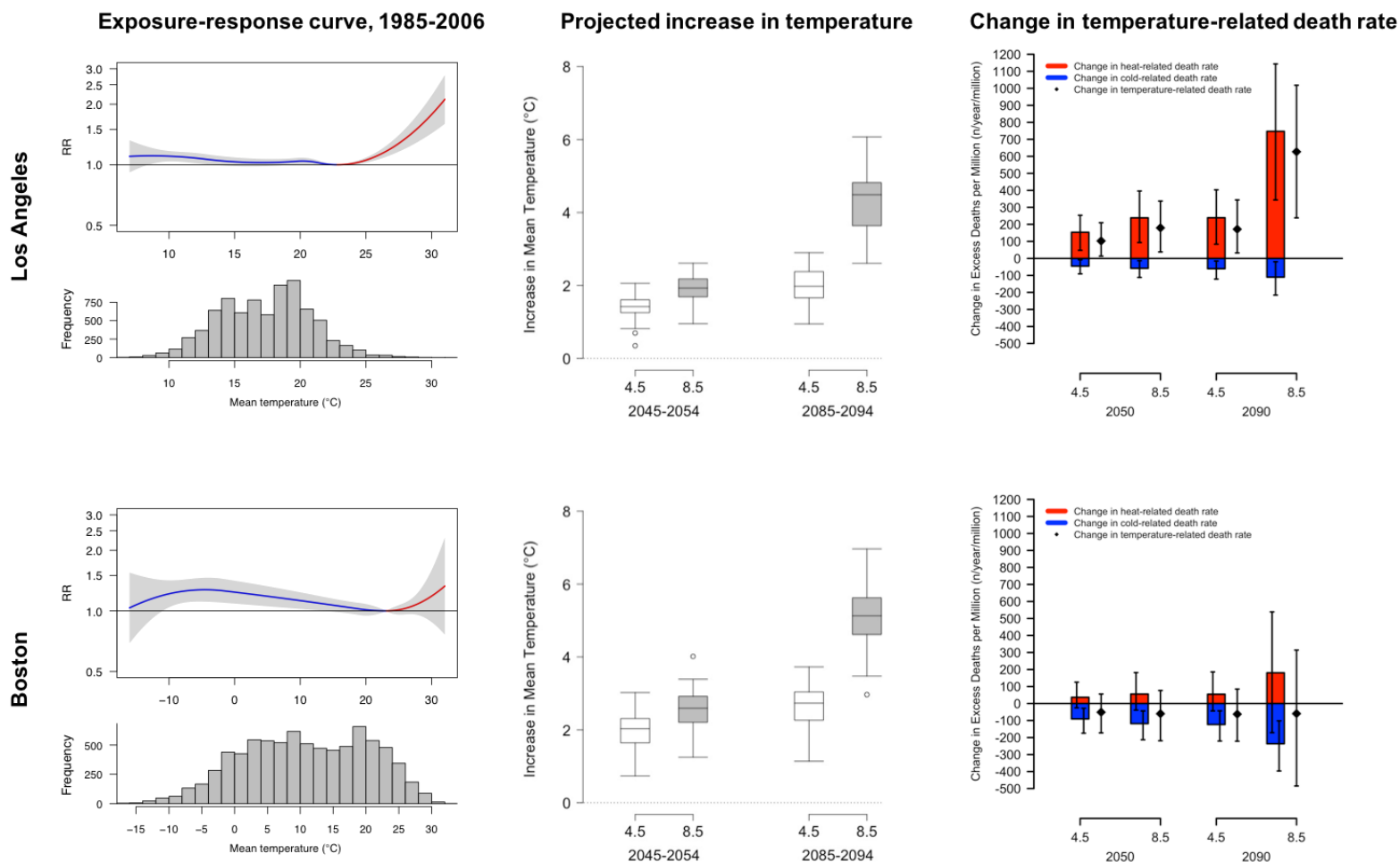
272

273 3.3) Projected Temperature-Related Mortality Rates:

274

275 Projected changes in temperature through the end of the century are expected to lead to higher
276 heat-related mortality rates which may be offset, in whole or in part, offset by lower rates of
277 cold-related mortality. However, the sign, magnitude, and degree of uncertainty of the net
278 change in temperature-related mortality rates is expected to vary by location. To illustrate this

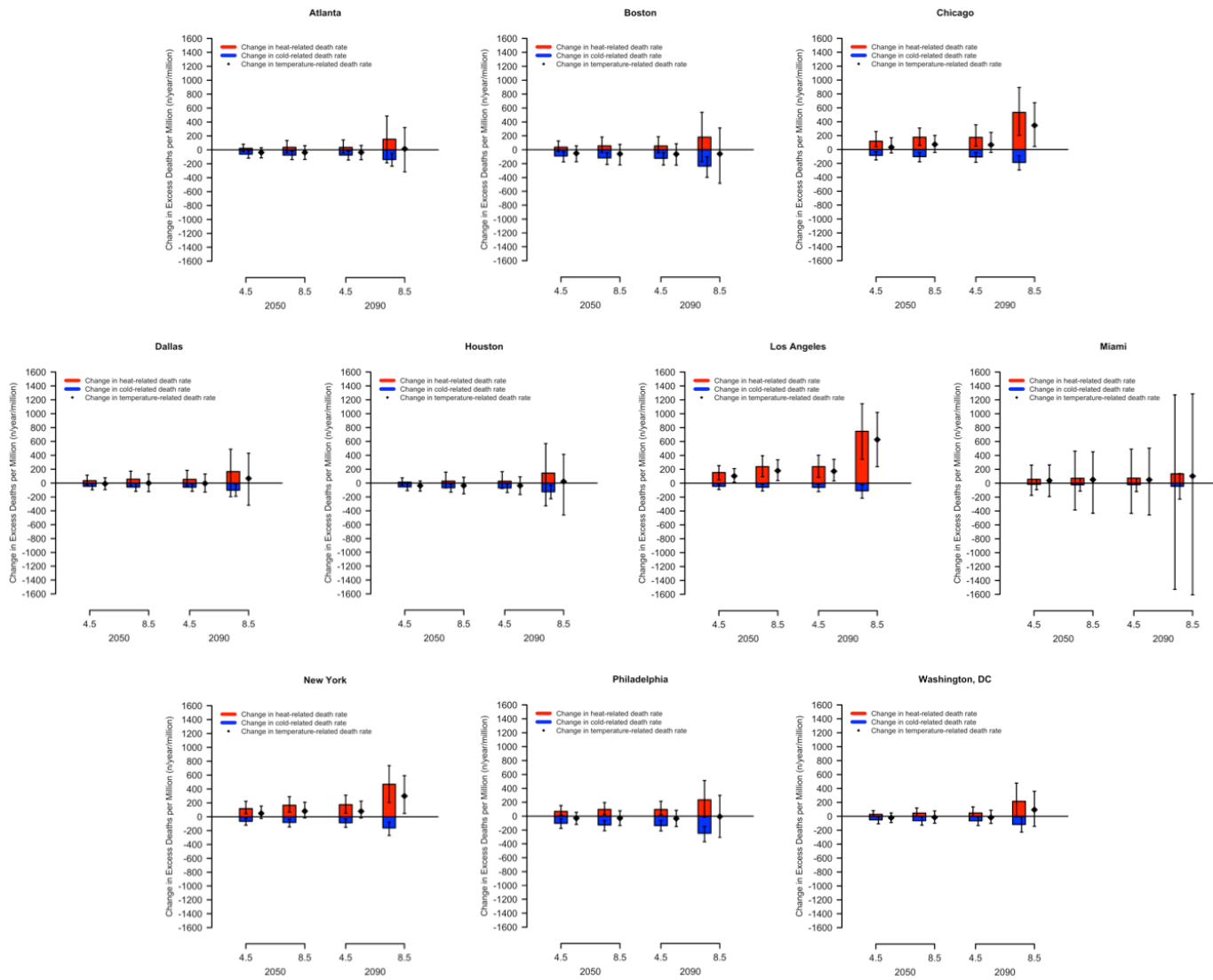
279 point, Figure 1 shows the projected change in heat-, cold-, and temperature-related mortality
280 rates in Los Angeles and Boston in both decades and under both RCPs. These quantities are a
281 function of each metropolitan area's exposure-response curve, present-day daily mean
282 temperature distribution, and projected change in temperature through the end of the 21st century,
283 all of which are also shown in Figure 1. If the 1997 population of Los Angeles were exposed to
284 the temperatures projected for 2090 under RCP 8.5, we estimate that there would be 747 (95%
285 eCI: 342, 1144) more heat-related deaths/million and 110 (95% eCI: -216, -19) fewer cold-
286 related deaths/million each year, resulting in an annual net increase of 627 (95% eCI: 239, 1018)
287 temperature-related deaths/million. In contrast, if the 1997 population of Boston were exposed to
288 the temperatures projected for 2090 under RCP 8.5, we estimate that there would be 181 (95%
289 eCI: -172, 539) more heat-related deaths/million but 237 (95% eCI: -396, -102) fewer cold-
290 related deaths/million each year, resulting in an annual net *decrease* of 59 (95% eCI: -485, 314)
291 temperature-related deaths/million. However, while the point estimate for the net change in
292 Boston is negative, the 95% empirical confidence intervals include both positive and negative
293 values.



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

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

311
312 The net change in temperature-related mortality rates in each metropolitan area is projected to be
313 larger and/or more positive under RCP 8.5 than RCP 4.5. For example, in New York, the
314 projected change in the annual temperature-related mortality rate is 299 (95% eCI: 48, 593)
315 deaths/million under RCP 8.5, but only 79 (95% eCI: -19, 225) deaths/million under RCP 4.5. In
316 Atlanta, we estimate that the temperature-related mortality rate will decrease slightly by 2090
317 under RCP 4.5, but increase slightly under the hotter temperatures projected by 2090 under RCP
318 8.5. Additionally, projected changes in temperature-related mortality rates in all 10 metropolitan
319 areas are projected to be smaller in 2050 than in 2090. In Miami, the 95% empirical confidence
320 intervals around estimates for both 2050 and 2090 were wide, due to the large number of days
321 projected to exceed the maximum daily temperature recorded during 1985-2006, where the
322 exposure-response curve has high uncertainty.



323

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

327 3.4) Projected Number of Temperature-Related Deaths:

328

329 During the baseline period there were an estimated 58,7 million people living in these 10
330 metropolitan areas with an estimated 29,115 (95% eCI: 21,957, 36,112) deaths per year
331 attributable to deviations in daily temperature from the MMT (Table 1). Considering heat-related
332 and cold-related deaths separately, we found that a substantially larger number of deaths are
333 attributable to cold than to heat in each city (see Supplemental Material, Table S4).

334

335 Assuming that the population size of each metropolitan area remains at 1997 levels (i.e., holding
336 all other factors constant), we project that the total number of temperature-related deaths across
337 these 10 metropolitan areas will increase to 32,285 (95% eCI: 25,315, 39,050) in 2050 and
338 43,709 (95% eCI: 34,136, 53,242)) in 2090 under RCP 8.5 (Table 1). This net increase across the
339 10 metropolitan areas considered together occurs as the projected increase in the number of heat-
340 related deaths outweighs the projected decrease in the number of cold-related deaths when
341 comparing future years to the baseline period (see Supplemental Material, Table S4).

342 Substantially fewer total temperature-related deaths are projected under the lower greenhouse
343 gas emission RCP 4.5 scenario versus RCP 8.5.

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, 10328)
		8.5	6126 (2358, 9653)	6813 (3180, 10196)	9170 (4746, 13488)
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)	10988 (5774, 16030)
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, 11060)	7754 (3770, 11634)	8172 (4132, 12002)
		8.5	7133 (2865, 11000)	8145 (4123, 11871)	10725 (6410, 14808)
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	29144 (21967, 36155)	30688 (23759, 37447)	32208 (25202, 39367)
		8.5	29115 (21959, 36112)	32285 (25315, 39050)	43709 (34136, 53242)

344

345 **Table 1:** Projected number of annual deaths (95% eCI) attributable to temperature in 1997, 2050, and 2090 under two representative
346 concentration pathways (RCP) in 10 metropolitan areas assuming population size in each metropolitan remains constant at 1997
347 levels.

348

349

350 The above analysis implausibly assumes that the population size in each metropolitan area will
351 remain constant at 1997 levels. Accordingly, we next estimated the number of temperature-
352 related deaths in each metropolitan region due to a combination of projected population growth
353 and projected changes in daily temperature through the end of the century (Table 2). The
354 combination of population growth and temperature changes are projected to lead to substantially
355 more heat-related deaths, cold-related deaths, and total temperature-related deaths. Specifically,
356 we estimate that across these 10 metropolitan areas with a projected combined population size of
357 128.0 million people in 2090, there will be 63,111 (95% eCI: 48,036, 77,874) deaths annually
358 attributable to temperature under RCP4.5 and 86,152 (95% eCI: 63,431, 107,419) under RCP
359 8.5. Compared to 1997, we project that both heat- and cold-related deaths will increase in future
360 decades (see Supplemental Material, Table S5). The increase in cold-related mortality occurs as
361 population growth leads to an increase in the number of people exposed to cold temperatures,
362 even as the frequency of cold days declines due to climate change.

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, 13300)	14,549,152	10627 (5106, 16102)
	8.5		9146 (4270, 13688)		14296 (7400, 21029)
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, 11254)	22,938,867	10736 (5237, 16453)
	8.5		8672 (4200, 13088)		21199 (11139, 30925)
Miami	4.5	5,615,565	825 (-1728, 3245)	8,921,801	1397 (-3588, 6115)
	8.5		877 (-2191, 3655)		1714 (-12584, 11766)
New York	4.5	20,932,311	13809 (6713, 20717)	28,383,887	19734 (9977, 28984)
	8.5		14505 (7342, 21139)		25898 (15479, 35760)
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	47940 (36547, 59108)	128,031,385	63111 (48036, 77874)
	8.5		50506 (39144, 61778)		86152 (63431, 107419)

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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.

368 **4) Discussion**

369
370 Local officials are best equipped to implement policies that promote resilience against the effects
371 of climate change projected for their communities. The development of effective adaptation
372 strategies requires detailed, local information about potential future climate impacts. To provide
373 evidence to inform local adaptation plans, we estimated the change in heat-related, cold-related,
374 and total temperature-related mortality rates over the 21st century in each of 10 large US
375 metropolitan areas under differing assumptions about future greenhouse gas emissions. In
376 addition, to assist public health planning efforts, we estimated the total number of deaths
377 attributable to temperature in 1997, 2050, and 2090, first assuming that the population size of
378 each metropolitan area remains constant at 1997 levels throughout the 21st century, and then
379 accounting for projected population growth.

380
381 Looking at results from across all 10 metropolitan areas, several patterns emerge. First, we found
382 that rates of heat-related deaths will increase in all 10 metropolitan areas in 2050 and increase
383 further in 2090, as compared to 1997. We estimate that the metropolitan area with the largest
384 increase in heat-related mortality will be Los Angeles, with an additional 747 (95% eCI: 344,
385 144) heat-related deaths per million people, under the high emissions RCP 8.5 scenario in 2090.
386 In the absence of population change and holding all other factors constant, we estimate that the
387 total annual number of heat-related deaths in Los Angeles will increase substantially from 645
388 (95% eCI: 283, 1068) in 1997 to 9,535 (95% eCI: 4720, 14347) in 2090 under RCP 8.5. Across
389 all 10 cities and again holding population and all other factors constant, we project that under
390 RCP 8.5 heat-related deaths will increase from approximately 2,300 annual deaths in 1997 to

391 10,304 annual deaths in 2050 and 26,050 annual deaths in 2090. In all metropolitan areas,
392 estimates for the future number of heat-related deaths were substantially larger after allowing for
393 projected population changes, due to a large increase in the number of people expected to be
394 exposed to high ambient temperatures.

395

396 While future heat-related mortality has the potential to be large, there is evidence that the
397 implementation of heat warning systems, heat response plans, and perhaps other adaptation
398 measures is beginning to mitigate some of the effects of extreme heat. For example, in Montreal,
399 the 2004 implementation of a heat action plan that included a warning component was associated
400 with a decrease in mortality, especially among the elderly (Benmarhnia et al. 2016). The
401 implementation of heat warning systems may have also played a role in reducing mortality in
402 other locations, including France (Fouillet et al. 2008) and the United States (Weisskopf et al.
403 2002). However, while heat warning systems are typically focused on reducing mortality on
404 extremely hot days, the public health burden of moderate warm temperatures is likely larger than
405 that of extreme hot temperatures in regions across the globe, including Australia, the United
406 Kingdom, and the United States (Gasparrini et al. 2015a). Additional research is needed to
407 identify strategies that are effective in preventing the burden of disease attributable to frequent
408 days with moderate rather than extreme heat.

409

410 As average temperatures are projected to rise over the course of the century, it is plausible that
411 many areas could see a decrease in the number of cold-related deaths. Our analysis confirms this
412 hypothesis: we found that the cold-related death rate per million people is projected to decrease
413 in each of the 10 metropolitan areas. For example, we estimate that if the 1997 population of

414 Atlanta experienced the warmer temperatures projected for 2090, there would be 110 fewer (95%
415 eCI: -215, -19) deaths per million residents under RCP 8.5, partially offsetting the projected
416 increase in heat-related deaths. Despite this reduction in the cold-related mortality rate, there will
417 still be a substantial number of preventable deaths due to cold in future decades. For example,
418 even assuming no change in population size from 1997 levels, we estimate that there would still
419 be 977 (95% eCI: -21, 1880) cold-related deaths per year in Atlanta in 2090 under RCP 8.5,
420 down from an estimated 1543 (95% eCI: 191, 2731) in 1997, but still a substantial number. In
421 addition, when accounting for future population growth, we project that the absolute number of
422 cold-related deaths will *increase* sharply in all study sites in 2050 and 2090, as the number of
423 people exposed to sub-optimal temperature on either side of the MMT outweighs the decrease in
424 the cold-related death rate per million people. Thus, preventing cold-related deaths should
425 remain an important public health goal both now and in the future.

426

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

434

435 In each metropolitan area, our results further suggest that adhering to a lower versus higher
436 greenhouse gas emission scenario (i.e., RCP 4.5 rather than RCP 8.5) would result in smaller

437 elevations in average annual temperatures, smaller increases in the heat-related death rate, fewer
438 heat-related deaths, and smaller increases in the total temperature-related death rate and
439 temperature-related deaths. This pattern was observed in each metropolitan area and in both 2050
440 and 2090. For example, assuming that population size in each metropolitan area remains at 1997
441 levels, across these 10 cities temperature-related deaths would increase from around 29,100
442 deaths in 1997 to 43,709 deaths in 2090 under RCP 8.5, but a more modest 32,208 temperature-
443 related deaths under RCP 4.5. If causal, these observations suggest that investments in climate
444 change mitigation strategies that lead to lower greenhouse gas emissions could lead to substantial
445 health benefits.

446

447 Our results should be interpreted in light of some important limitations. First, while our analysis
448 is intended to be relevant on a national scale, we did not provide estimates of the change in
449 temperature-related mortality for every US metropolitan area. However, the 10 metropolitan
450 areas we selected for inclusion in this study collectively contain almost a quarter of the US
451 population (U.S. Census Bureau 2002) and encompass both geographic and climatic diversity.
452 Second, we did not account for changes in population age structure over time, as our mortality
453 data and population projections were not broken down by age or other demographic
454 characteristics. Third, we assumed that the rate ratio for the maximum temperature observed
455 during the baseline period in each metropolitan area would apply to even higher temperatures
456 projected for the future. This conservative assumption may lead to an underestimate of future
457 heat-related mortality; however, we believe it this is a reasonable approach in the absence of
458 information about the relative risk of mortality at very high temperatures. Fourth, we assumed
459 that the shape of the exposure-response curve for the relationship between temperature and

460 mortality stays constant in future decades, equivalent to assuming that there will be no adaptation
461 to changes in temperature. However, results from studies examining temperature-mortality
462 relationships over long periods of time reveal an attenuation of the impact of heat on health in
463 recent years, possibly due to increased adaptation (Åström et al. 2016, Bobb et al. 2014,
464 Gasparrini et al. 2015b). Thus, future adaptation could result in smaller increases in heat-related
465 mortality than estimated here. However, it remains uncertain the degree to which adaptation to
466 heat will continue in the US, where air conditioning prevalence is already very high in much of
467 the country, especially in urban areas.

468

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

481

482

483 **5) Conclusions**

484

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

499

500

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513

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