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Supplementary appendix

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Appendix

Title

Projections of excess mortality related to diurnal temperature range under four climate change scenarios: a multi-country modelling study

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1. Data collection details

The dataset has been collected through the Multi-City Multi-Country (MCC) network, an international collaboration of research teams working on a program aiming to produce epidemiological evidence on associations between weather and health (http://mccstudy.lshtm.ac.uk/). Following dataset descriptions of 16 countries/regions (Canada, USA, Brazil, UK, Ireland, Spain, Japan, Korea, Australia, Finland, France, Mexico, Moldova, Switzerland, Taiwan, and Thailand) were also reported in the previous publications.[1-5] Here we provide details on dataset from four additional countries (Argentina, South Africa, Portugal, and Estonia).

Canada. We obtained daily data on all-cause mortality from Statistics Canada through access to the Canadian Mortality Database for the period of 1986 to 2011 for 25 census metropolitan areas (CMA). Daily meteorological data were obtained from Environment Canada using the airport monitoring station located closest to the CMA centre. Daily averages of temperature and relative humidity were computed based on hourly measurements.

United States. We collected data from 132 cities between 1st of January 1985 and 31st of December 2006. Daily mortality, obtained from the National Center for Health Statistics (NCHS), is represented by counts of deaths for non-external causes only (ICD-9: 0-799; ICD-10: A00-R99). Daily minimum, mean (in ˚C, computed as the 24-hour average based on hourly measurements) and maximum temperatures and relative humidity (in %, computed from the 24-h average of hourly measurements of dew point temperature) were obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). A single weather station was selected for each city in the land-based station data or NCDC, based on the proximity to the city's population centre. In 6 cities where multiple observations were missing from all the nearby monitors, hourly data from the Integrated Surface Database Lite of NCDC were converted in daily values. For 25 stations missing dew point data, dew point data were obtained from the nearest station with dew point data.

Brazil. We collected data on daily deaths for non-external causes only (ICD-10 codes: A00-R99) in 18 cities between 1st of January 1997 and 31st of December 2011 were collected from Ministry of Health, Brazil. Data on daily mean, minimum and maximum temperature (computed as the 24-hours average based on hourly measurements) and relative humidity were obtained during the same study period from Weather Meteorological Service of Brazil.

United Kingdom. We obtained daily data on all-cause mortality from the Office of National Statistics during 1990–2012. Records include the date of death and postcode of residence at time of death. The postcodes were used to divide deaths into 10 government regions and date to make daily series of counts for each region. The daily weather data (daily minimum, mean, and maximum temperatures and mean relative humidity) were downloaded from the British Atmospheric Data Centre. There was a mean of 29 stations contributing data to each regional series, from a minimum of 7 in London to a maximum of 44 in Wales.

Ireland. Data on daily deaths for non-external causes only (ICD-10 codes: A00-R99) in 6 cities between 1st of January 1984 and 31st of December 2007 were collected from the Irish Central Statistics Office and the Northern Ireland Social Research Agency. Data on daily mean, maximum and minimum temperature (computed as the 24-hours average based on hourly measurements) and relative humidity were obtained during the same study period from the Met Eireann and the United Kingdom Meteorological Office.

Spain. We obtained daily data on all causes mortality for the 50 capital cities from the Spain National Institute of Statistics for summer months (from 1st June to 30th September) from 1990 to 2010. Daily minimum, mean and maximum temperatures for the 51 capital cities were collected from the Spain National Meteorology Agency for the same study period. We did not get the data on relative humidity, because it is not available.

Japan. Data on daily deaths for all causes in 47 prefectures between 1st of January 1972 and 31st of December 2012 were collected. Data on daily minimum, mean (computed as the 24-hours average based on hourly measurements) and maximum temperatures and relative humidity were obtained for the same study period.

South Korea (Korea). Data on daily deaths for all causes only in 6 cities between 1st of January 1992 and 31st of December 2010 were collected. Data on daily minimum, mean (computed as the 24-hours average based on hourly measurements) and maximum temperatures and relative humidity were obtained for the same study period.

Australia. We collected data from Melbourne, Sydney and Brisbane between 1st of January 1988 and 31st of

May 2009. Daily mortality, obtained from the Australian Bureau of Statistics, is represented by counts of deaths for non-external causes only (ICD-9: 0-799; ICD-10: A00- R99). Daily minimum, mean (24-hour average) and maximum temperature (in ˚C) and relative humidity (in %) were obtained from the Australian Bureau of Meteorology. We selected all available meteorological stations located within ≤30 km of each city's Central Business District (CBD) (7 stations in Brisbane, 7 stations in Melbourne and 11 stations in Sydney). We calculated the daily averages of climatic variables using all records from meteorological stations in each city. When there was a missing value (≤1.3%) for a particular meteorological station, observations recorded from the remaining weather stations were used to compute the daily average values.

Finland. We collected data from the city of Helsinki between the 1st of January 1994 and 31st of December 2011. Daily mortality, obtained from Statistics Finland, is represented by counts of deaths for all causes. A dataset containing minimum, mean, and maximum daily temperatures was obtained from the Finnish Meteorological Institute. In this dataset, point measurements from the weather measuring stations around the country have been interpolated onto a 10×10 km grid covering the whole of Finland, using a Kriging model. The temperature variables in the Helsinki Temperature Time-series have been extracted from the GIS-database for KKJ-coordinates 6675470:2552920 (KKJ, Finnish National Coordinate System based on ED50). These are the coordinates for weather measuring station Kallion urheilukenttä of Helsinki Region Environmental Services Authority HSY. In total, missing data amount for 0·00% and 0·00% of the mortality and temperature series, respectively.

France. We collected data from 18 cities between 1st of January 2000 and 31st of December 2010. Daily mortality, obtained from the French National Institute of Health and Medical Research (CepiDC), is represented by counts of deaths for all causes. Mean daily temperature (in ˚C), computed as the average between daily minimum and maximum, were obtained from the Meteo France. A single weather station was selected for each city; for 15 out 18 locations the weather station was located at the nearest airport. Two cities (Lille and Lens) have the same temperature series from the same weather station. In total, missing data amount for 0·00% and 0·06% of the mortality and temperature series, respectively.

Mexico. We collected data from 5 metropolitan areas between 1st of January 1998 and 31st of December 2014. Daily mortality, obtained from the National Institute of Statistics, Geography and Informatics is represented by counts of deaths for all causes. Temperature and relative humidity data, were obtained from Servicio Meteorológico Nacional (SMN) and the Instituto Nacional de Ecología y Cambio Climático (INECC). Daily mean temperature as well as the maximum or minimum daily temperature was calculated using hourly data, with a minimum of adequacy of information of 50%. In the case of the data from airports, these were daily averages of temperature and relative humidity. We obtained the maximum and minimum temperatures as well as the average relative humidity across all stations that met the sufficiency criteria of having at least 75% data for the day. In total, missing data account for 0·00% and 26·67% of the mortality and temperature series, respectively.

Moldova. We collected data from the city of Anenii Noi (1st of January 2003 to 31st of December 2010), Cahul (1st of January 2003 to 31st of December 2010), Chisinau (1st of January 2001 to 31st of December 2010), and Falesti (1st of January 2003 to 31st of December 2010). Daily mortality, obtained from the National Centre for Health Management, Moldova, is represented by counts of deaths for all causes. Mean daily temperature (in ˚C) computed as the average between daily minimum and maximum, were obtained from State Hydrometeorological Service, Moldova. A single weather station was selected for each city. In total, missing data amount for 0·00% and 0·00% of the mortality and temperature series, respectively.

Switzerland. We collected data from 8 cities (Basel, Bern, Zurich, Geneva Lausanne, Luzern, Lugano, St Gallen) between 1st January 1995 to 31st December 2013. Lugano also includes the small municipalities around the main city of Lugano with similar altitude. Daily mortality, provided by the Federal Office of Statistics (Switzerland), is represented by counts of deaths for all causes, Daily data on several meteorological indicators were collected from the IDA web database (Federal Office of Meteorology and Climatology, MeteoSwiss). A single weather station located within or near the urban area was selected for each city. The meteorological indicators were: mean daily temperature (in ˚C) and relative humidity (in %), computed as the 24-hour average based on hourly measurements. In total, missing data amount for 0·00% and 0·00% of the mortality and temperature series, respectively.

Taiwan. We collected data in Kaohsiung, Taipei and Taichung between 1st of January 1994 and 31st of December 2014. Daily mortality is represented by counts of deaths for all causes. Mortality data was provided from the National Death Registry of Taiwan. Weather data include daily minimum, maximum, and mean temperature and daily mean relative humidity, and they were measured from a single station in Kaohsiung, two stations in Taichung, and three stations in Taipei. The weather data was provided by the Taiwan Environmental Protection Administration. Weather data were originally hourly measured at various monitoring sites and 24-hour average, maximum, and minimum values were averaged across all monitoring sites for each day in each community. In total, missing data amount for 0.00% and 0.00% of the mortality data and the temperature series, respectively.

Thailand. We obtained daily data on non-accidental deaths from the Ministry of Public Health, Thailand for 61 provinces during 1999–2008. The daily weather data (daily minimum, mean, and maximum temperatures and mean relative humidity) were obtained from the Meteorological Department, Ministry of Information and Communication Technology. There was at least one weather monitoring station in each province.

Argentina. We collected data from the three most populated cities from 2005-2015. Daily all-cause mortality information was provided by the Ministerio de Salud de la Nación (the National Health Ministry). Meteorological data was distributed by the Servicio Meteorológico Nacional (the National Weather Service), measured from one station for each city, with no missing data. Daily mean temperature was calculated from hourly temperature data.

South Africa. We collected data from all 38 district municipalities in South Africa from 1997-2013, inclusive. Daily minimum and maximum temperature was obtained from the Agricultural Research Council of South Africa and the National Oceanographic and Atmospheric Association (NOAA) of the United States. The mortality data was kindly supplied by Statistics South Africa, who had no role in the study design, data analysis or interpretation.

Portugal. We obtained data from two cities in Portugal from 1997 to 2012. Daily mortality, obtained from Statistics Portugal, is represented by counts of deaths for non-external causes only (ICD-9: 0-799; ICD-10: A00-R99). Mean daily temperature was computed as the 24-hour average based on hourly measurements collected from the National Oceanic and Atmospheric Administration (NOAA). In total, missing data amount for 0.0 and 0.1% of the daily mortality and mean temperature, respectively.

Estonia. We collected data from 5 cities between 1st of January 1997 and 31st of December 2015. Daily mortality, obtained from the Estonian Causes of Death Registry, is represented by counts of deaths for all causes. Mean daily temperature (in ˚C) computed as the average of measured temperatures as well as daily minimum and maximum, were obtained from the Estonian Environmental Board, provided by Estonian Weather Service. A single weather station was selected for each city (except Kohtla-Järve and Narva) that were represented by the same weather station). In total, missing data amount for 0·00% and 0·00% of the mortality and temperature series, respectively.

2. Analytical framework details

Observed DTR-mortality risks

The observed DTR-mortality association was analyzed using observed data set and a two-stage time-series approach. Our modelling strategies were based on previous studies investigating the effect of DTR on mortality[4-6].

First-stage analysis. We applied the quasi-Poisson regression separately to the observed data from each community to estimate the community-specific diurnal temperature range (DTR)–mortality association.

$$Y_{obs,t} \sim quasi - Poisson(\lambda_t)$$
$$\log(\lambda_t) = \beta_0 + s(\mathbf{DTR}_{obs,t}; \boldsymbol{\eta}) + g(\mathbf{T}_{obs,t}; \psi) + factor(DOW_t) + ns(Time, df = 8\ /years)$$

where $\mathbf{DTR}_{obs,t}$=$(DTR_{obs,t}, DTR_{obs,t-1}, \ldots, DTR_{obs,t-L})$ be the vector of daily observed DTR on day *t* and over the previous *L* days. And $Y_{obs,t}$ is the observed death count on day *t*, λ_t is the expected death count on day *t*, and β_0 is an intercept. $s(\cdot)$ is a flexible function (spine with two equally spaced knots on the log scale for lag-mortality relation with maximum lag of 14 days (L)) characterized by parameter $\boldsymbol{\eta}$ to depict the non-linear lagged effects of DTR on mortality.). $g(\mathbf{T}_{obs,t}; \psi)$ is a cross-basis function of daily observed mean temperature (on day *t* and over the previous *l* days**)** with a quadratic B-spline with three internal knots (10th, 75th, and 90th percentiles of location-specific temperatures) for temperature dimension and a natural cubic B-spine with an intercept and three equally spaced knots on the log scale for lag dimension with maximum lag of 21 days (*l*). Long-term trend and seasonality were adjusted using a natural cubic B-spline of time with 8 degrees of freedom (df) per year, and day of the week was included as an indicator variable.

Second-stage analysis. The community-specific associations (lag-cumulative one by a single coefficient; η^*) were pooled using multivariate meta-analysis. Multivariate random-effect meta-regression was used to pool the parameters by country. We used indicators of country as predictors in the meta-regression to country-pooled estimates and city-specific predicted parameters (Best Linear Unbiased Prediction, BLUP; η_b^*). We found indications for residual heterogeneity, with a 33.3% I^2 index. An I^2 index was 34.3% in a meta-analysis performed without country indicators.

Excess mortality. The overall lag-cumulative (up to 14 lag days) relative risk estimated from BLUP for each city was used to compute the daily relative risk and attributed number of deaths, using 0°C DTR as the reference. The total number of deaths attributed to DTR was calculated as the sum of all days in the series, and could be interpreted as excess mortality due to exposure to the entire range of DTRs. The daily attributable mortality was aggregated for time periods and locations, and then the corresponding attributable fraction was calculated as the ratio using the corresponding total number of deaths.

The total number of deaths attributed to DTR was calculated as the sum of all days in the series when DTR contributed to death and its ratio with the total number of deaths; this provides the 'total attributable fraction'

Estimation of the excess mortality

For each day of the series of each community, we computed the number of deaths attributed to the whole range of DTR, D_{attr} for each period and for each warming hypothesis as:

Current: $(1 - \exp(-(\eta_b^* * DTR_{mod}))) * D_{obs}$

Future: without interactive effect of temperature: $(1 - \exp(-(\eta_b^* * DTR_{mod}))) * D_{mod}$

Future: with interactive effect of temperature: $(1 - \exp(-(\eta_b^* + \hat{\theta} * T_{avg}) * DTR_{mod}))) * D_{mod}$

where DTR_{mod} is a modeled and recalibrated DTR during the current and future periods from GCM-ensemble (current: country-specific study period, future: 2020 to 2099) and η_b^* is the city-specific predicted parameters (BLUPs; overall cumulative DTR-mortality association over 14 lag-days). Projected death D_{mod} is the average observed counts for each day of the year; thus, the projected DTR impact must be interpreted under a scenario with no population changes. $\hat{\theta}$ is an estimated increase in DTR-mortality risk per 1°C increase in average temperature (T_{avg}) using a linear mixed effect model described subsequently (Increase in DTR-mortality risk by average temperature).

Increase in DTR-mortality risk by long-term average temperature (Interaction between the long-term temperature and DTR)

In order to estimate the association between DTR-mortality risk and long-term average temperature ($\hat{\theta}$) and the corresponding variance, we applied a linear mixed effect model, which allowed for simultaneous consideration of spatio-temporal variation in the DTR-mortality risk, long-term average temperature, and other predictors. Firstly, to derive the time-varying DTR-mortality relationship, we added a linear interaction term between the $s(\mathbf{DTR}_{obs,t};\boldsymbol{\eta})$ and time, adopted in a previous multi-country study[4]. The previous study showed that the DTR-mortality risk has increased over recent decades in eight of the total ten countries/regions. Then, we derived lag-cumulative coefficients (which represents the DTR-mortality risk) and the corresponding variances at the mid-point (1 July, as a centering point) for each five-year period (1985-1989/1990-1994/1995-1999/2000-2004/ 2005-2009/2010-2014) within each community's study period. Details of the centering points of each community are presented in the following table.

Country/region	# of community	Study period	Centering points (1 July)
Argentina	3	2005-2015	2007, 2012
Brazil	18	1997-2011	1997, 2002, 2007
Mexico	5	1998-2014	2002, 2007, 2012
United States	132	1985-2006	1987, 1992, 1997, 2002
Canada	25	1986-2011	1987, 1992, 1997, 2002, 2007
Korea	6	1992-2010	1992, 1997, 2002, 2007
Japan	47	1985-2015	1987, 1992, 1997, 2002, 2007, 2012
Taiwan	3	1994-2014	1997, 2002, 2007, 2012
Thailand	61	1999-2008	2002, 2007
Australia	3	1988-2009	1992, 1997, 2002, 2007
South Africa	38	1997-2013	1997, 2002, 2007, 2012
Spain	50	1990-2010	1992, 1997, 2002, 2007
Portugal	2	1985-2012	1987, 1992, 1997, 2002, 2007, 2012
France	18	2000-2010	2002, 2007
Switzerland	8	1995-2013	1997, 2002, 2007, 2012
Moldova	4	2001-2010	2002, 2007
Estonia	5	1997-2015	1997, 2002, 2007, 2012
Finland	1	1994-2011	1997, 2002, 2007
United Kingdom	10	1990-2012	1992, 1997, 2002, 2007, 2012
Ireland	6	1985-2007	1987, 1992, 1997, 2002, 2007

We also calculated the community-specific average temperatures for five years (if impossible due to data period, then three or four years) before and after each centering point. Then, we applied linear mixed effect models with country indicators, community-specific random intercepts, overall and community-specific time trend (both linear) adjustment, and other confounders/covariates, and then we adopted the main model by considering the goodness of fit test results (R^2 and AIC (Akaike Information Criterion)). The model selection results are displayed in Table A2. The inverse of the variances of the DTR risk was used as weight. In addition, under the independent assumption, the variance of $\eta_b^* + \hat{\theta} * T_{avg}$ was calculated as sum of variances of η_b^* and $\hat{\theta} * T_{avg}$.

Finally, the final mixed effect model includes an average temperature, country indicator variables, year, and average DTR as fixed effect terms, and also community specific intercept (random intercept), community specific year trend (random intercept), community specific slope for long-term average temperature (random slope), and community specific slope for year (random slope) as random effect terms.

3. Reliability of recalibration method

Table S1. Distributions of observed and modeled daily DTR during the current period (study period for each country). Data constitute average mean and standard deviation (SD) country/region-specific DTR (range). GCM-ensemble DTR was used as modeled DTR. GCM=general circulation model. All countries are arranged in order of latitudes within each region.

		Mean		**SD**	
	Study period	**Observed**	**Modeled**	**Observed**	**Modeled**
Total	1985-2015	10.20 (4.2-19.09)	10.20 (4.05-19.09)	3.56 (1.31-6.14)	2.19 (0.8-4.18)
North America					
Canada	1986-2011	10.04 (7.07-12.77)	10.04 (7.06-12.72)	4.17 (2.68-5.19)	2.41 (1.68-2.81)
United States	1985-2006	10.94 (6.85-15.86)	10.93 (6.86-15.84)	3.92 (1.77-5.36)	2.24 (1.10-4.11)
Central America					
Mexico	1998-2014	13.12 (9.84-16.13)	13.11 (10.02-16.24)	3.94 (3.20-5.02)	2.58 (1.59-3.13)
South America					
Brazil	1997-2011	8.87 (6.12-12.49)	8.85 (6.09-12.49)	2.32 (1.31-3.71)	1.46 (0.80-2.65)
Argentina	2005-2015	11.51 (9.45-12.81)	11.50 (9.45-12.86)	3.82 (3.09-4.20)	1.85 (1.55-2.14)
East Asia					
Korea	1992-2010	8.14 (6.79-9.43)	8.17 (6.85-9.44)	3.05 (2.36-3.66)	2.05 (1.72-2.33)
Japan	1985-2015	8.33 (4.88-10.57)	8.35 (4.89-10.61)	3.06 (1.50-3.78)	1.82 (1.28-2.34)
South-East Asia					
Taiwan	1994-2014	7.59 (6.99-8.22)	7.57 (6.92-8.18)	2.56 (2.36-2.94)	1.66 (1.35-2.17)
Thailand	1999-2008	9.78 (4.20-12.47)	9.76 (4.05-12.59)	2.74 (1.58-4.52)	2.16 (1.09-4.12)
Oceania					
Australia	1988-2009	8.19 (7.39-8.84)	8.21 (7.43-8.85)	3.19 (2.85-3.48)	1.85 (1.67-1.96)
Northern Europe					
Finland	1994-2011	6.09 (-)	6.08 (-)	3.01 (-)	1.96 (-)
Estonia	1997-2015	7.62 (7.08-8.01)	7.61 (7.06-7.99)	4.21 (3.75-4.51)	2.69 (2.43-2.86)
Ireland	1985-2007	6.69 (5.87-7.89)	6.68 (5.87-7.87)	2.56 (1.89-3.13)	1.62 (1.35-1.90)
United Kingdom	1990-2012	7.28 (6.72-7.84)	7.28 (6.72-7.84)	2.85 (2.41-3.18)	1.86 (1.57-2.16)
Central Europe					
Moldova	2001-2010	9.69 (8.42-10.72)	9.67 (8.40-10.7)	4.41 (3.68-5.18)	2.88 (2.53-3.13)
Switzerland	1995-2013	7.56 (6.19-8.79)	7.55 (6.18-8.78)	3.52 (2.76-4.10)	2.24 (1.59-2.61)
France	2000-2010	8.43 (4.66-10.91)	8.43 (4.67-10.92)	3.62 (2.03-4.71)	2.24 (1.08-2.89)
Southern Europe					
Spain	1990-2010	10.61 (5.84-15.38)	10.64 (5.85-15.60)	3.78 (1.63-5.51)	2.35 (1.04-3.54)
Portugal	1985-2012	8.40 (8.00-8.80)	8.41 (8.01-8.82)	3.29 (3.18-3.40)	1.91 (1.84-1.97)
South Africa					
South Africa	1997-2013	14.32 (6.82-19.09)	14.35 (6.86-19.09)	4.42 (2.40-6.14)	2.57 (1.31-4.18)

Table S2. Number of days (frequency) of negative DTRs projected over the period ranging from 2020 to 2099. GCM-ensembles were used.

RCP2.6	RCP4.5	RCP6.0	RCP.5
2 days (0.006%) - Helsinki (Finland) - Jaen (Spain) - St. Gallen (Switzerland) - Barstable-Yarmouth, MA (United States) **1 day (0.003%)** - San Sebastian (Spain) - Atlantic City, NJ (United States) Brownsville, TX (United States)	**2 days (0.006%)** - Boston, MA (United States) **1 day (0.003%)** - Melilla (Spain) - St. Gallen (Switzerland)	**1 day (0.003%)** - Helsinki (Finland) - San Sebastian (Spain) - Lausanne (Switzerland) - St. Gallen (Switzerland) - Barstable-Yarmouth, MA (United States) - Boston, MA (United States)	**2 days (0.006%)** - St. Gallen (Switzerland) - Boston, MA (United States) **1 day (0.003%)** - Jaen (Spain) - Barstable-Yarmouth, MA (United States) - Cleveland, OH (United States) - Youngstown-Warren, OH (United States)

4. Supplementary Figures and Tables

Figure S1. The geographical distributions of the 445 communities within 20 countries/regions. Data are average values of diurnal temperature range (DTR).

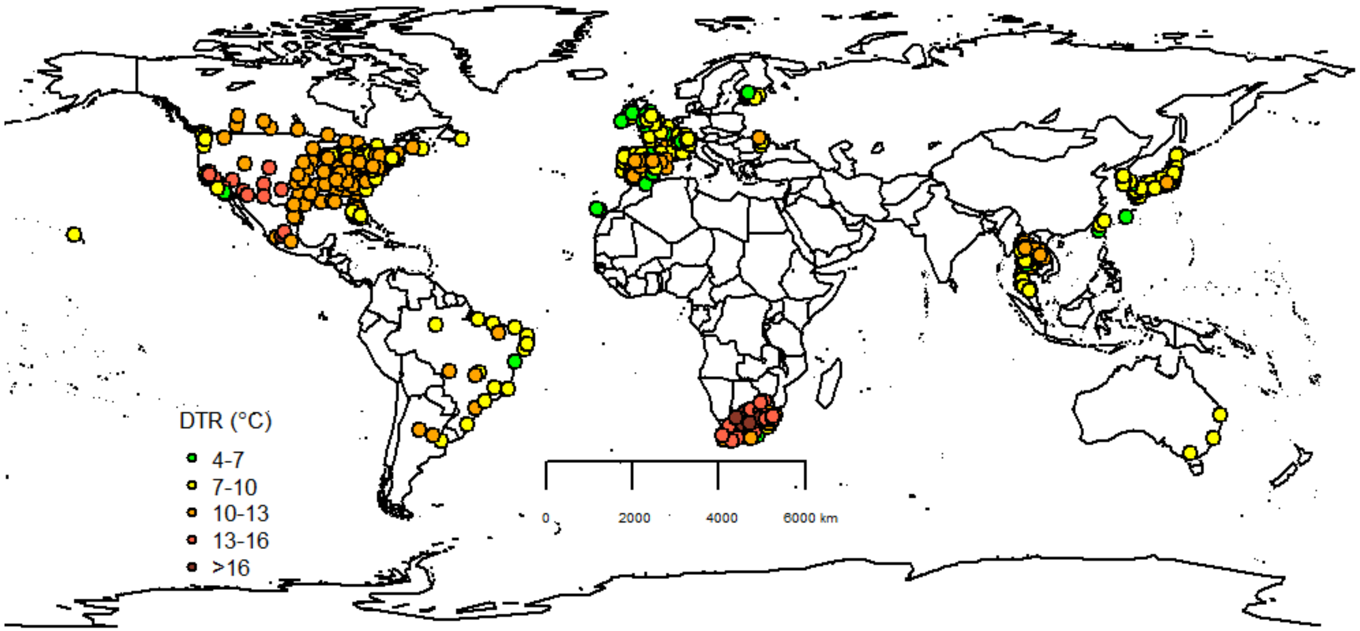


Table S3. Distribution of DTR and daily mean temperature (Tmean) for each country/region by seasons (warm: warmest four months, cold: coldest four months, and moderate: remainder of the year). Values: Mean (average inter quartile range; average IQR).

	Whole		Warm		Moderate		Cold	
	DTR	**Tmean**	**DTR**	**Tmean**	**DTR**	**Tmean**	**DTR**	**Tmean**
North America								
Canada	10.0 (6.1)	6.8 (16.6)	11.3 (5.2)	17.4 (5.2)	10.1 (6.3)	7.0 (7.5)	8.7 (5.4)	-4.2 (8.8)
USA	10.9 (5.4)	14.8 (13.8)	11.2 (4.0)	23.3 (4.2)	11.4 (5.7)	14.8 (6.9)	10.2 (5.8)	6.2 (7.0)
Central America								
Mexico	13.1 (5.6)	18.3 (4.6)	13.0 (5.1)	21.1 (2.9)	12.1 (5.2)	18.6 (2.3)	14.3 (5.2)	15.2 (3.6)
South America								
Brazil	8.9 (3.2)	24.6 (2.8)	9.0 (2.7)	26.1 (1.8)	8.6 (3.1)	24.7 (2.0)	8.9 (3.2)	23.0 (2.1)
Argentina	11.5 (5.3)	18.2 (9.5)	11.6 (4.4)	23.7 (4.3)	11.6 (5.4)	18.5 (5.5)	11.3 (6.3)	12.4 (5.5)
East Asia								
Korea	8.1 (4.2)	13.6 (16.3)	7.1 (3.8)	23.7 (4.3)	9.2 (4.5)	14.0 (6.7)	8.2 (3.9)	3.1 (6.2)
Japan	8.3 (4.2)	15.4 (14.6)	7.7 (3.6)	24.5 (4.9)	9.1 (4.6)	15.4 (5.7)	8.2 (4.0)	6.2 (4.3)
South-East Asia								
Taiwan	7.6 (3.5)	23.6 (8.0)	7.5 (2.5)	28.4 (2.2)	7.4 (3.4)	24.2 (3.7)	7.9 (4.3)	18.2 (4.4)
Thailand	9.8 (3.8)	27.6 (2.5)	9.7 (3.0)	29.0 (1.8)	8.6 (2.5)	28.0 (1.5)	11.1 (3.4)	25.7 (2.8)
Oceania								
Australia	8.2 (4.0)	18.1 (6.5)	7.7 (3.5)	22.2 (3.7)	8.3 (3.9)	18.1 (3.8)	8.6 (4.0)	14.0 (3.0)
Northern Europe								
Finland	6.1 (4.5)	6.2 (13.5)	7.0 (3.7)	15.5 (4.9)	6.0 (4.4)	5.7 (6.3)	5.2 (4.1)	-2.8 (6.5)
Estonia	7.6 (6.3)	6.2 (13.8)	9.5 (5.5)	15.5 (4.7)	7.7 (6.2)	6.0 (6.8)	5.7 (4.8)	-2.9 (7.0)
Ireland	6.7 (3.4)	9.7 (6.8)	7.5 (3.1)	14.2 (2.9)	6.9 (3.5)	9.2 (4.0)	5.7 (3.4)	5.8 (3.8)
UK	7.3 (3.9)	10.3 (8.0)	8.5 (3.9)	15.6 (3.3)	7.4 (3.8)	9.9 (4.4)	5.9 (3.1)	5.4 (4.4)
Central Europe								
Moldova	9.7 (7)	10.7 (15.8)	12.2 (4.9)	20.6 (5.2)	9.9 (6.9)	10.8 (7.3)	7.0 (5.4)	0.5 (7.2)
Switzerland	7.6 (5.4)	10.4 (12.0)	9.0 (4.8)	17.9 (5.2)	8.2 (5.4)	10.4 (6.4)	5.4 (3.8)	2.9 (5.8)
France	8.4 (5.2)	12.6 (10.4)	10.0 (5.0)	19.4 (4.4)	8.6 (5.1)	12.4 (5.6)	6.6 (4.1)	5.9 (5.8)
Southern Europe								
Spain	10.6 (5.6)	15.5 (10.2)	12.2 (4.4)	22.2 (4.4)	10.7 (5.3)	14.7 (5.0)	8.9 (5.0)	9.4 (4.1)
Portugal	8.4 (4.4)	15.9 (7.1)	9.6 (4.5)	20.5 (2.9)	8.1 (4.0)	15.5 (4.1)	7.5 (4.1)	11.6 (3.8)
South Africa								
South Africa	14.3 (6.2)	17.9 (7.7)	13.2 (4.9)	22.1 (3.4)	14.3 (6.2)	18.5 (4.7)	15.5 (5.7)	13.2 (4.2)

Figure S2. Decadal changes in projected average DTR (compare to the baseline period: 2010-2019) by seasons (warm [red]: warmest four months, cold [blue]: coldest four months, and moderate [orange]: other months) during the period 2010-2099. X-axis: 2010-19, 2020-29, …, 2099-2099). Y-axis: average DTR (°C). RCP 8.5 was used.

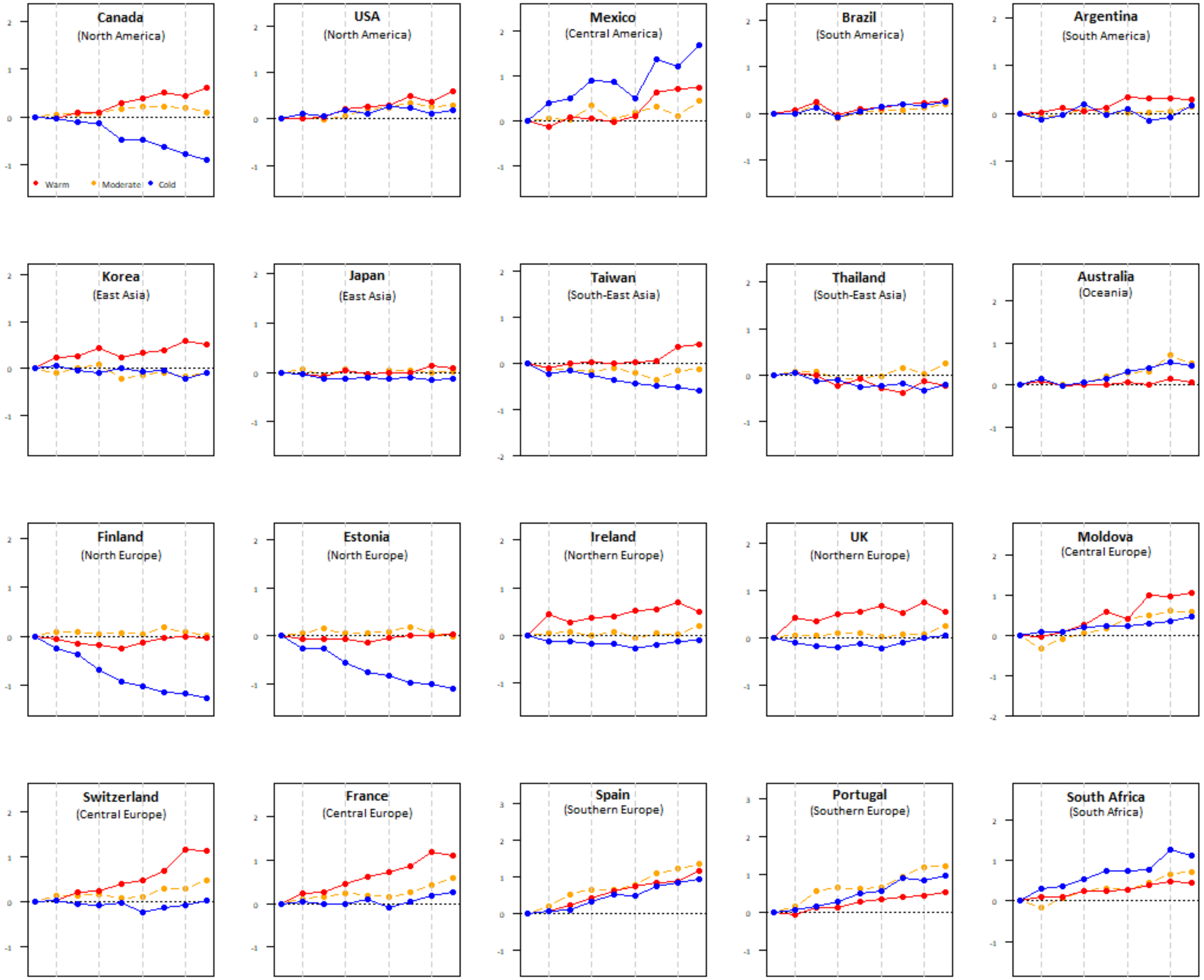


Figure S3. The community-specific DTR changes between 2010-2019 and 2090-2099 by RCP scenarios (RCP2.6 and RCP8.5). Data are differences in averages of diurnal temperature range (DTR) across all seasons as GCM-ensemble. RCP=representative concentration pathway. GCM=general circulation model.

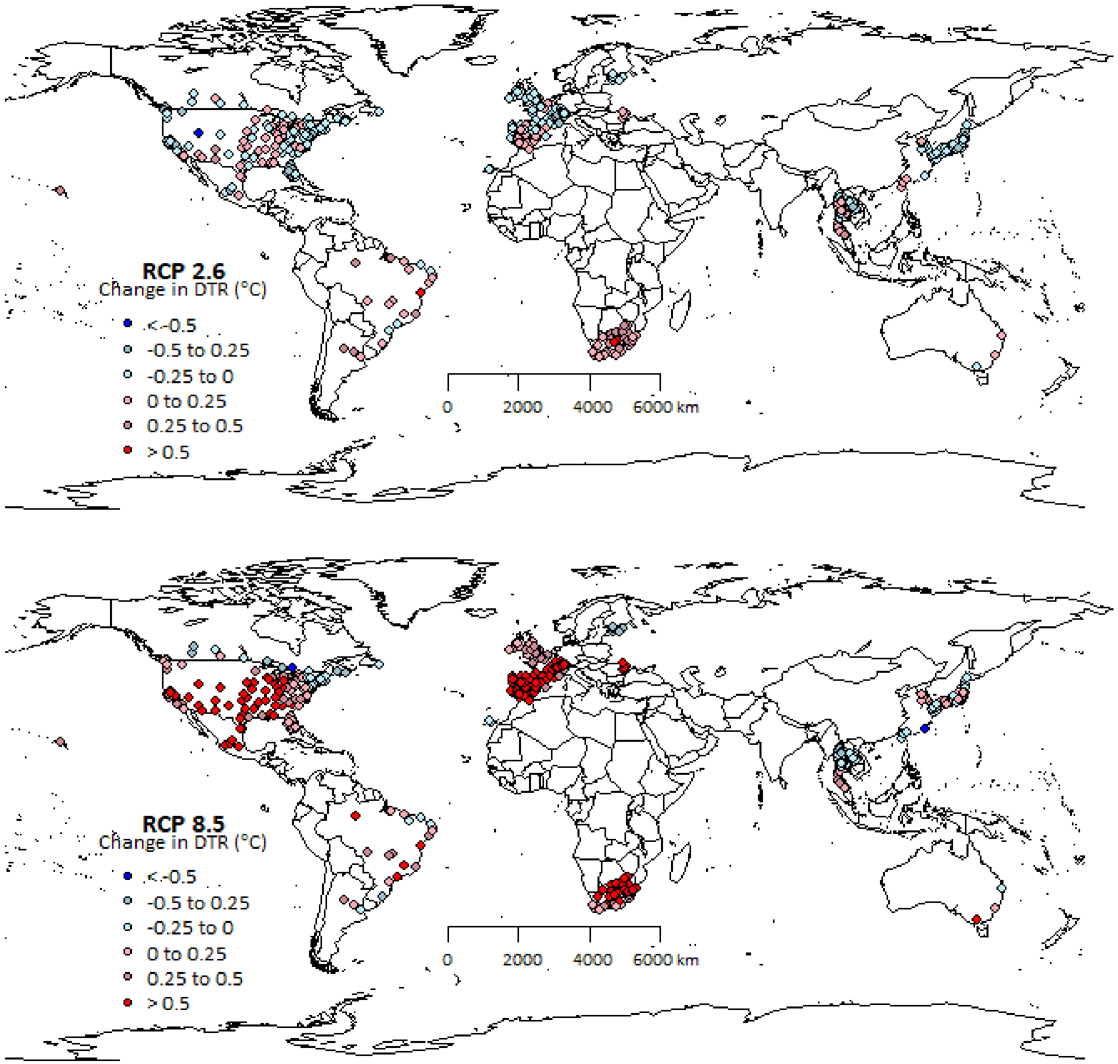


Figure S4. The decadal trend of projected average DTR (°C) by four RCPs and country/region during the period 2010-2099. Data area average mean country/region-specific DTR as GCM-ensemble. DTR=diurnal temperature range, RCP=representative concentration pathway. GCM=general circulation model. Y-axis is °C.

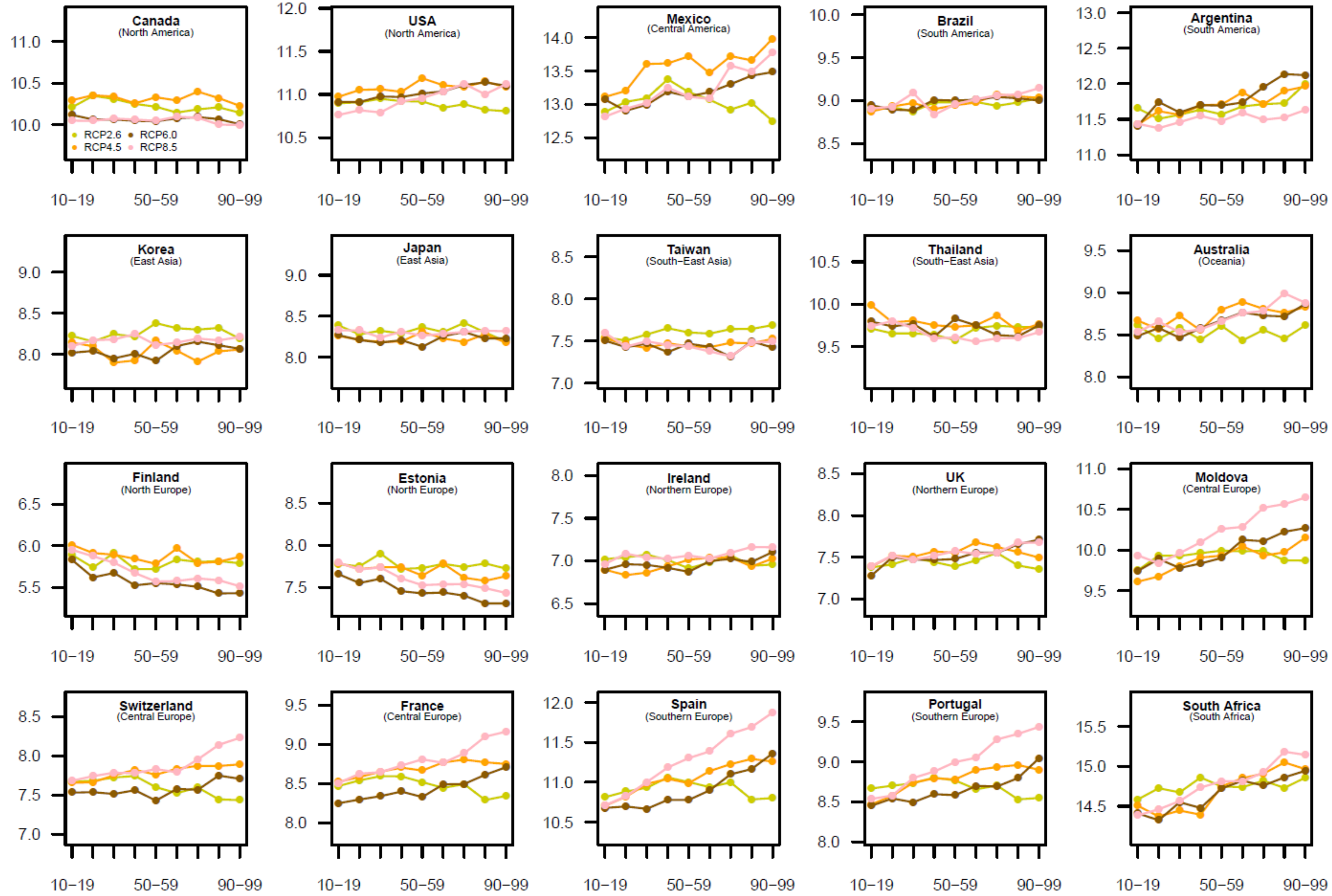


Figure S5. The decadal trend of projected average temperature (°C) by four RCPs and country/region during the period 2010-2099. Data area average mean country/region-specific DTR as GCM-ensemble. RCP=representative concentration pathway. GCM=general circulation model. Y-axis is °C.

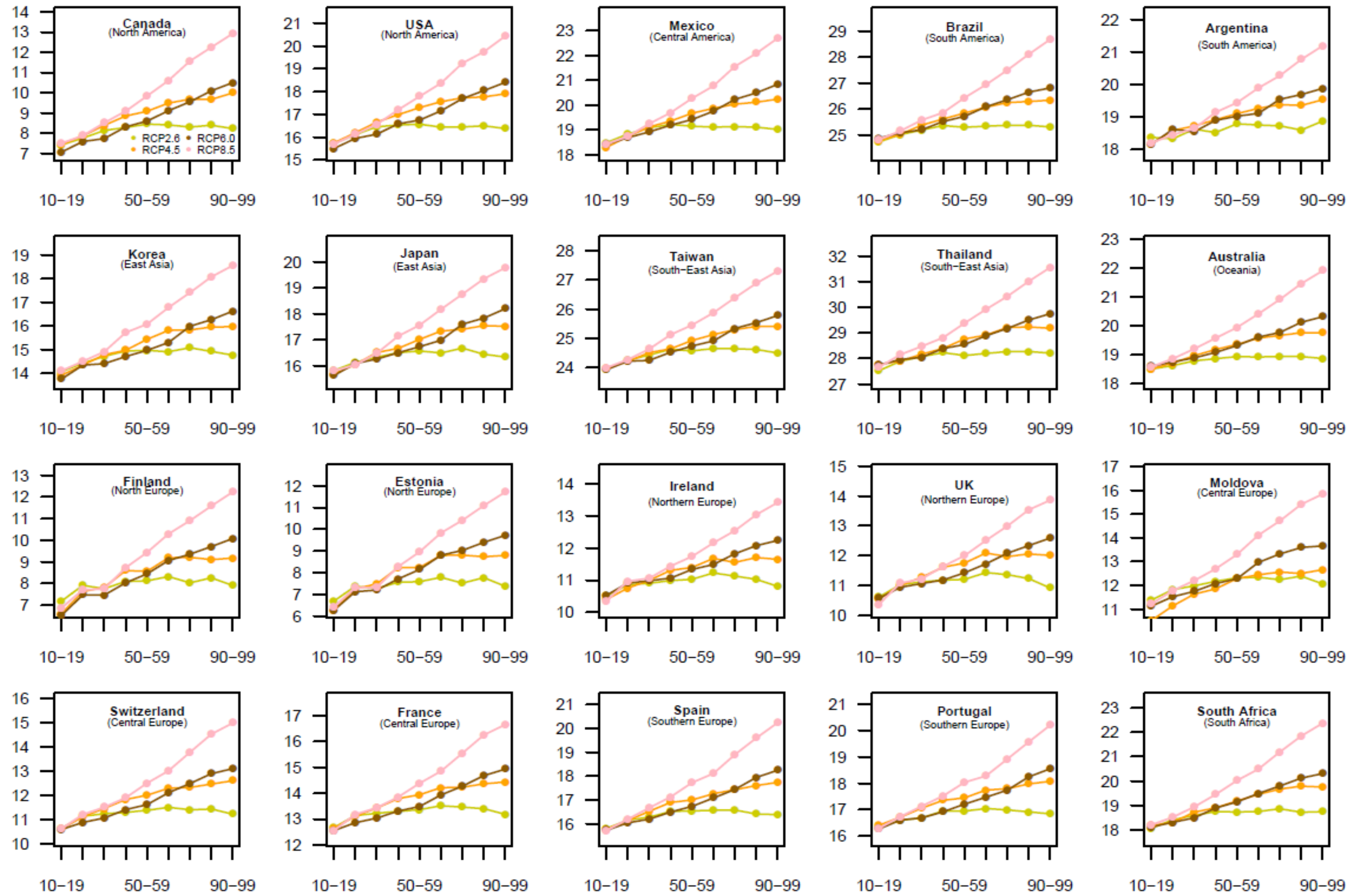


Figure S6. Distribution of the community-specific coefficients of temperature by the linear mixed model. The parameters were predicted by a random slope term of average temperature.

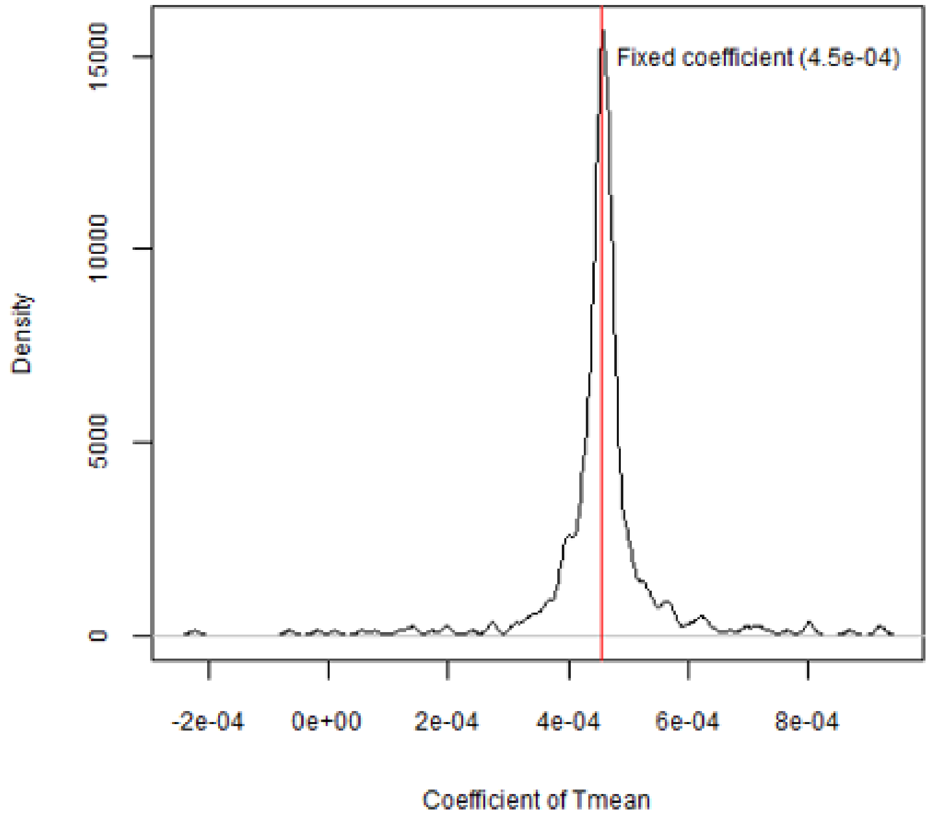
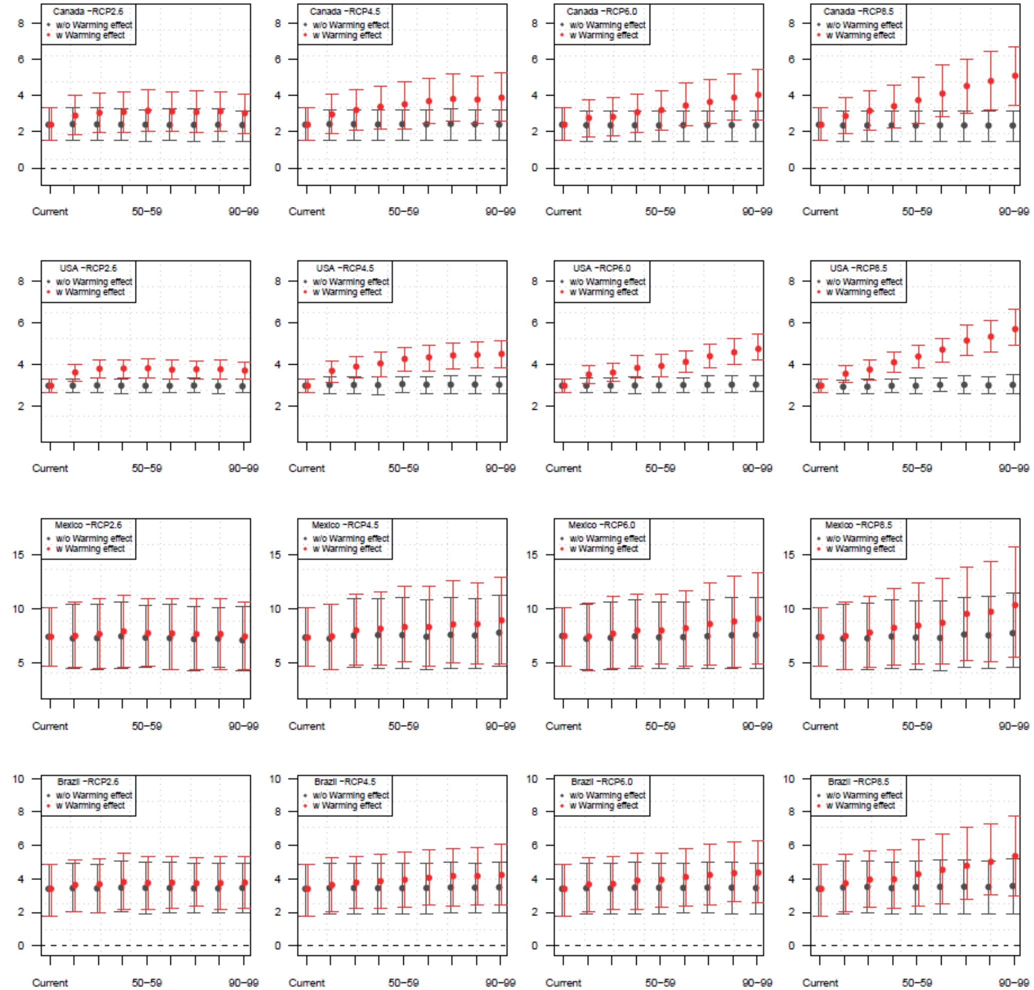
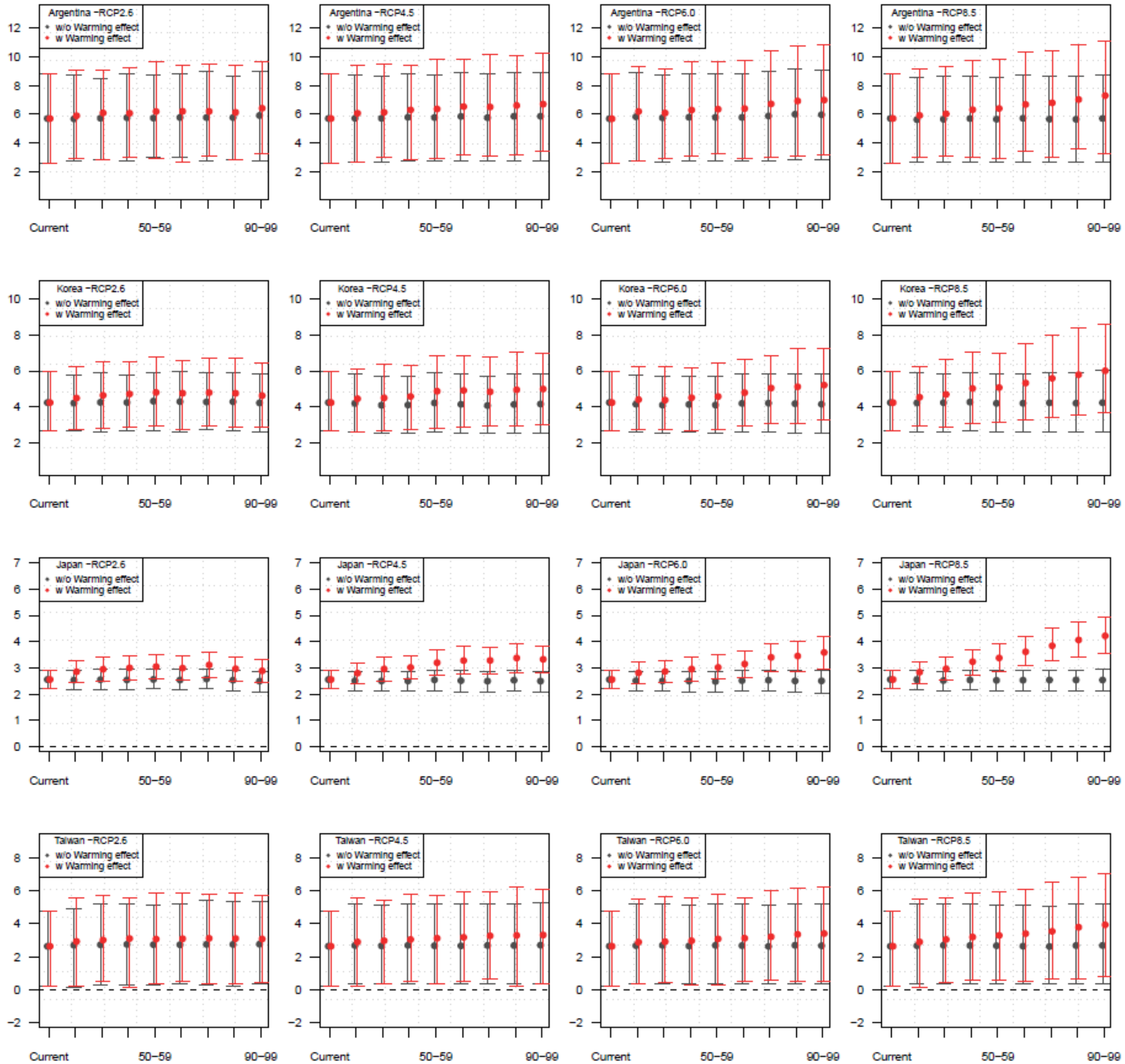
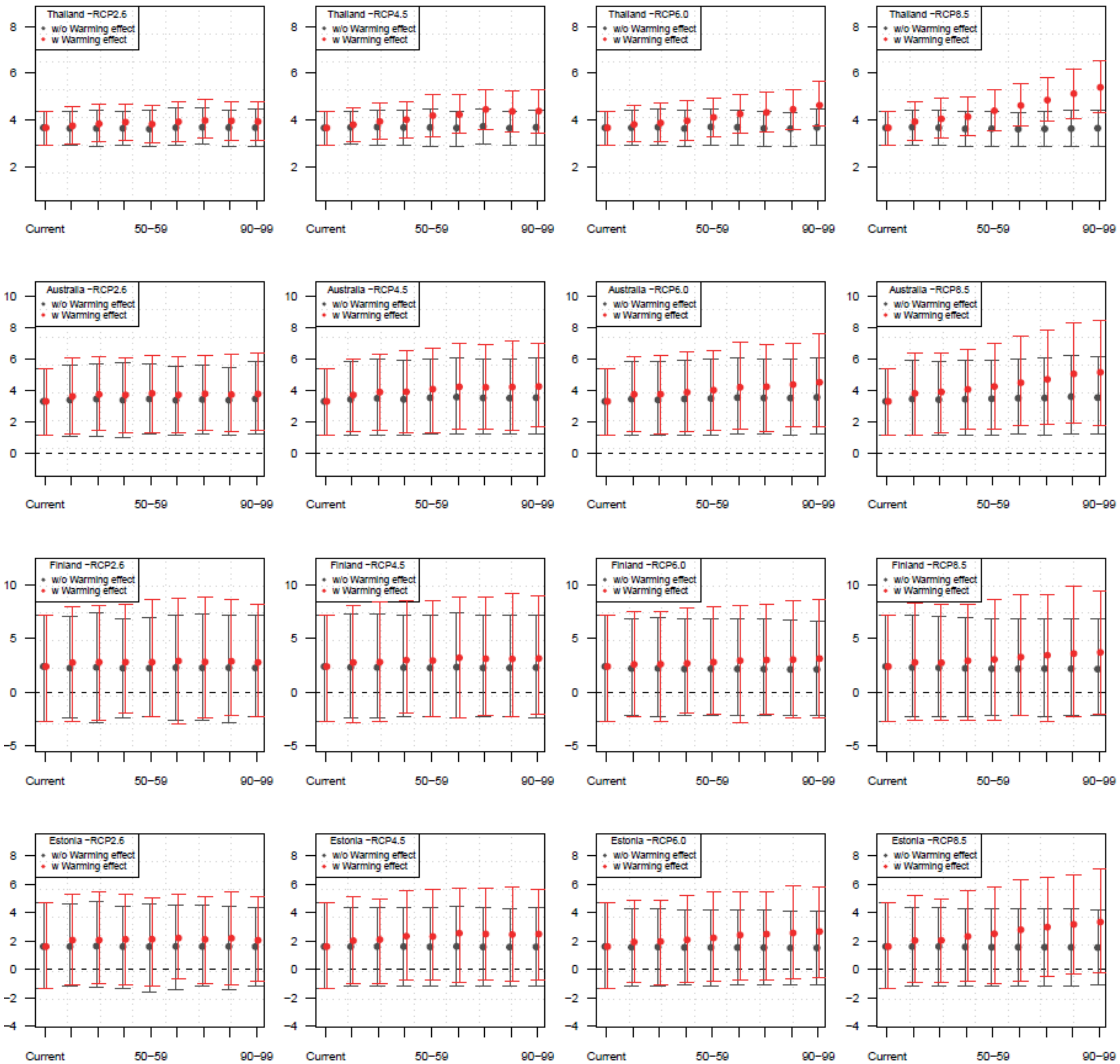


Figure S7. The projected DTR-related excess mortality 'without an interactive effect with long-term temperature (grey; w/o warming effect)' or 'with an interactive effect with long-term temperature (red; with warming effect) by RCPs. Results are estimated using GCM-ensemble. Vertical lines: 95% eCI. X-axis: Period from the current to 2099 by decade. Unit of Y-axis: %. GCM-ensemble. DTR=diurnal temperature range, RCP=representative concentration pathway. GCM=general circulation model.




Argentina -RCP2.6
Argentina -RCP4.5
Argentina -RCP6.0
Argentina -RCP8.5
Korea -RCP2.6
Korea -RCP4.5
Korea -RCP6.0
Korea -RCP8.5
Japan -RCP2.6
Japan -RCP4.5
Japan -RCP6.0
Japan -RCP8.5
Taiwan -RCP2.6
Taiwan -RCP4.5
Taiwan -RCP6.0
Taiwan -RCP8.5
w/o Warming effect
w Warming effect
Current
50–59
90–99


Thailand -RCP2.6
Thailand -RCP4.5
Thailand -RCP6.0
Thailand -RCP8.5
Australia -RCP2.6
Australia -RCP4.5
Australia -RCP6.0
Australia -RCP8.5
Finland -RCP2.6
Finland -RCP4.5
Finland -RCP6.0
Finland -RCP8.5
Estonia -RCP2.6
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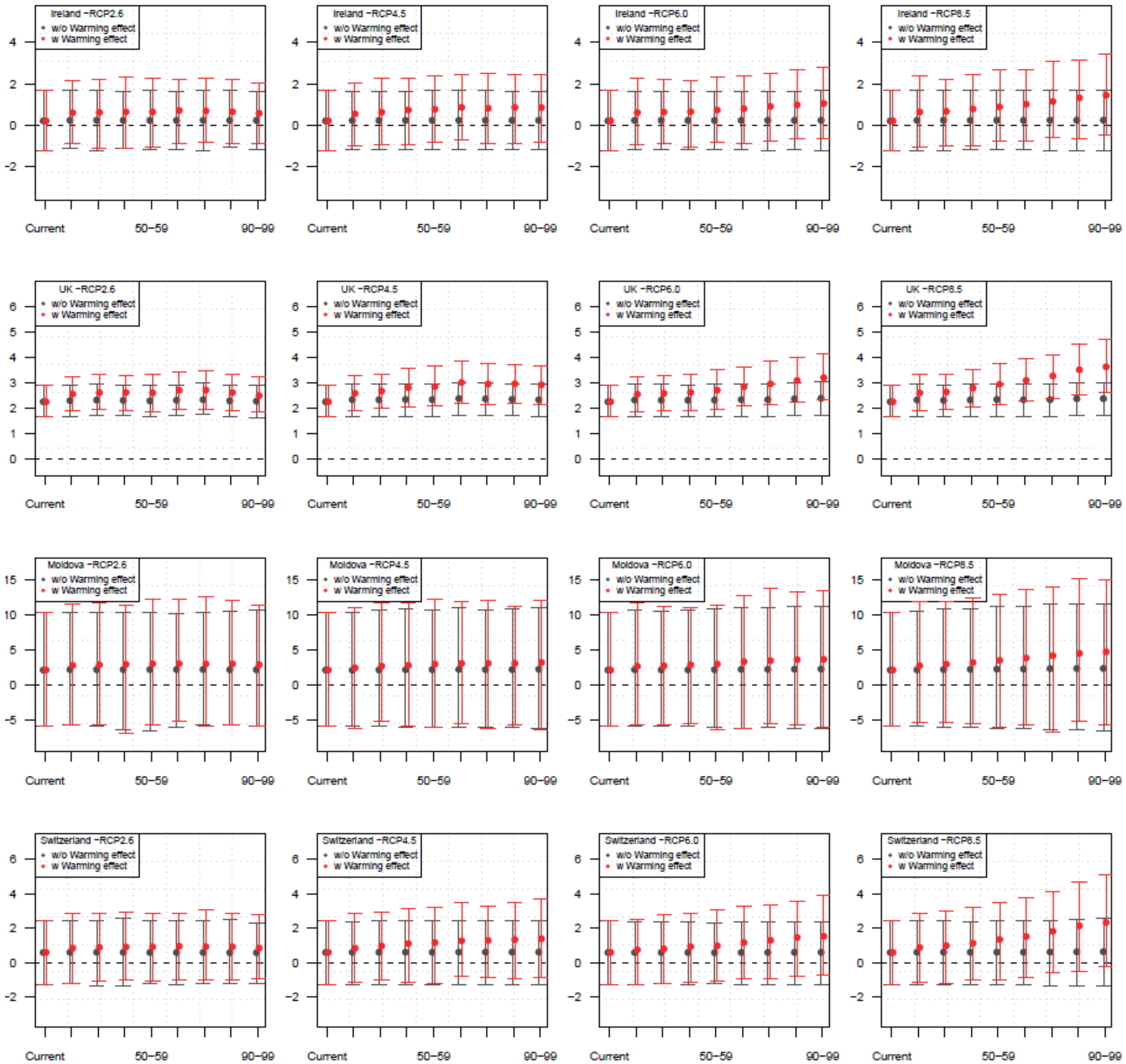
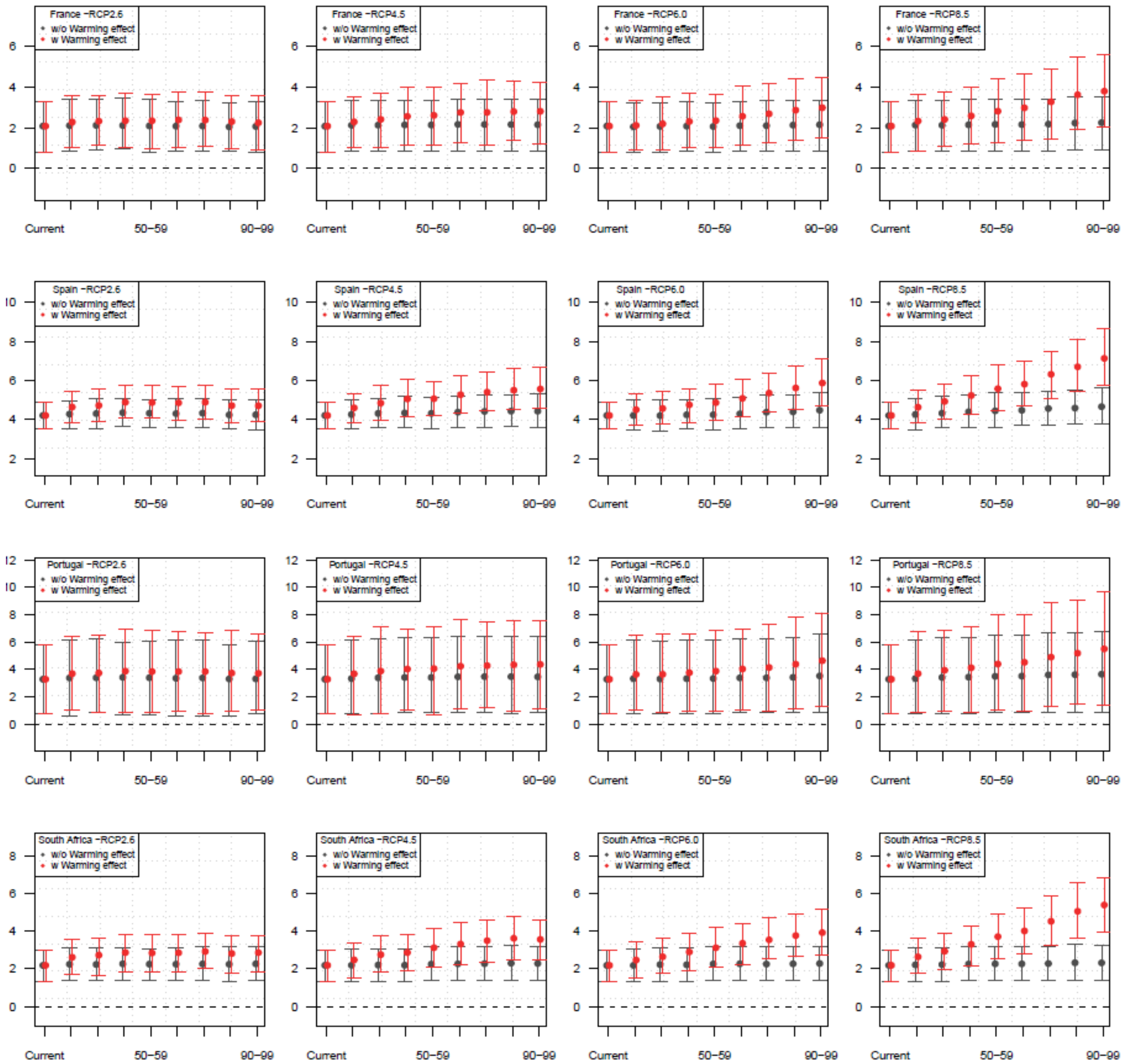
Estonia -RCP8.5
w/o Warming effect
w Warming effect
Current
50–59
90–99



Ireland -RCP2.6
w/o Warming effect
w Warming effect
Ireland -RCP4.5
Ireland -RCP6.0
Ireland -RCP8.5
UK -RCP2.6
UK -RCP4.5
UK -RCP6.0
UK -RCP8.5
Moldova -RCP2.6
Moldova -RCP4.5
Moldova -RCP6.0
Moldova -RCP8.5
Switzerland -RCP2.6
Switzerland -RCP4.5
Switzerland -RCP6.0
Switzerland -RCP8.5
Current
50-59
90-99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France -RCP6.0
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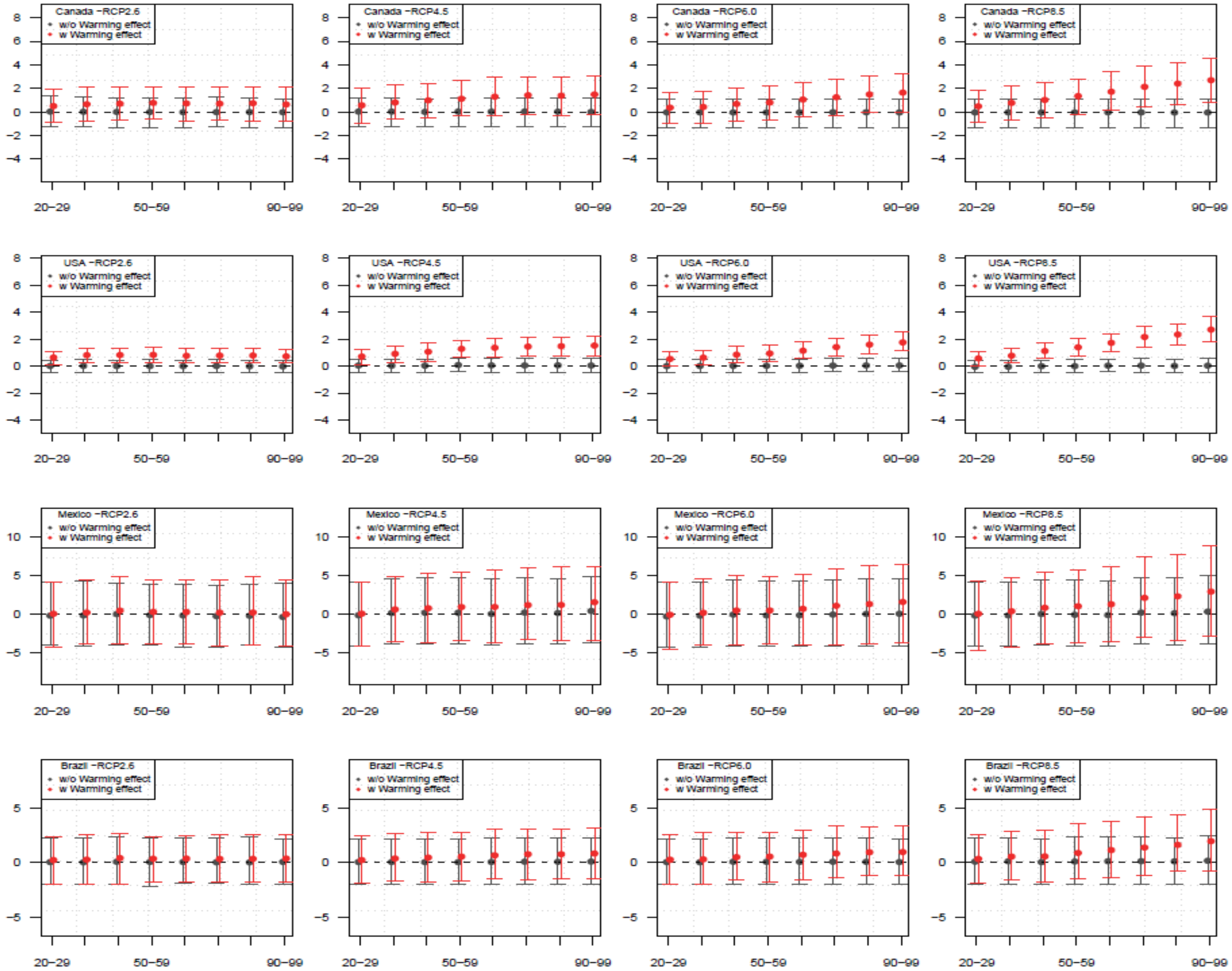
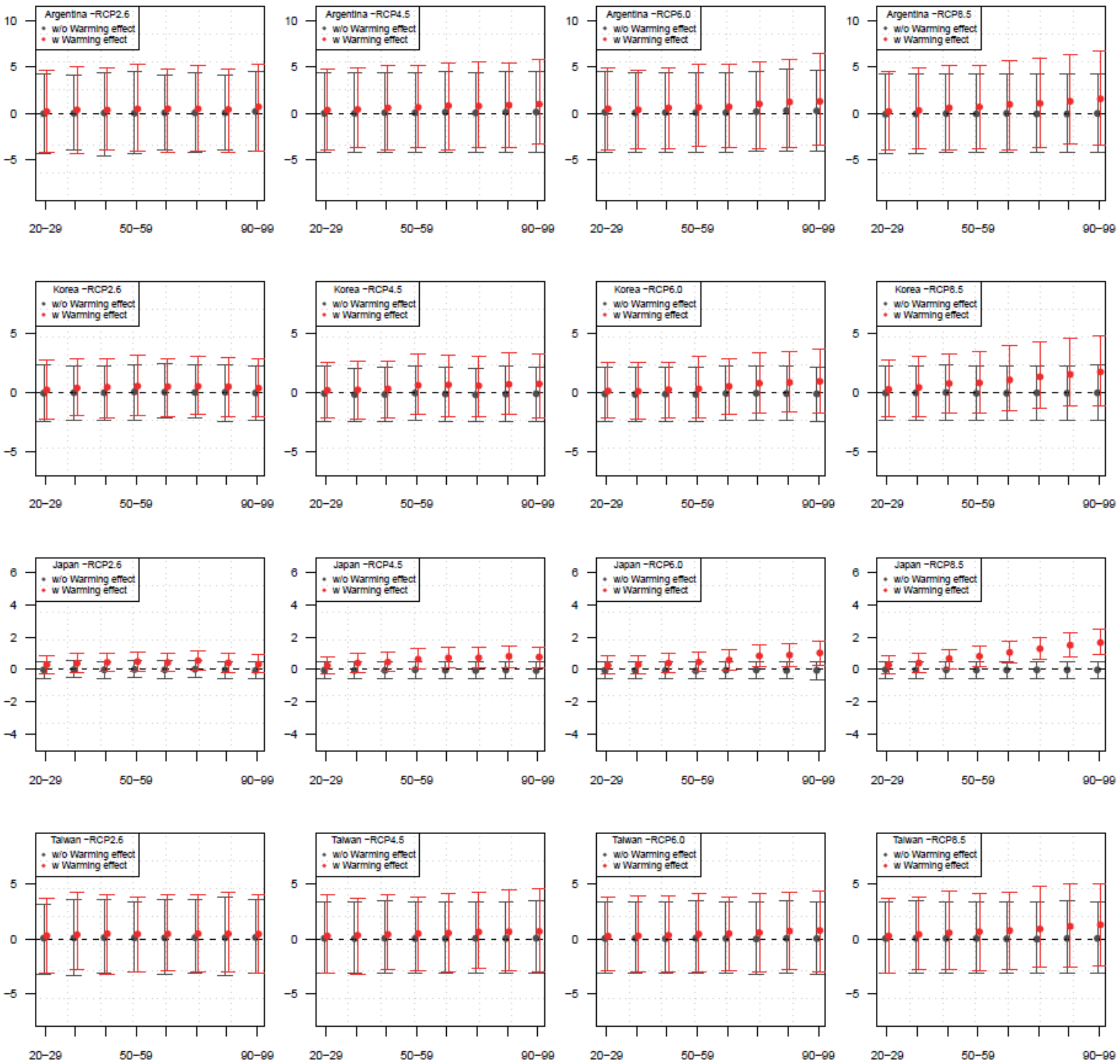
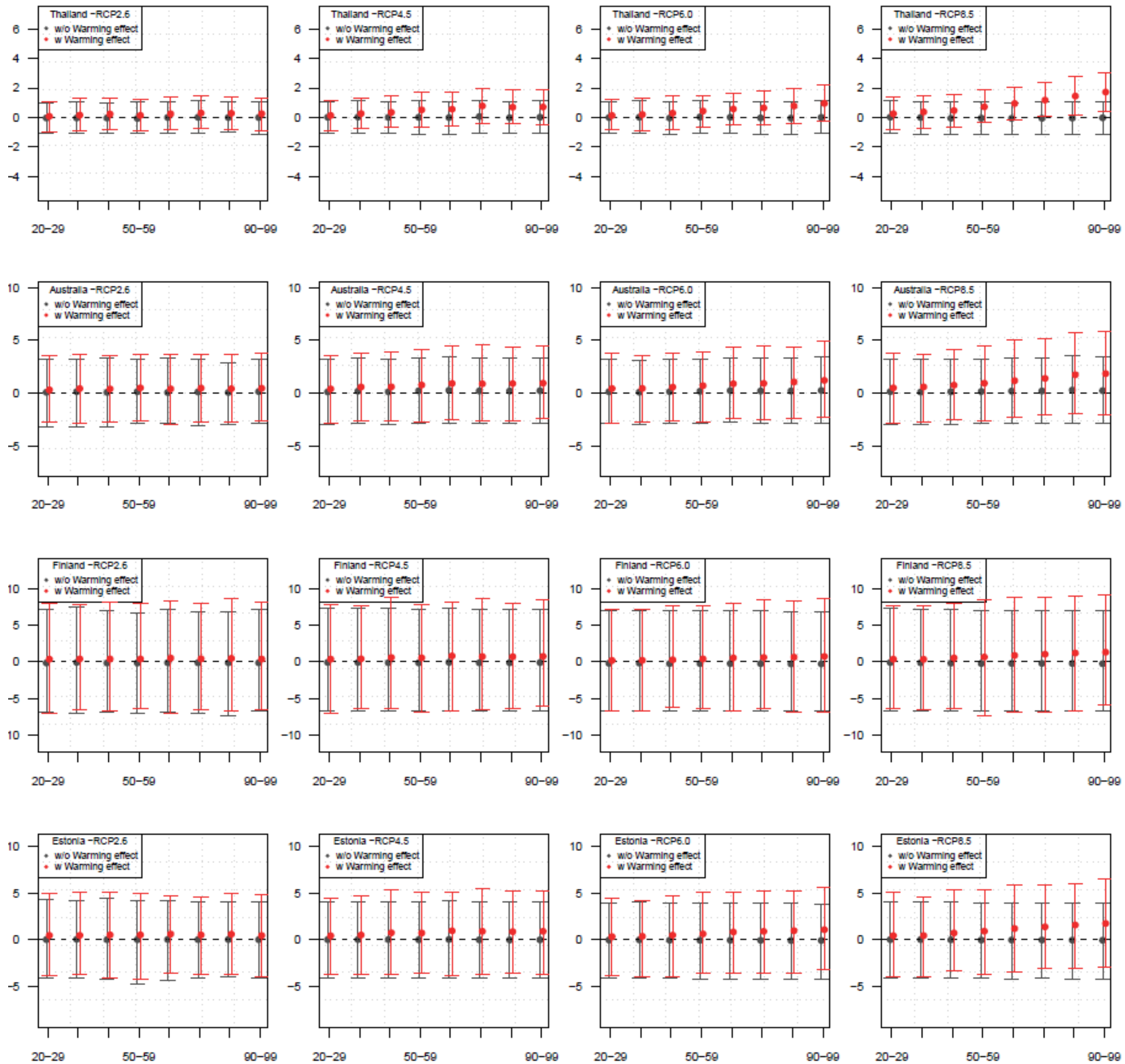
Spain -RCP4.5
Spain -RCP6.0
Spain -RCP8.5
Portugal -RCP2.6
Portugal -RCP4.5
Portugal -RCP6.0
Portugal -RCP8.5
South Africa -RCP2.6
South Africa -RCP4.5
South Africa -RCP6.0
South Africa -RCP8.5
w/o Warming effect
w Warming effect
Current
50-59
90-99

Figure S8. The changes in projected DTR-related excess mortality 'without an interactive effect with long-term temperature (grey; w/o warming effect)' or 'with an interactive effect with long-term temperature (red; with warming effect)' by RCPs, compared to the current period. Vertical lines: 95% eCI. X-axis: Period from the current to 2099 by decade. Unit of Y-axis: %. GCM-ensemble. DTR=diurnal temperature range, RCP=representative concentration pathway. GCM=general circulation model.




Argentina -RCP2.6
Argentina -RCP4.5
Argentina -RCP6.0
Argentina -RCP8.5
Korea -RCP2.6
Korea -RCP4.5
Korea -RCP6.0
Korea -RCP8.5
Japan -RCP2.6
Japan -RCP4.5
Japan -RCP6.0
Japan -RCP8.5
Taiwan -RCP2.6
Taiwan -RCP4.5
Taiwan -RCP6.0
Taiwan -RCP8.5
w/o Warming effect
w Warming effect
20-29
50-59
90-99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Thailand -RCP4.5
Thailand -RCP6.0
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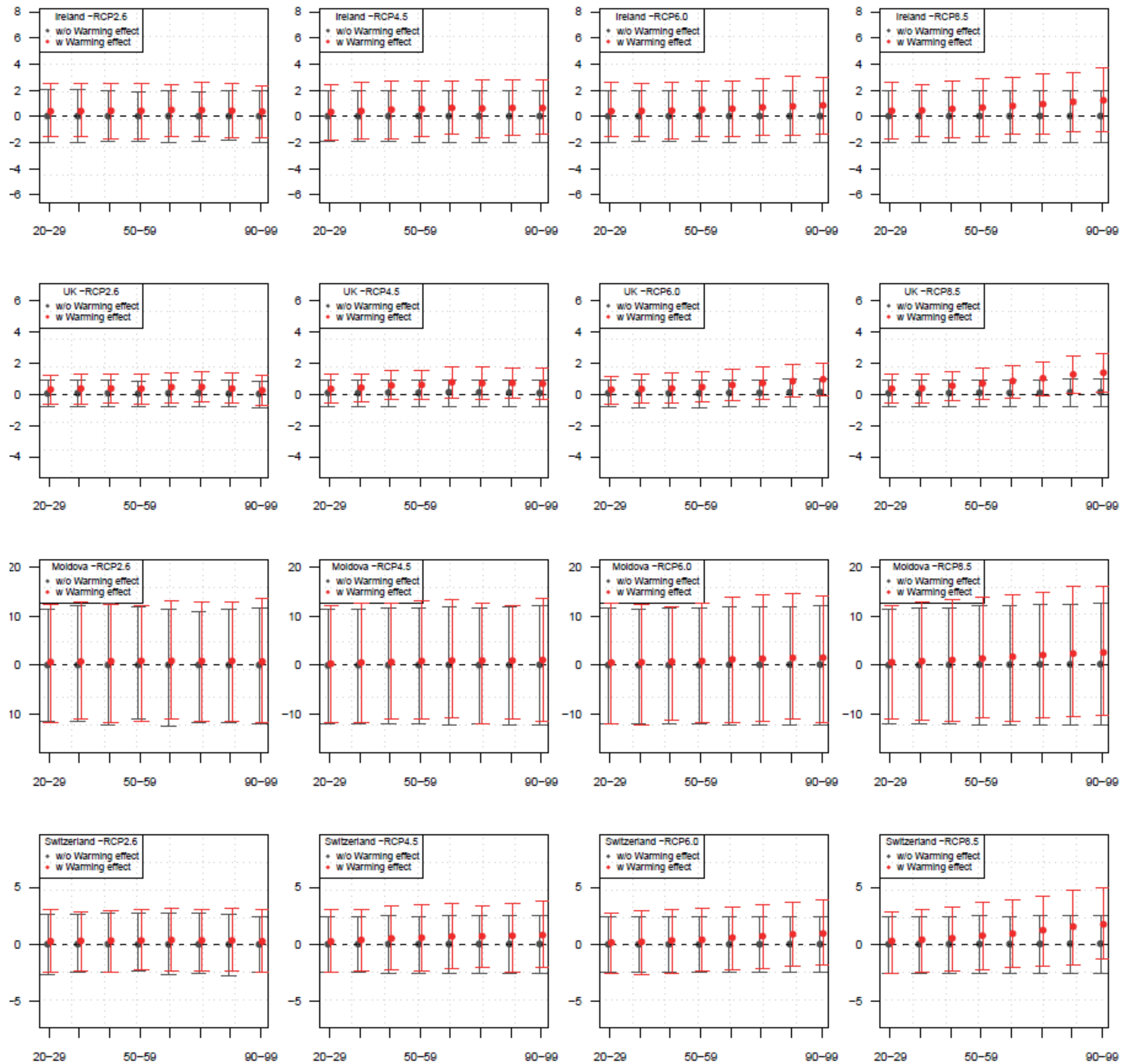
Australia -RCP2.6
Australia -RCP4.5
Australia -RCP6.0
Australia -RCP8.5
Finland -RCP2.6
Finland -RCP4.5
Finland -RCP6.0
Finland -RCP8.5
Estonia -RCP2.6
Estonia -RCP4.5
Estonia -RCP6.0
Estonia -RCP8.5
w/o Warming effect
w Warming effect
20-29
50-59
90-99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Ireland -RCP4.5
Ireland -RCP6.0
Ireland -RCP8.5
UK -RCP2.6
UK -RCP4.5
UK -RCP6.0
UK -RCP8.5
Moldova -RCP2.6
Moldova -RCP4.5
Moldova -RCP6.0
Moldova -RCP8.5
Switzerland -RCP2.6
Switzerland -RCP4.5
Switzerland -RCP6.0
Switzerland -RCP8.5
w/o Warming effect
w Warming effect
20-29
50-59
90-99

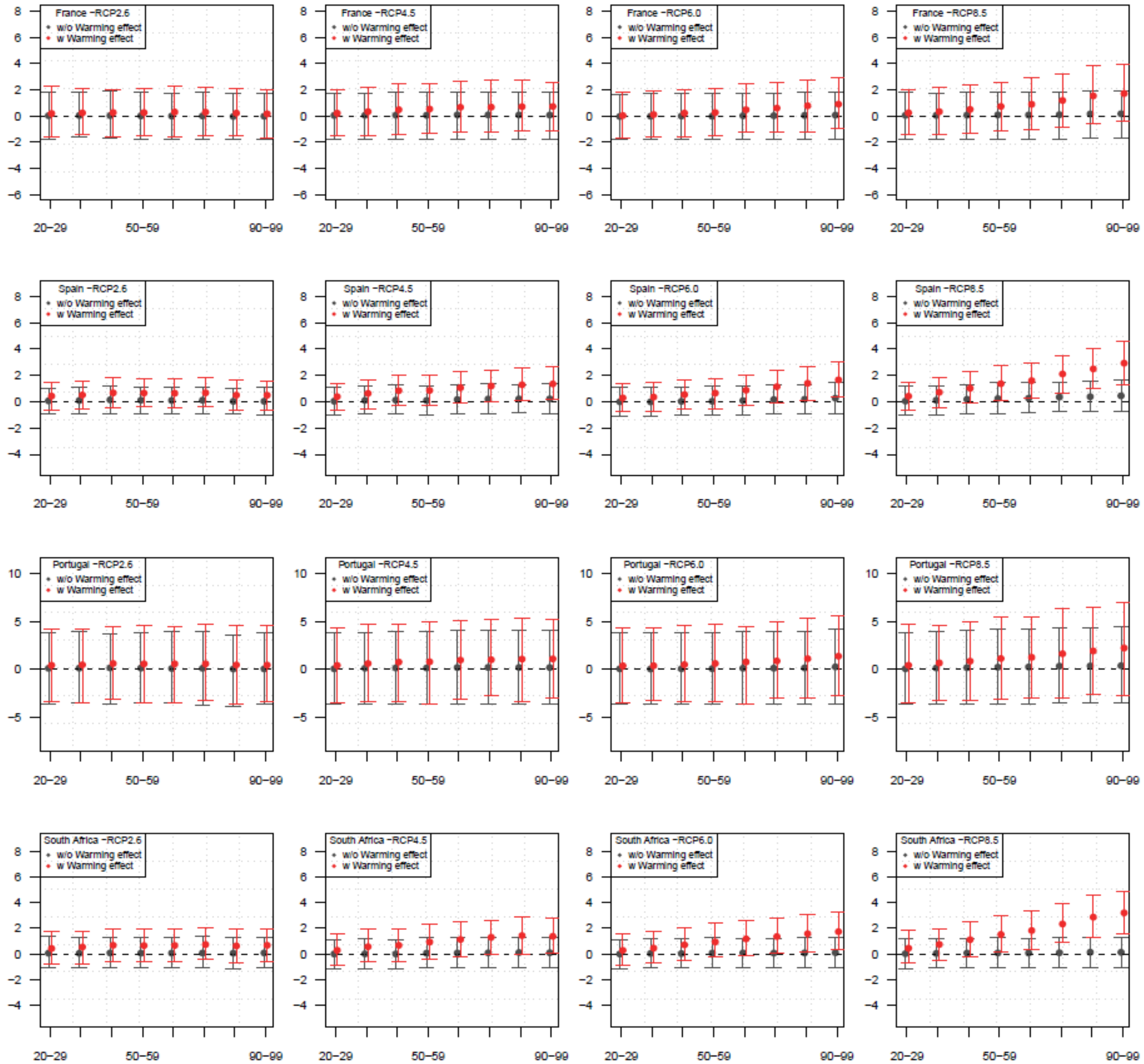
France -RCP2.6
France -RCP4.5
France -RCP6.0
France -RCP8.5
Spain -RCP2.6
Spain -RCP4.5
Spain -RCP6.0
Spain -RCP8.5
Portugal -RCP2.6
Portugal -RCP4.5
Portugal -RCP6.0
Portugal -RCP8.5
South Africa -RCP2.6
South Africa -RCP4.5
South Africa -RCP6.0
South Africa -RCP8.5
w/o Warming effect
w Warming effect
20-29
50-59
90-99

Table S4. Procedures for the linear-mixed model selection for estimating the increase in DTR-mortality risk by long-term average temperature (Tmean).

	Adjusted Variables		Goodness of Fit		Parameters (Fixed effect of Tmean)			
Model	**Fixed Effect**	**Random Effect**	**Predicted R^2**	**AIC**	**Coefficient**	**S.E.**	**P.I.**	**P-value**
#1	+Tmean +Country indicators + Year	+Community specific intercept +Community specific slope (Tmean) +Community specific intercept (Year) +Community specific slope (Year)	58.5	-7885	0.0004	0.0002	0.05%	0.063
#2	+Tmean +Country indicators + Year	+Community specific intercept +Community specific intercept (Year) +Community specific slope (Year)	57.6	-7876	0.0004	0.0002	0.04%	0.083
#3	+Tmean +Country indicators + Year	+Community specific intercept	57.7	-7882	0.0004	0.0002	0.04%	0.083
#4	+Tmean +Country indicators + Year	+Community specific intercept +Community specific slope (Tmean)	58.5	-7891	0.0004	0.0002	0.04%	0.046
#5	+Tmean +Country indicators	+Community specific intercept +Community specific slope (Tmean)	52.8	-7879	0.0004	0.0002	0.04%	0.063
#6	+Tmean +Country indicators	+Community specific intercept	52.0	-7871	0.0004	0.0002	0.04%	0.048
#7	+Tmean +Country indicators + Year +Average DTR	+Community specific intercept +Community specific slope (Tmean)	61.2	-7886	0.0005	0.0002	0.05%	0.028
Main Model	+Tmean +Country indicators + Year +Average DTR	+Community specific intercept +Community specific slope (Tmean) +Community specific intercept (Year) +Community specific slope (Year)	61.2	-7880	0.0005 (0.00046)	0.0002 (0.00021)	0.05%	0.028

Note) AIC: Akaike's Information Criterion

Table S5. Excess mortality attributed to DTR (attributable mortality risk fraction due to DTR) in the current period (study period for each country/region) in 20 countries/regions.

	Excess mortality attributable to DTR (95% empirical confidence interval)
North America	
Canada	2.4 (1.5-3.3)
USA	3.0 (2.7-3.3)
Central America	
Mexico	7.4 (4.6-10.1)
South America	
Brazil	3.4 (1.8-4.9)
Argentina	5.7 (2.6-8.8)
East Asia	
Korea	4.2 (2.7-5.9)
Japan	2.6 (2.2-2.9)
South-East Asia	
Taiwan	2.6 (0.2-4.8)
Thailand	3.7 (2.9-4.4)
Oceania	
Australia	3.3 (1.1-5.4)
Northern Europe	
Finland	2.4 (-2.8-7.2)
Estonia	1.6 (-1.4-4.7)
Ireland	0.2 (-1.2-1.7)
UK	2.3 (1.7-2.9)
Central Europe	
Moldova	2.1 (-5.9-10.3)
Switzerland	0.6 (-1.3-2.5)
France	2.1 (0.8-3.3)
Southern Europe	
Spain	4.2 (3.5-4.9)
Portugal	3.3 (0.7-5.8)
South Africa	
South Africa	2.2 (1.3-3.0)

Table S6. DTR-mortality risk per IQR increase in the entire seasons and according to each season (warm: warmest four months, cold: coldest four months, and moderate: remainder of the year).

	Whole	Warm	Moderate	Cold
North America				
Canada	1.4 (0.4-2.4)	0.7 (-0.1-1.5)	1.7 (0.8-2.6)	1.3 (0.3-2.3)
USA	1.4 (1.1-1.8)	0.8 (0.6-1.0)	1.6 (1.3-1.9)	1.3 (1.0-1.6)
Central America				
Mexico	4.1 (2.5-5.7)	2.9 (1.8-4.1)	3.3 (2.0-4.7)	3.6 (2.2-5.0)
South America				
Brazil	1.2 (0.3-2.2)	1.0 (0.2-1.9)	1.3 (0.3-2.3)	1.2 (0.2-2.2)
Argentina	2.9 (1.0-4.8)	1.9 (0.5-3.4)	3.0 (1.2-4.8)	2.3 (0.5-4.2)
East Asia				
Korea	2.3 (1.0-3.6)	1.7 (0.6-2.8)	2.8 (1.5-4.1)	2.4 (1.0-3.8)
Japan	1.2 (0.9-1.6)	1.2 (0.9-1.5)	2.1 (1.7-2.5)	0.8 (0.4-1.2)
South-East Asia				
Taiwan	1.2 (-0.3-2.8)	1.7 (0.3-3.1)	2.5 (0.7-4.3)	0.9 (-0.8-2.7)
Thailand	1.4 (0.5-2.3)	1.2 (0.4-2.0)	0.8 (0.2-1.5)	0.5 (-0.2-1.1)
Oceania				
Australia	1.6 (0.3-3.0)	1.3 (0.1-2.5)	1.5 (0.0-2.9)	1.6 (0.1-3.1)
Northern Europe				
Finland	1.8 (-1.7-5.4)	2.3 (-0.8-5.6)	2.3 (-1.3-6.1)	0.8 (-3-4.7)
Estonia	1.4 (-2.3-5.1)	1.9 (-1.3-5.3)	0.6 (-3.0-4.3)	0.8 (-3.2-4.8)
Ireland	0.1 (-1.0-1.3)	0.1 (-1.0-1.3)	0.0 (-1.3-1.3)	0.2 (-1.2-1.6)
UK	1.2 (0.6-1.8)	1.0 (0.5-1.6)	1.5 (0.8-2.1)	1.1 (0.4-1.8)
Central Europe				
Moldova	2.0 (-5.1-9.7)	3.0 (-1.5-7.6)	1.1 (-4.6-7.1)	-0.5 (-6.5-5.9)
Switzerland	0.4 (-2.3-3.2)	-0.1 (-2.8-2.7)	1.4 (-1.6-4.4)	-0.2 (-3.2-3.0)
France	1.2 (-0.2-2.6)	0.6 (-0.6-1.9)	1.7 (0.4-3.0)	1.0 (-0.4-2.4)
Southern Europe				
Spain	2.4 (1.6-3.2)	1.4 (0.8-1.9)	2.4 (1.7-3.0)	1.7 (1.0-2.4)
Portugal	1.7 (0.1-3.4)	1.8 (0.3-3.4)	1.9 (0.3-3.4)	1.3 (-0.3-2.9)
South Africa				
South Africa	1.1 (0.4-1.8)	1.1 (0.6-1.6)	0.7 (0.0-1.3)	1.1 (0.4-1.8)

Table S7. Sensitivity analysis. Attributable mortality risk fraction due to diurnal temperature range (DTR) in the total population (20 study countries). RCP 8.5 with GCM-ensemble DTR-averages were used.

		Without an interactive effect with long-term average temperature		With an interactive effect with long-term average temperature	
Modelling specification	**Current**	**2050-59**	**2090-99**	**2050-59**	**2090-99**
Main model	2.8%	3.0%	3.0%	4.0%	5.1%
DTR lag periods: 7 days	2.4%	2.4%	2.4%	2.9%	3.5%
DTR lag periods: 21 days	3.5%	3.8%	3.9%	4.7%	5.7%
Number of knots for DTR lag periods: 1	2.9%	3.0%	3.0%	4.0%	5.1%
Number of knots for DTR lag periods: 3	2.8%	3.0%	3.0%	4.0%	5.1%
Temperature lag periods: 14 days	3.0%	3.2%	3.2%	4.2%	5.2%
Temperature lag periods: 28 days	2.9%	2.9%	3.0%	4.0%	5.2%
Knots for temperature-mortality: 25th, 50th, and 75th percentiles	2.9%	3.0%	3.1%	4.1%	5.3%
Seasonality and long-term trend control: df=7/per year	2.9%	2.9%	2.9%	4.1%	5.4%
Seasonality and long-term trend control: df=9/per year	2.7%	2.7%	2.8%	3.7%	4.7%
Relative humidity adjusted*	3.6%	3.7%	3.8%	5.5%	7.4%
Relative humidity unadjusted*	3.0%	3.1%	3.2%	3.7%	4.3%
All-causes death[†]	2.6%	2.6%	2.7%	0.6%	-1.6%
Non-external death[†]	2.6%	2.6%	2.7%	1.6%	0.6%
Common periods: 1998-2009	2.8%	2.9%	2.9%	5.1%	7.7%
Common periods: 1999-2008	2.9%	3.0%	3.0%	5.3%	7.8%
Common periods: 2000-2007	2.6%	2.6%	2.7%	4.9%	7.4%

Note) A total of 13 countries were available: Argentina, Australia, Brazil, Canada, Estonia, Ireland, Japan, Mexico, Switzerland, Thailand, United States, South Korea, and Taiwan. Daily mean relative humidity (at lag 0) was adjusted as a linear term.
Note) † A total of 6 countries (30 communities) were available: Finland, Portugal, Switzerland, United Kindom, South Korea, and Taiwan.

References for Appendix

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2 Guo, Y. *et al.* Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS medicine* **15**, e1002629 (2018).

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6 Lee, W., Kim, Y., Honda, Y. & Kim, H. Association between diurnal temperature range and mortality modified by temperature in Japan, 1972–2015: Investigation of spatial and temporal patterns for 12 cause-specific deaths. *Environment international* **119**, 379-387 (2018).