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Temperature-related excess mortality in German cities at 2☐°C and higher degrees of global warming

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1 # Temperature-related excess mortality in German cities at 2°C and
2 # higher degrees of global warming
3

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21 **Abstract**

22 *Background:* Investigating future changes in temperature-related mortality as a function of

23 global mean temperature (GMT) increases allows for the evaluation of policy-relevant

24 climate change targets. So far, only few studies have taken this approach, and, in particular,

25 no such assessments exist for Germany, the most populated country of Europe.

26 *Methods:* We assess temperature-related mortality in 12 major German cities based on daily

27 time-series of all-cause mortality and daily mean temperatures in the period 1993-2015,

28 using distributed-lag non-linear models in a two-stage design. Resulting risk functions are

29 applied to estimate excess mortality in terms of GMT increases relative to pre-industrial

30 levels, assuming no change in demographics or population vulnerability.

31 *Results*: In the observational period, cold contributes stronger to temperature-related

32 mortality than heat, with overall attributable fractions of 5.49% (95%CI: 3.82 – 7.19) and

33 0.81% (95%CI: 0.72 – 0.89), respectively. Future projections indicate that this pattern could

34 be reversed under progressing global warming, with heat-related mortality starting to

35 exceed cold-related mortality at 3°C or higher GMT increase. Across cities, projected net

36 increases in total temperature-related mortality were 0.45% (95%CI: -0.02 – 1.06) at 3°C,

37 1.53% (95%CI: 0.96 – 2.06) at 4°C, and 2.88% (95%CI: 1.60 – 4.10) at 5°C, compared to

38 today's warming level of 1°C. By contrast, no significant difference was found between

39 projected total temperature-related mortality at 2°C versus 1°C of GMT increase.

40 *Conclusions*: Our results can inform current adaptation policies aimed at buffering the health

41 risks from increased heat exposure under climate change. They also allow for the evaluation

42 of global mitigation efforts in terms of local health benefits in some of Germany's most

43 populated cities.

44

45 **Keywords:** temperature-related mortality, climate change, future projections, Germany,

46 global mean temperature

47

48 **Introduction**

49 Climate change is expected to alter the currently observed pattern of temperature-related

50 excess mortality around the globe. Quantitative assessments of temperature-related

51 mortality under climate change scenarios have often focused on heat, concluding that heat-

52 related excess mortality is likely to increase under global warming (Huang et al., 2011; Li et

53 al., 2018; Sanderson et al., 2017; Wang et al., 2019). The fewer studies that investigated the

54 entire temperature range generally estimated concomitant decreases in cold-related

55 mortality (Martin et al., 2012; Li et al., 2013; Schwartz et al., 2015; Gasparrini et al., 2017;

56 Weinberger et al., 2017; Sanchez Martinez et al., 2018; Vicedo-Cabrera et al., 2018), albeit

57 some of these results have been controversially discussed (Arbuthnott et al., 2018; Kinney et

58 al., 2015).

59

60 The majority of projection studies has presented changes in excess mortality for different

61 emission scenarios and future time periods. Yet, given that the international climate change

62 policy targets, as, e.g., implemented in the Paris Agreement, are expressed as temperature

63 limits, there is a growing need to present mortality projections as a function of global mean

64 temperature (GMT) rise (Ebi et al., 2018). In addition, the focus on temperature magnitudes

65 rather than on time periods facilitates the construction of damage functions to integrate

66 health impacts in integrated assessment models (Carleton et al., 2018), and allows for the

67 derivation of impact emulators required to quickly judge emission pledges in terms of

68 climate impacts (Ostberg et al., 2018). So far, there are few projection studies of

69 temperature-related mortality focusing on the magnitudes of GMT change (Chen et al.,

70 2019; Vicedo-Cabrera et al., 2018; Wang et al., 2019; Mitchell et al., 2018; Lo et al., 2019).

71 Most of these studies focus on the lower levels of possible GMT increase within this century

72 (1.5°C, 2°C, and 3°C above pre-industrial levels), while we also take the higher global

73 warming levels (4°C and 5°C above pre-industrial levels) into account.

74

75 Furthermore, we are the first to present projections of temperature-related mortality based

76 on a newly assembled observational dataset of death counts and climate variables in 12

77 large cities of Germany, the most populated country of Europe. Although temperature-

78 related excess mortality in Germany has been studied based on observational data for

79 specific cities (Breitner et al., 2014), regions (Laschewski and Jendritzky, 2002; Muthers et

80 al., 2017), and the entire country (Karlsson and Ziebarth, 2018), there is only a very limited

81 number of quantitative climate change projection studies. The few existing ones are limited

82 to specific cities or regions of Germany (Chen et al., 2019; Rai et al., 2019), neglect the

83 effects of cold (Zacharias et al., 2015; Kendrovski et al., 2017), or use only one simplified

84 model for the relationship between temperature and mortality for the entire country

85 (Hübler et al., 2008).

86

87 The main objective of this study is to evaluate the policy-relevant climate change target of

88 limiting global warming to below 2°C compared to higher warming levels in terms of changes

89 in temperature-related mortality in Germany, focussing on the potential for local benefits

90 versus damages of climate change. To this aim, we derive temperature-mortality

91 associations in 12 large German cities, using state-of-the art statistical techniques developed

92 in time-series modelling (Gasparrini et al., 2012, 2010). Based on these associations and an

93 ensemble of locally bias-corrected climate projections (Frieler et al., 2017), we estimate

94 temperature-related excess mortality at different degrees of global warming (1°C, 2°C, 3°C,

95 4°C, and 5°C of GMT rise above pre-industrial levels). Since we make the counterfactual

96 assumption of no future changes in adaptation and demography, our estimates are best

97 interpreted as exposing the current population of Germany's major cities, embedded in

98 current infrastructures and health care systems, to different possible temperature

99 distributions of the future.

100

101 **Material and methods**

102 *Observational data*

103 We obtained daily death counts of all-cause mortality in 12 major German cities (> 500 000

104 inhabitants; see Table A1 for city coding and population data) from the Research Data

105 Centres of the Federation and the Federal States of Germany for the period 1 January 1993

106 to 31 December 2015 (individual datasets are available as doi:

107 10.21242/23211.[year].00.00.1.1.0). The cities are spread across the entire country (Fig. A1),

108 and represent around 16% of the total German population in 2015 (Table A1). Given the

109 susceptibility of a wide range of death causes to non-optimal temperatures (e.g., Anderson

110 and Bell, 2009; Gasparrini et al., 2012b), it is a common approach in studies of temperature-

111 related mortality to work with total death counts. More specifically, it has been shown that

4

112 results on temperature-mortality associations are practically insensitive to the use of all-

113 cause versus non-accidental mortality data across a large number of locations (Gasparrini et

114 al., 2015).

115

116 Data of daily mean temperature (24-h averages) for the study period was derived from the

117 Climate Data Centre of the German National Meteorological Service (Deutscher

118 Wetterdienst). If several weather stations existed within the city boundaries, stations closest

119 to the city centre were chosen, provided that measurements were available for the whole

120 study period. (Table A2). We decided to use temperature data from a single weather station,

121 given that more spatially refined exposure data does not generally yield different estimates

122 of temperature-mortality associations compared to simpler one-station data (Schaeffer et

123 al., 2016; Weinberger et al., 2019). Details on the processing of missing values are given in

124 Appendix A.

125

126 *Temperature projections*

127 Projections of daily mean temperatures for the 12 cities were derived from the second phase

128 of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler et al., 2017),

129 comprising gridded (0.5° x 0.5°), bias-corrected data from 4 general circulation models

130 (GCMs) (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5), which contributed

131 simulations to the 5th Coupled Model Intercomparison Project (CMIP5). For each GCM, we

132 considered the historical run in the period 1986-2005 and 4 different climate-change

133 scenario runs (Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP 6.0,

134 RCP8.5) in the period 2006-2099 (2006-2100 for RCP8.5 simulations from IPSL-CM5A-LR).

135 Time-series from the grid cell enclosing the respective city coordinates were extracted, and

136 the data was additionally bias-corrected using the local weather station data from each city

137 following the approach by Lange (2017). Through this additional bias-correction step we

138 mapped the spatial temperature mean of the grid cell to the local scale of the city. The

139 remaining bias in the distribution of daily mean temperatures was relatively small (Fig. A2).

140 In addition to local projection data, we also considered annual averages of corresponding

141 GMT series.

142

143 *Defining global warming levels*

5

144   To select time slices corresponding to the considered levels of global warming, we first

145   computed a series of annual GMT differences against pre-industrial levels for each GCM and

146   RCP (extended backwards in time using data from the historical run). In this step, given that

147   some of the GCMs considered (especially HadGEM2-ES and IPSL-CM5A-LR) simulate

148   historical global warming trends that deviate substantially from the observed trend, we

149   chose 1986-2005 as a reference period and added the observed global warming of 0.6°C

150   between this reference period and pre-industrial levels (following Schleussner et al., 2016).

151   Subsequently, we computed 21-year running means of GMT increases above pre-industrial

152   levels and determined the corresponding temporal windows when the considered levels of

153   global warming (1°C to 5°C) were reached for the first time (see Table A3 for selected time

154   windows). Finally, we extracted the local temperature projections in these temporal

155   windows (for an example of the resulting temperature distributions for Berlin, based on

156   RCP8.5, see Fig. 1). It can be noted that only HadGEM2-ES and IPSL-CM5A-LR reached 4°C

157   and 5°C above pre-industrial levels in the scenarios considered (Fig. 1, Table A3). We

158   computed changes in projected excess mortality against mortality simulated for the lowest

159   warming level 1°C, which roughly corresponds to the historical warming up to present-day.

160
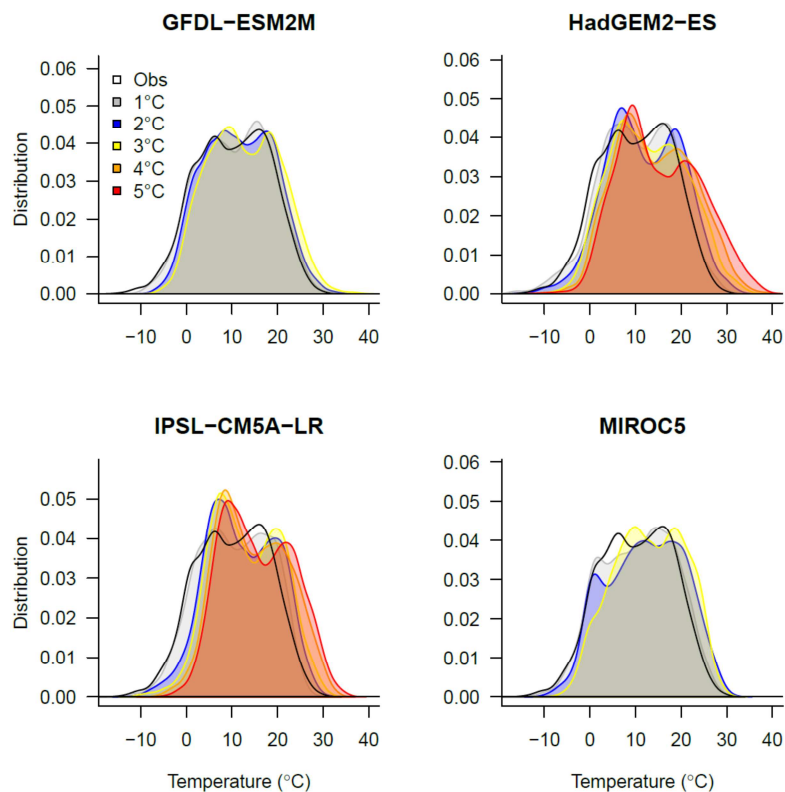
Figure 1. Example distributions of observed (black) and projected (colours) mean daily temperatures
at different levels of global warming in Berlin, by global climate model. Distributions were
constructed based on daily simulation data (1986-2099, historical run + shown here RCP8.5), mapped

6

164 to global warming levels by considering 21-year running means of annual differences in global mean

165 temperature (GMT) above pre-industrial levels (see Table A3).

166

167 *Deriving temperature-mortality associations*

168 Temperature-mortality associations were estimated with a two-stage approach, following

169 Gasparrini et al. (2015). The details of the methodology are extensively documented in

170 Gasparrini et al. (2010) and Gasparrini et al. (2012a). In the first stage, we used time-series

171 quasi-Poisson regression to estimate city-specific exposure-response functions.

172 Temperature-mortality associations were modelled with distributed-lag non-linear models

173 (DLNMs). We fitted a natural cubic spline function with three internal knots placed at the

174 10th, 75th, and 90th percentiles of the local temperature distribution to model the exposure-

175 response curve. This choice assures a log-linear extrapolation of the exposure-response

176 curve beyond the observed temperature range (Vicedo-Cabrera et al., 2019). The lag-

177 response curve was modelled with a natural cubic spline with an intercept and three internal

178 knots equally distributed in the log-space, accounting for up to 21 days of lag. We controlled

179 for day of the week with an indicator, and for seasonal and long-term trends with a natural

180 cubic spline of time with 7 degrees of freedom per year. The chosen number of degrees of

181 freedom for control of season and long-term trends corresponded to the minimum quasi-

182 Akaike information criterion (QAIC) summed across all cities (Fig. A3). Model choices were

183 further tested in a sensitivity analysis (Table A4).

184

185 In the second stage, we performed a multivariate meta-regression on reduced coefficients

186 from the first stage, which describe the overall cumulative exposure-response curve across

187 the 21 days of lag. Long-term average temperature and temperature range (difference

188 between maximum and minimum temperature) (Table 1) were included as meta-predictors

189 in the model. Both meta-predictors explained part of the heterogeneity between cities

190 (Table A5). From the meta-regression model, we derived the best linear unbiased predictors

191 (BLUPs) for each city, which represent a trade-off between the location-specific association

192 provided by the first-stage regression and the pooled association, and identify the minimum

193 mortality temperature (MMT) (Table 1).

194

195 *Computation of attributable mortality*

196 All computations of daily mortality attributable to non-optimal temperatures, in the

197   observational period and at different levels of GMT rise (1 to 5°C) followed a similar setup.

198   We used the exposure-response curve defined by the BLUPs and centred on the MMTs, and

199   combined these with different daily series of temperature and mortality. To derive

200   attributable mortality in the observational period (1993-2015), we used the observed

201   temperature series and forward moving averages of observed deaths counts across the lag

202   period as described in Gasparrini and Leone (2014). To estimate projected attributable

203   mortality at different levels of global warming, we built upon the approach by Gasparrini et

204   al. (2017) and Vicedo-Cabrera et al. (2018). A series of projected daily mortality was

205   constructed by averaging observed deaths counts per day of the year. We then replicated

206   the annual pattern 21-times, in order to derive mortality series of the same length as the

207   projected temperature series. We summed attributable numbers in the observational period

208   (across each series of projected temperatures) to derive total temperature-related excess

209   mortality. We also separated components due to heat and cold by considering only days

210   with temperatures higher or lower than the MMT. Dividing by the total number of observed

211   deaths (the sum of projected mortality series) we also derived the corresponding

212   attributable fractions. Overall attributable fractions, for all cities combined, were derived by

213   summing daily attributable numbers across all cities, and dividing by the total number of

214   deaths. The ensemble mean at each level of GMT rise was calculated as the average across

215   all GCM-specific, and RCP-specific attributable fractions. In averaging across RCPs, we

216   assumed that it did not matter when in time a specific warming level was reached (see also

217   Table A3), i.e., we assumed a scenario-independence of results.

218

219   **Table 1.** Descriptive statistics, estimated minimum mortality temperatures (MMT), and attributable
220   fractions in the observational period (1993-2015).

221

City	Total deaths	Mean daily temperature	MMT	Attributable fractions		
				Total	Cold	Heat
		mean (min, max)	°C (perc)	% (95%CI)	% (95%CI)	% (95%CI)
Berlin	811,051	10.2 (-15.6 – 30.5)	18.9 (85th)	6.95 (5.24 – 8.61)	5.95 (4.25 – 7.61)	1.00 (0.89 – 1.13)
Bremen	150,608	9.8 (-14.1 – 27.6)	17.6 (87th)	3.56 (0.23 – 6.81)	3.21 (-0.07 – 6.39)	0.36 (0.16 – 0.55)
Cologne	229,457	10.6 (-16.5 – 29.3)	17.7 (84th)	6.78 (4.84 – 8.79)	5.7 (3.69 – 7.77)	1.08 (0.93 – 1.24)
Dortmund	155,233	10.5 (-15.2 – 28.9)	17.9 (86th)	6.23 (4.21 – 8.23)	5.44 (3.44 – 7.5)	0.79 (0.68 – 0.91)
Dresden	125,866	9.6 (-16.3 – 30.4)	18.7 (86th)	5.42 (2.41 – 8.37)	4.72 (1.68 – 7.7)	0.69 (0.53 – 0.87)

Dusseldorf	160,069	10.9 (-14.6 – 30.0)	17.9 (84th)	6.84 (4.6 – 9.05)	5.76 (3.42 – 8.08)	1.08 (0.9 – 1.27)
Frankfurt	168,417	11.0 (-12.9 – 29.9)	19.8 (87th)	9.59 (5.99 – 12.87)	8.5 (4.97 – 11.73)	1.09 (0.88 – 1.29)
Hamburg	445,338	9.6 (-13.5 – 28.8)	18.5 (90th)	4.93 (1.54 – 8.16)	4.63 (1.37 – 7.75)	0.31 (0.15 – 0.44)
Hannover	279,125	9.9 (-16.9 – 29.0)	17.2 (84th)	4.62 (2.81 – 6.46)	3.83 (1.99 – 5.75)	0.79 (0.64 – 0.95)
Leipzig	152,861	10.0 (-17.5 – 29.0)	17.7 (82nd)	5.09 (3.1 – 7.11)	4.03 (2 – 6.11)	1.07 (0.87 – 1.26)
Munich	290,962	10.0 (-13.4 – 29.5)	19.7 (88th)	7.23 (4.77 – 9.57)	6.62 (4.21 – 8.95)	0.61 (0.47 – 0.74)
Stuttgart	136,878	10.7 (-13.0 – 30.3)	19.2 (86th)	7.98 (5.54 – 10.34)	7.07 (4.57 – 9.5)	0.91 (0.76 – 1.08)
All cities	3,105,865	10.3 (-17.5 – 30.5)	18.4 (86th)*	6.30 (4.6 – 7.98)	5.49 (3.82 – 7.19)	0.81 (0.72 – 0.89)

222   * median of city-specific estimates

223

224   *Uncertainty estimation*

225   To assess the uncertainty stemming from the fitted exposure-response functions, we

226   conducted Monte Carlo simulations drawing 1000 times from a multivariate normal

227   distribution defined by the BLUPs and the corresponding co-variance matrix. We determined

228   95% empirical confidence intervals (CI) by considering the 2.5th and 97.5th percentiles of the

229   resulting sample. In the projections, we additionally determined the uncertainty stemming

230   from the use of different GCMs, and RCPs. Total uncertainty, including epidemiological and

231   climate uncertainties, was assessed by considering the 2.5th and 97.5th percentiles of mean

232   excess mortality in each GMT bin across all Monte Carlo samples, GCMs, and RCPs.

233

234   In addition, we were interested in determining the contribution of different sources of

235   uncertainty to the overall variability in excess mortality estimates. To assess climate

236   uncertainty, due to differences between GCMs and RCPs, we calculated the standard

237   deviations of mean excess mortality estimates based on central BLUPs across GCMs (SD_{gcm}),

238   and across RCPs (SD_{rcp}), respectively. As a measure of epidemiological uncertainty, we

239   computed the average of standard deviations resulting from Monte Carlo simulations,

240   considering GCMs and RCPs one at a time (SD_{epi}). We normalized these standard deviations

241   (reflecting uncertainties in GCMs, RCPs, and exposure-response functions, respectively)

242   dividing by their sum: $SD_{gcm}+SD_{rcp}+SD_{epi}$. It can be noted that the differentiation between

243   GCMs and RCPs in contributing to climate uncertainty was only possible for global warming

244   levels 1°C to 3°C, because results for higher warming levels were based on RCP8.5 only (cf.,

245   Table A3). Thus, for warming levels >3°C we only considered SD_{gcm} and SD_{epi}.

246

247   All computations were done using R (version 3.4.3) with packages *dlnm* and *mvmeta*. The

248   code was partly adapted from Gasparrini et al. (2015), Gasparrini et al. (2017), and Vicedo-

249   Cabrera et al. (2019), and is available on request from the first author.

250

251   **Results**

252   Our dataset of 12 major German cities included a total of 3,105,865 deaths in the period

253   1993-2015 (Table 1). The mean (min, max) of daily mean temperatures across cities was

254   10.3°C (-17.5°C, 30.5°C). Overall cumulative temperature-mortality associations were

255   relatively similar across cities (Fig. 2), showing a gradually rising RR for cold (i.e., below the

256   MMT), and a more steeply increasing RR for heat (i.e., above the MMT). MMT estimates fell

257   in the range 17.2°C to 19.8°C, corresponding to the 82th to 90th percentiles of the distribution

258   of daily mean temperatures in the individual cities (Table 1). All cities showed a similar

259   temporal lag structure: The effect of cold peaked a few days after the exposure and lasted

260   up to 3 weeks, while the effect of heat was more immediate and vanished (or reversed sign,

261   indicative of mortality displacement) after a few days (Fig. A4).

262

263   Total excess mortality attributable to non-optimal temperatures across cities was 6.30%

264   (95%CI: 4.60 – 7.98) (Table 1). Out of this, 0.81% (95%CI: 0.72 – 0.89) were attributable to

265   heat, and 5.49% (95%CI: 3.82 – 7.19) to cold. Comparing city-specific estimates, the lowest

266   total excess mortality was observed in Bremen (3.56%; 95%CI: 0.23 – 6.81) and the highest in

267   Frankfurt (9.59%; 95%CI: 5.99 – 12.87) (Table 1, Fig. 3). Confidence intervals of attributable

268   fractions were significant (i.e., did not include zero) in all cities, except for cold attributable

269   mortality in Bremen. The sensitivity analysis showed that modelling choices only marginally

270   affected our estimates of present-day attributable fractions (Table A4).
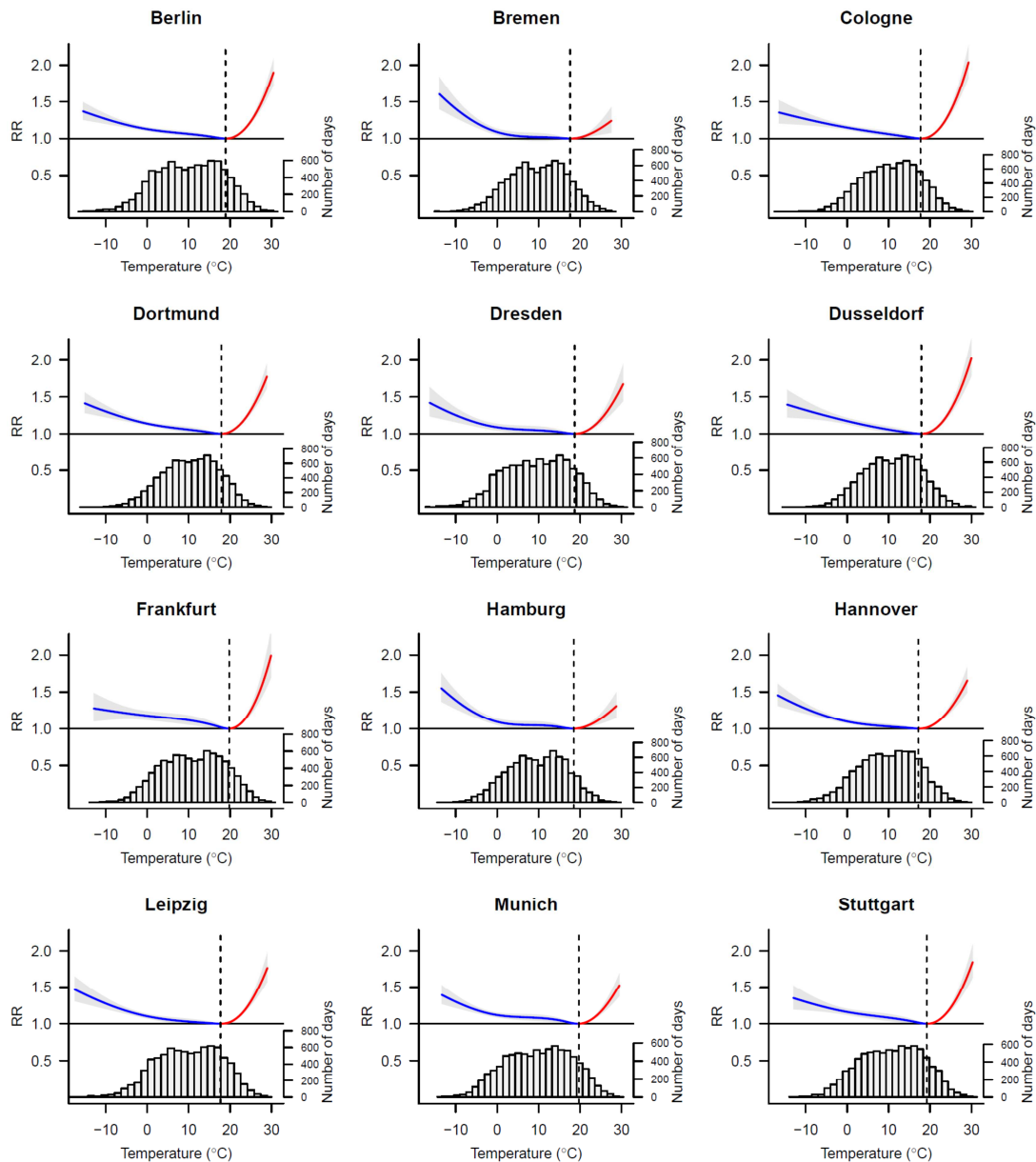
Figure 2. Temperature-mortality associations in German cities estimated from observed deaths counts and mean daily temperatures in 1993-2015. Mortality is reported as relative risk (RR) with respect to the minimum mortality temperature (MMT) (dashed line). Cold-related RR (temperature < MMT) is shown in blue, heat-related RR (temperature >MMT) in red. Shading corresponds to empirical 95%CIs. Lower panels depict daily mean temperature distributions.

Projections of excess mortalities for 1°C of GMT rise above pre-industrial levels, roughly

corresponding to historical global warming up to today, were very close to the estimates

based on observational data (Fig. 3). In all cities, heat excess mortality was projected to

increase from today's GMT level towards higher magnitudes of global warming, while cold

excess mortality was projected to decrease (Fig. 3, Table A6). Whereas at lower levels of

GMT rise cold contributed considerably stronger to total excess mortality than heat, this

pattern was reversed at higher levels of GMT rise (see crossing points of blue and red curves

11

285 in Fig. 3). For a 5°C increase in GMT above pre-industrial levels total excess mortality

286 attributable to non-optimal temperatures was projected to reach 9.02% (95%CI: 6.60 –

287 11.44) across cities, with heat contributing the larger part 5.75% (95%CI: 4.48 – 7.09), and

288 cold contributing only 3.27% (95%CI: 1.93 – 4.60) (Table 2, Fig. 3).

289

290 **Table 2.** Projected excess mortality (GCM-RCP-ensemble averages) at different levels of GMT rise
291 above pre-industrial for all 12 German cities combined. Relative changes (net differences, change
292 factor) are computed relative to 1°C GMT rise.

293

GMT rise above pre-industrial	Temperature range	Attributable fractions % (95%CI)	Net differences % (95%CI)	Change factor (95%CI)
1°C	Heat	0.89 (0.66 – 1.18)	-	-
	Cold	5.29 (3.61 – 6.99)	-	-
	Total	6.19 (4.45 – 7.92)	-	-
2°C	Heat	1.64 (1.25 – 2.01)	0.73 (0.41 – 1.03)	1.8 (1.4 – 2.3)
	Cold	4.58 (3.00 – 6.18)	-0.74 (-1.03 – -0.50)	0.9 (0.8 – 0.9)
	Total	6.22 (4.56 – 7.87)	-0.01 (-0.39 – 0.31)	1 (0.9 – 1.1)
3°C	Heat	2.60 (2.00 – 3.36)	1.68 (1.21 – 2.30)	2.8 (2.3 – 3.4)
	Cold	4.10 (2.59 – 5.62)	-1.22 (-1.68 – -0.87)	0.8 (0.7 – 0.8)
	Total	6.70 (4.87 – 8.51)	0.45 (-0.02 – 1.06)	1.1 (1 – 1.2)
4°C	Heat	4.06 (3.44 - 4.69)	3.26 (2.81 – 3.70)	5.1 (4.6 – 6)
	Cold	3.61 (2.20 – 5.02)	-1.72 (-2.11 – -1.35)	0.7 (0.6 – 0.7)
	Total	7.67 (5.83 – 9.45)	1.53 (0.96 – 2.06)	1.2 (1.1 – 1.4)
5°C	Heat	5.75 (4.48 – 7.09)	4.95 (3.84 – 6.10)	7.2 (6.5 – 7.9)
	Cold	3.27 (1.93 – 4.60)	-2.07 (-2.56 – -1.62)	0.6 (0.5 – 0.7)
	Total	9.02 (6.60 – 11.44)	2.88 (1.60 – 4.10)	1.5 (1.2 – 1.8)

294

295 In all cities, net changes in total excess mortality from today's 1°C to a 2°C increase in GMT

296 above pre-industrial levels were marginal and not significant from zero (Fig. 4). At this

297 warming level, projected increases in heat-related mortality were largely compensated for

298 by decreases in cold-related mortality. In most cities, significant net increases in total excess

299 mortality started to appear at 3°C, 4°C, or 5°C of GMT increase above pre-industrial levels

300 (Fig. 4, Table A6).
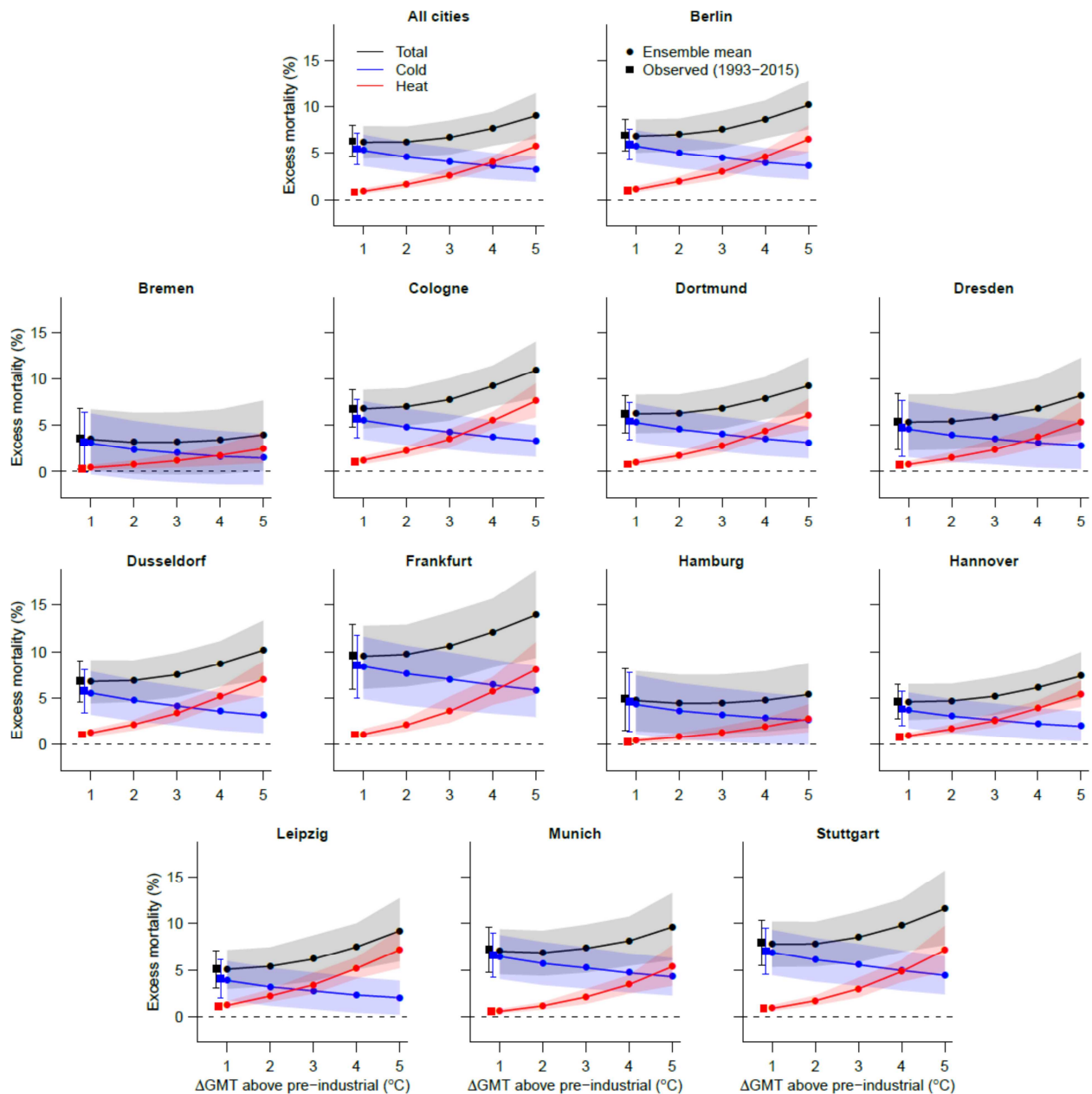
Figure 3. Projected total (black), cold-related (blue) and heat-related (red) excess mortality at different levels of global warming, for all cities combined, and by individual city. Circles show mean excess mortality, averaged across climate models (GCMs) and scenario types (RCPs), for considered increases in global mean temperature (ΔGMT) above pre-industrial levels. Squares depict excess mortality estimates based on observations (see Table 1). Shading and whiskers correspond to 95%CIs, taking into account uncertainty related to temperature-mortality associations and climate projections (GCMs and RCPs).

For all cities combined, total excess mortality was estimated to increase by 0.45% (95%CI: -0.02 – 1.06) towards 3°C, 1.53% (95%CI: 0.96 – 2.06) towards 4°C and 2.88% (95%CI: 1.60 – 4.10) towards 5°C, compared to the current 1°C rise in GMT (Table 2, Fig. 4). Underlying these net changes were marked increases in heat-related mortality by 1.68% (95%CI: 1.21 – 2.30) at 3°C, 3.26% (95%CI: 2.81 – 3.70) at 4°C, and 4.95% (95%CI: 3.84 – 6.10) at 5°C,

13

316 corresponding to a 2.8-fold (95%CI: 2.3 – 3.4), a 5.1-fold (95%CI: 4.6 – 6.0) and a 7.2-fold

317 (95%CI: 6.5 – 7.9) rise in heat-related excess mortality, respectively, compared to today's

318 warming of 1°C (Table 2, Fig. 4).

319
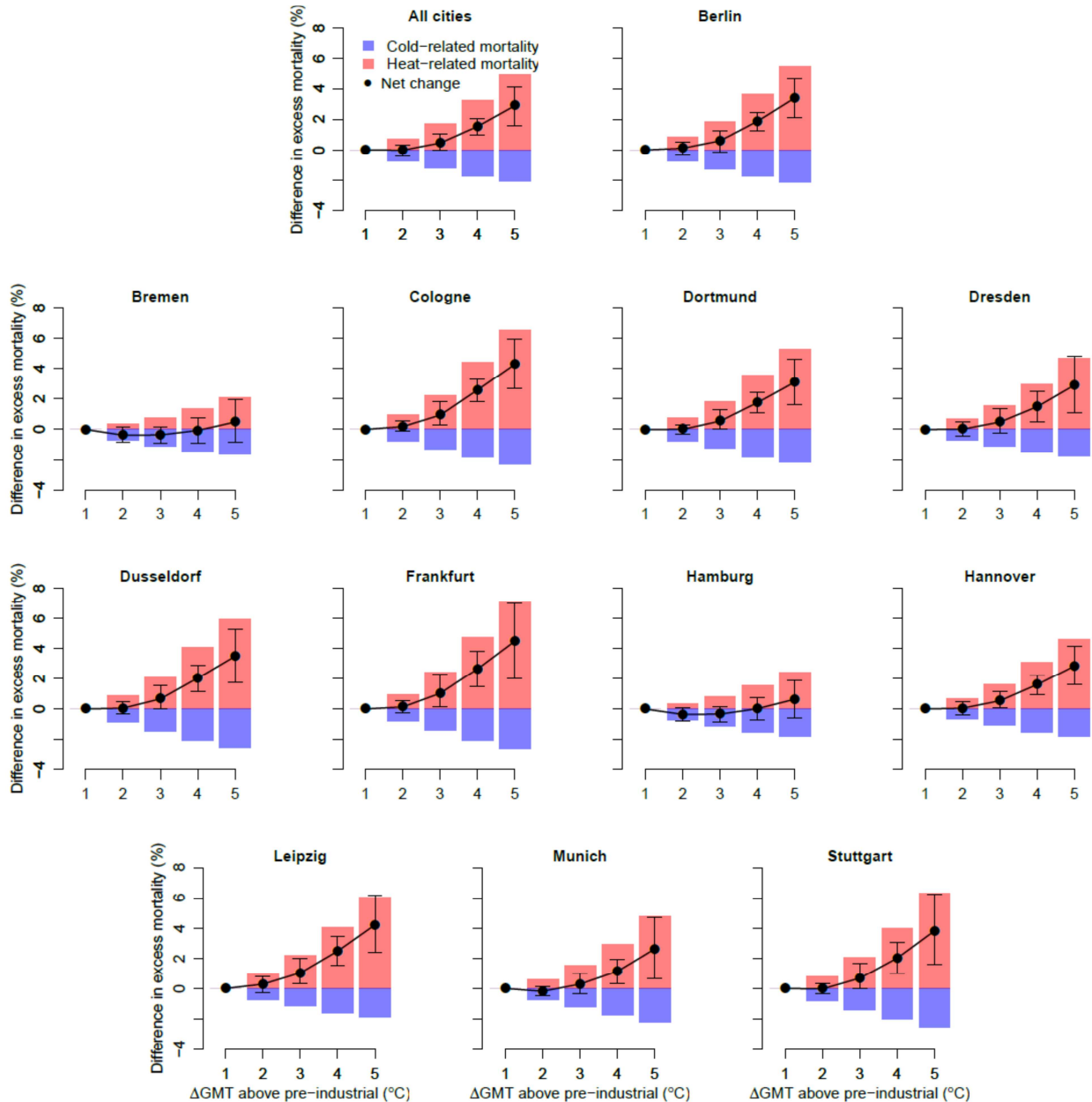
321 **Figure 4**. Differences in excess mortality compared to today's 1°C of global warming for all cities
322 combined, and by individual city. Bars and circles correspond to GCM-RCP-ensemble averages (cf. Fig.
323 3). Whiskers show 95%CIs in net differences.

324

325 The estimated standard deviations indicated that differences in climate simulations

326 (originating from the use of various GCMs and from considering different RCPs) were the

327 dominant source of uncertainty in projections of heat-related excess mortality (Fig. 5). By

328 contrast, for cold-related mortality, uncertainties in the temperature-mortality associations

329 were the main contributor to total uncertainty in projections. Climate uncertainty

330 contributed increasingly to total uncertainty in projected total excess mortality along the

331 gradient of global warming considered. The choice of RCP was generally the least important

332 source of uncertainty, compared to differences among GCMs and uncertainties inherent in

333 exposure-response functions, with the exception of warming levels 1°C and 2°C for heat-

334 related mortality (Fig. 5).
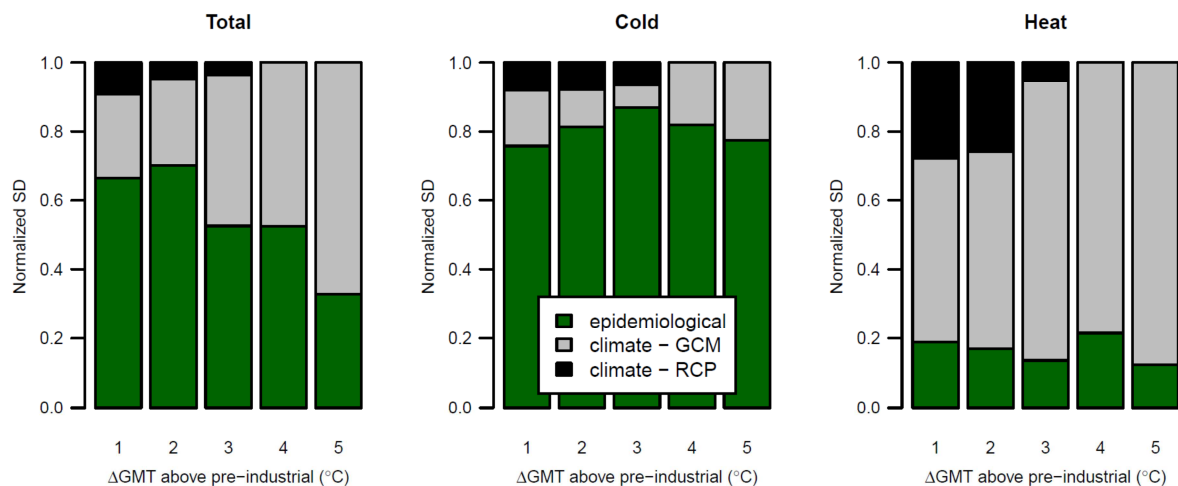
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Figure 5. Relative uncertainty (expressed as normalized SDs) arising from GCMs and RCPs (climate uncertainty), and exposure-response functions (epidemiological uncertainty) in projections of total excess mortality (left), cold-related excess mortality (middle) and heat-related excess mortality (right) for all cities combined, by level of global warming.

341

Discussion

343 Here, we present for the first time a comprehensive assessment of temperature-related

344 excess mortality under current and possible future climate conditions in major German

345 cities, taking into account both heat- and cold-related mortality. Our findings indicate that

346 while low temperatures currently contribute stronger to overall excess mortality than high

347 temperatures across the cities studied, this pattern could be reversed if GMTs rise more than

348 3°C relative to pre-industrial levels. Higher levels of global warming on the order of 3°C, 4°C

349 and 5°C are accompanied in our projections with marked net increases in total temperature-

350 related excess mortality compared to today. By contrast, limiting the rise in GMT to 2°C

351 would avoid any significant change in total temperature-related mortality compared to

352 today. Yet, underlying increases in heat-related mortality at this warming level are still

353 considerable on a relative scale, with a mean projected 1.8-fold rise in the attributable

354 fraction across cities.

355

356 Our results on attributable mortality in the observational period (1993-2015) agree with

357 Gasparrini et al. (2015), who found that a larger fraction of the current temperature-related

358 excess mortality in cities around the world can be attributed to cold than to heat. The

359 temperature-mortality associations estimated here are also in qualitative agreement with

360 Breitner et al. (2014), who showed that both very low and very high ambient temperatures

361 increase non-accidental mortality in three southern German cities. E.g., for Munich our RR

362 estimates translate into a 8.7% and 19.9% increase in mortality between the 1st vs 10th, and

363 99th vs 90th percentiles of daily mean temperatures, respectively, compared to 8.5% and

364 6.8% estimated by Breitner et al. (2014). By contrast, a recent study on temperature-related

365 mortality across all German counties (Karlsson and Ziebarth, 2018) found evidence for heat-

366 related mortality, but remained inconclusive on the effect of cold. The difference with our

367 findings might stem from methodological differences in modelling the lagged effects of

368 temperature. In fact, Gasparrini (2017) suggested that simpler approaches such as moving

369 averages or linear lag functions (as adopted by Karlsson and Ziebarth, 2018) tend to

370 underestimate cold effects on mortality, compared to more sophisticated methods such as

371 the DLNMs used in our study.

372

373 Our findings on projected mortality qualitatively match the estimates presented recently by

374 Vicedo-Cabrera et al. (2018), who found moderate increases in net excess mortality for

375 warming levels 3°C and 4°C relative to 1.5°C for cities in Central Europe (which in this

376 analysis comprise France, Switzerland, Czech Republic, and Moldova as the countries

377 geographically closest to Germany). Our results can also be compared to the only study that

378 has so far presented quantitative projections on heat- and cold-related mortality for the

379 whole of Germany (Hübler et al., 2008). Disregarding the effect of an aging population, this

380 study found a doubling of heat-related fatalities for a scenario (SRES A1B) corresponding to

381 approximately 3°C global warming by the end of the century (conversion of scenario and

382 time period into GMT level based on Ebi et al., 2018). Our aggregated results across all cities

383 are approximately in line with these findings (Table 2: we found a mean increment factor of

384 2.8 [95% CI: 2.3 – 3.4]). Furthermore, Hübler et al. (2008) found that at 3°C the effects of

385 cold and heat only roughly balanced each other, with a slight surplus of additional deaths

386 due to heat, which is also in accordance with our results.

387

388 Our study has several limitations. Most importantly, our projections do not take into account

389 possible shifts in the vulnerability of the population towards non-optimal temperatures over

390 time, which might occur due to demographic changes, alteration of health care services,

391 physiological acclimatization, or adaptation measures. These shifts have been documented

392 for the past, especially regarding decreasing vulnerability towards heat (e.g., Achebak et al.,

393 2018; Barreca et al., 2016; ; Chung et al., 2018). Some recent projection studies have also

394 explicitly accounted for demographic changes, based on age-specific exposure response

395 functions (Lee et al., 2018; Rai et al., 2019). However, our approach does not easily allow us

396 to incorporate these changes in time. By integrating different climate scenarios (RCPs) in our

397 definition of global warming levels we break up the temporal structure of projections and

398 thus cannot directly integrate possible future changes in demography or adaptive behaviour.

399 Thus, our results should by no means be misinterpreted as future predictions of

400 temperature-related excess mortality. Instead, our approach allows us to isolate the effect

401 of climate from other socio-economic factors known to influence mortality.

402

403 Consistently with previous published studies we estimated large uncertainties in projected

404 excess mortalities (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018), stemming from the

405 imprecision in estimated temperature-mortality associations, from differences among GCMs,

406 and from sampling uncertainty related to different RCPs. Yet, even though we capture

407 important elements of the total uncertainty, there are some limitations to our uncertainty

408 measures. First, our approach does not account for the uncertainty in choosing the

409 functional form for extrapolating exposure-response curves beyond the maximum

410 temperatures in the observational datasets (Benmarhnia et al., 2014; Vicedo-Cabrera et al.,

411 2018). This shortcoming would lead to an underestimation of the contribution of

412 epidemiological uncertainty to total uncertainty in heat-related mortality projections (Fig. 5).

413 Second, by using temperature projections derived from transient climate simulations in a

414 limited time period we base our estimates on an incomprehensive sampling of the

415 temperature distributions corresponding to the different magnitudes of global warming

416 considered. This concerns in particular the higher warming levels (4°C and 5°C), where our

417 estimates are based on RCP8.5 simulations of two GCMs only (Table A3), and, thus, the

418 resulting bias in the estimation of climate uncertainty should be greatest.

419

420 Last but not least, our study leaves to further research the more detailed investigation of

421 observed heterogeneity between cities. Sera et al. (2019) recently showed that some of the

422 differences in the magnitude of attributable fractions observed among cities around the

423 world can be related to variability in external factors such as demographic parameters, air

424 pollution levels, socio-economic indicators, and urban infrastructure. In this regard, it is

425 interesting to note that the two cities with the most maritime climate, and thus the

426 comparatively coolest summers, Bremen and Hamburg, showed the lowest heat-related

427 excess mortality (Table 1). Further analyses relating differences in exposure-response

428 functions to local climate characteristics is a promising avenue to account for potential shifts

429 in vulnerability to non-optimal temperature in more refined future projection studies.

430

431 **Conclusions**

432 In conclusion, our findings show that keeping global warming below 2°C above pre-industrial

433 levels implies considerable health benefits in German cities compared to higher warming

434 levels, especially those to be reached if global greenhouse gas emissions are not drastically

435 reduced in the coming decades. While we found marked net increases in temperature-

436 related excess mortality for global warming by 3°C and more, ambitious mitigation in ac-

437 cordance with the Paris Agreement would avoid a net increase in overall excess mortality

438 compared to today. At the same time, even at 2°C of global warming, adaptation efforts

439 would need to be implemented in order to buffer the estimated increase in heat-related

440 mortality, which, independent of concomitant shifts in cold-related mortality, appears as a

441 considerable future public health risk in Germany.

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List of abbreviations

BLUPs: Best linear unbiased predictors; CI: Confidence interval; GCM: general circulation model (or global climate model); GMT: global mean temperature; MMT: minimum mortality temperature; RR: relative risk

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT author contribution statement

VH: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft; LK: Investigation, Software, Writing - Review & Editing; CPO: Conceptualization, Methodology, Resources, Writing - Review & Editing; SL: Methodology, Data Curation, Writing - Review & Editing; AG: Methodology, Software, Writing - Review & Editing; AVC: Methodology, Software, Writing - Review & Editing; RG-H: Supervision, Writing - Review & Editing; KF: Funding acquisition, Writing - Review & Editing

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632

Highlights (no longer than 85 characters including spaces)

Huber et al: Temperature-related excess mortality in German cities at 2°C and higher degrees of global warming

- German cities face risk of net mortality increases if global warming higher than 2°C
- Above 3°C of global warming heat may cause more deaths than cold in Germany
- Global warming of 4°C risks to quintuple heat-related mortality in German cities

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: