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

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Summary

Background Various retrospective studies have reported on the increase of mortality risk due to higher diurnal temperature range (DTR). This study projects the effect of DTR on future mortality across 445 communities in 20 countries and regions.

Methods DTR-related mortality risk was estimated on the basis of the historical daily time-series of mortality and weather factors from Jan 1, 1985, to Dec 31, 2015, with data for 445 communities across 20 countries and regions, from the Multi-Country Multi-City Collaborative Research Network. We obtained daily projected temperature series associated with four climate change scenarios, using the four representative concentration pathways (RCPs) described by the Intergovernmental Panel on Climate Change, from the lowest to the highest emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). Excess deaths attributable to the DTR during the current (1985–2015) and future (2020–99) periods were projected using daily DTR series under the four scenarios. Future excess deaths were calculated on the basis of assumptions that warmer long-term average temperatures affect or do not affect the DTR-related mortality risk.

Findings The time-series analyses results showed that DTR was associated with excess mortality. Under the unmitigated climate change scenario (RCP 8.5), the future average DTR is projected to increase in most countries and regions (by –0·4 to 1·6°C), particularly in the USA, south-central Europe, Mexico, and South Africa. The excess deaths currently attributable to DTR were estimated to be 0·2–7·4%. Furthermore, the DTR-related mortality risk increased as the long-term average temperature increased; in the linear mixed model with the assumption of an interactive effect with long-term average temperature, we estimated 0·05% additional DTR mortality risk per 1°C increase in average temperature. Based on the interaction with long-term average temperature, the DTR-related excess deaths are projected to increase in all countries or regions by 1·4–10·3% in 2090–99.

Interpretation This study suggests that globally, DTR-related excess mortality might increase under climate change, and this increasing pattern is likely to vary between countries and regions. Considering climatic changes, our findings could contribute to public health interventions aimed at reducing the impact of DTR on human health.

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Introduction

The Intergovernmental Panel on Climate Change (IPCC) reported that anthropogenic influences will exacerbate climate change.[1] These climatic changes are expected to increase the frequency of unstable weather conditions, which might result in additional mortality burden.[2] The diurnal temperature range (DTR) is a major index representing temperature variability, and has been reported as a risk factor for mortality in multiple countries.[3–5] This mortality risk was more pronounced in older people and those suffering from cardiorespiratory or renal diseases.[6,7] Sudden changes in short-term temperature might aggravate diseases by affecting heart rate and blood viscosity,[8] trigging inflammation in the respiratory system,[9] or disturbing the thermoregulatory system.[10] These risks were also influenced by season or weather.[2,5,10]

Previous studies have reported that, in recent decades, the global average of DTR has decreased as nocturnal minimum temperatures have risen faster than the daytime maximums.[11–13] This change has been driven by factors related to climate change, such as aerosols and cloudiness.[11–13] However, a global study[14] showed that the decreasing pattern of DTR was evident only during a particular period, 1950–80, with both minimum and maximum temperatures increasing similarly after

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Research in context

Evidence before this study
To investigate mortality related to diurnal temperature range (DTR), on May 1, 2020, we searched PubMed and Web of Science for papers published after Jan 1, 2000, using the terms ("diurnal temperature range-mortality" OR "DTR-mortality" OR "intra-day temperature variability" OR "within-day temperature variability") AND ("mortality" OR "excess death" OR "attributable death" OR "attributable risk"), with no language restriction. A multi-country study covering mortality and weather variables from 308 cities in ten countries reported the attributable fraction of total mortality due to DTR to be 2·5% (95% CI 2·3–2·7%). A nationwide study in Japan reported a positive DTR-related mortality risk, which was attributed to greater cardiovascular and respiratory diseases-related deaths. A study done in five east Asian countries showed that the attributable risk of non-accidental death due to DTR was 0·6% (0·5–0·7%). To date, there has been little information on the projected effect of DTR on mortality under different climate change scenarios.

Added value of this study
We used daily time-series observation data for DTR, daily mean temperature, and mortality from the Multi-Country Multi-City Collaborative Research Network. The observed dataset included 445 communities in 20 countries or regions, with a total of 93 886 489 deaths from Jan 1, 1985, to Dec 31, 2015. We also obtained daily series of projected temperature under four climate change scenarios with different representative concentration pathways (RCPs), as described in the fifth Intergovernmental Panel on Climate Change Assessment Report (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). The temperature series under each RCP was generated by general circulation models provided from the Coupled Model Intercomparison Project Phase 5 and the Inter-Sectoral Impact Model Intercomparison Project, which has historical (1950–2005) and projected (2006–99) periods. We used a two-stage analysis to estimate the community-specific DTR-related mortality risk using the observed data and time-series modelling with meta-regression. We projected the excess deaths attributable to DTR during the current (1985–2015) and future (2020–99) periods using daily DTR series for the four climate change scenarios. We then calculated future excess deaths based on two assumptions: warmer long-term average temperatures affect or do not affect the DTR-related mortality risk. In the total population, our time series results show that DTR was associated with increased excess mortality. Our results show that the future effects of DTR on mortality might increase in most countries with variable climatic conditions under the unmitigated climatic scenario (RCP 8.5). This result suggests the necessity of preparing public health interventions for mitigating the negative effects of DTR on death. In addition, our findings suggest that the projected DTR effects on mortality under climate change varied in the different countries and regions.

Implications of all the available evidence
Our study suggests that DTR-related excess mortality might increase with climate change and that this increasing pattern might differ according to country or region. Therefore, we believe that our findings can provide crucial information for international and regional action plans to address the future effect of DTR on health under climate change.

the 1970s in nearly all parts of the globe. Another study[15] projected a reduction in global average DTR by the end of this century (by 2070–99), although this projection was regionally dependent, with substantial increases in DTR projected across most of Europe, central and South America, and Australia during the same period. These projections suggest that the future health effects of DTR associated with climate change might depend on regional variations. To the best of our knowledge, no other study has provided a multi-country, comparative mortality projection attributed to future DTR.

The future health effects of DTR could increase along with climatic warming because the possible interaction between DTR and warm temperatures amplifies the risk of mortality. A previous multi-country study[4] showed that higher DTR-mortality risk was associated with warmer climates, and other studies in east Asia[2,7] reported that DTR-mortality risk was higher on warm days than on cold days. Therefore, a projection of the health effects of DTR, using a well quantified interaction between DTR and temperature, is required to better understand the future health burden attributable to DTR under climate change.

In this study, we aimed to project the excess deaths associated with DTR for the current period and the future in 20 countries or regions using climate change scenarios. To our knowledge, this study is the first and largest epidemiological investigation aiming to estimate the potential health effects associated to changes in DTR under different climate change scenarios.

Methods

Study design
In this multi-country modelling study, we aimed to project the excess deaths associated with DTR for the current period (1985–2015; specific periods varied according to country) and the future (2020–99) in 445 communities in 20 countries or regions using climate change scenarios. Our study focused on three aspects. First, we modelled the potential country-specific changes in DTR distribution for the future period under each climate change scenario compared with the current period. Second, we calculated the potential excess deaths due to DTR, considering the future changes in DTR distribution. Finally, we investigated

the association between long-term average temperatures and DTR-mortality risk, and we considered this association for the projection of future excess deaths attributed to DTR. Information on data collection and analytical frameworks, based on previous multi-country studies,[4,16,17] is described in detail in the appendix (pp 3–7). We did all analyses using R software (version 3.5.3).

Observed data

We obtained daily time-series observation data of temperatures and mortality from the Multi-Country Multi-City Collaborative Research Network. The data comprised 445 communities across 20 countries or regions from Jan 1, 1985, to Dec 31, 2015. Daily all-cause death counts were used; however, if a daily count of all-cause mortality was not available for a community, the death count for non-external causes (International Classification of Diseases 9 [ICD-9]: 0–799; ICD-10: A00–R99) was used instead. Daily temperature variables included maximum, minimum, and mean temperatures in °C. The primary exposure, DTR, was calculated as the difference between the daily maximum and minimum temperatures.

Projection data under climate change scenarios

We obtained daily projected temperature series associated with climate change scenarios using the four representative concentration pathways (RCPs) described in the fifth IPCC Assessment Report in 2014,[1] from the lowest to the highest emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5). The temperature series for each RCP were generated based on simulations by general circulation models (GCMs), as a product provided from the Coupled Model Intercomparison Project Phase 5[1] and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP).[18] The ISI-MIP database provided daily temperature variables for each RCP for five GCMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M.15. Each GCM under each RCP consists of historical (1950–2005) and projected (2006–99) periods, and their outputs were bias-corrected and downscaled to a 0·5°×0·5° spatial resolution. From the global database, we extracted the projected daily maximum, minimum, and mean temperatures from grid cells corresponding to the coordinates of each community, from the start date of the observed data to the end of 2099. All the extracted variables were then recalibrated using the observed series for each community.[19] The recalibration produced modelled series of temperatures that were based on the monthly mean temperature and the daily variability around the monthly mean of observed temperature, preserving the trend in the original data.[16] Daily series of DTRs were then calculated as the difference between the recalibrated maximum and minimum temperatures. The reliability of the recalibration procedures is discussed in the appendix (pp 8–9).

Observed DTR mortality risks

We used a two-stage approach to derive the community-specific mortality risk related to DTR. First, we estimated the DTR-related mortality risk for each community using a generalised linear model with quasi-Poisson distribution, controlling for the daily mean temperature, seasonality, long-term trends, and day of the week. We modeled the linear DTR–mortality relationship and the non-linear lag–mortality relationship using a natural cubic spline basis function with a maximum lag of 14 days.[2,4,5,7] The daily mean temperature was adjusted using a distributed lag non-linear model with a cross-basis function: a quadratic B-spline with three internal knots (the 10th, 75th, and 90th percentiles of community-specific temperatures) for the temperature–mortality relationship, and a natural cubic spline with an intercept and three equally spaced knots on the log scale for lag days (up to 21 days).[20]

In the second stage, the lag-cumulative DTR mortality risks specific to communities were pooled using a meta-regression. Indicators of country were used as predictors in the meta-regression,[4] which was also used to derive the best empirical linear unbiased prediction of the DTR mortality risk for each community.

Estimation of excess mortality in the current period

To determine DTR in the current period, we used the modelled weather data (not observed data) derived from the GCMs to avoid potential bias that can be generated from deviations, such as a large variability in data resolution or poor performance of climatic models in areas receiving sparse information from monitoring stations.[16,17,21,22] All GCMs in our study reproduced the observed temporal DTR distribution with reasonable accuracy.[18]

Therefore, we calculated the current excess mortality attributable to DTR using the modelled daily series of DTR and observed mortality. We used the lag-cumulative relative risk corresponding to the DTR from each day to calculate the daily attributable deaths and attributable fraction for the following 14 days, using a DTR of 0°C as the reference (ie, attributable deaths due to a full range of DTR). The sum of attributable deaths for the whole series represents the total excess mortality attributable to DTR. These procedures for calculating the excess mortality were reported and used in previous studies,[17,23] and more details are described in the appendix (pp 6–7).

We computed the excess mortality for each community by combining GCMs and RCPs. Attributable fractions were calculated for GCM ensemble averages by aggregating according to country and RCP, and using the related total number of deaths as the denominator. Monte Carlo simulations were used to quantify the uncertainty (ie, the empirical confidence interval [eCI]) in the DTR mortality risk estimations and projections across GCMs, using 1000 replicates.

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See Online for appendix

Projection of excess mortality in the future

To project excess mortality and its uncertainty in 2020–99 according to country, decade (2020–29, 2030–39 etc, until 2090–99), and RCP, we used the same approach as for the current attributable fraction calculation already described. We assumed no changes in the population; therefore, when calculating the potential excess deaths, we used the average of the observed daily all-cause mortality for the projections, and multiplied them by the daily attributable fraction during the projection period.

Furthermore, we calculated the future excess deaths attributable to DTR, considering temporal changes in the DTR mortality risk associated with climate change. First, we hypothesised that the DTR mortality risk will be constant in the future, and that future excess mortality attributable to DTR will be affected by only the future distribution of DTR. We refer to the first hypothesis as the DTR mortality risk projection without an interactive effect with long-term average temperature.

	Number of communities	Study period	Total deaths	Diurnal temperature ranges, °C	Temperature, °C
North America					
Canada	25	1986–2011	2 734 629	10·0 (7·1–12·8)	6·8 (2·6–10·7)
USA	132	1985–2006	22 690 332	10·9 (6·9–15·9)	14·8 (7·9–25·5)
Central America					
Mexico	5	1998–2014	2 169 253	13·1 (9·8–16·1)	18·3 (16·4–20·6)
South America					
Brazil	18	1997–2011	3 435 535	8·9 (6·1–12·5)	24·6 (17·7–27·4)
Argentina	3	2005–15	688 061	11·5 (9·5–12·8)	18·2 (17·8–18·5)
East Asia					
South Korea	6	1992–2010	1 671 728	8·1 (6·8–9·4)	13·6 (12·5–14·9)
Japan	47	1985–2015	30 746 547	8·3 (4·9–10·6)	15·4 (9·1–23·2)
Southeast Asia					
Taiwan	3	1994–2014	1 162 844	7·6 (7·0–8·2)	23·6 (23·1–24·2)
Thailand	61	1999–2008	1 801 653	9·8 (4·2–12·5)	27·6 (25·1–29·3)
Oceania					
Australia	3	1988–2009	1 177 950	8·2 (7·4–8·8)	18·1 (15·7–20·3)
Northern Europe					
Finland	1	1994–2011	130 395	6·1 (6·1–6·1)	6·2 (6·2–6·2)
Estonia	5	1997–2015	146 347	7·6 (7·1–8·0)	6·2 (5·6–6·7)
Ireland	6	1985–2007	1 012 684	6·7 (5·9–7·9)	9·7 (9·1–10·6)
UK	10	1990–2012	12 075 786	7·3 (6·7–7·8)	10·3 (9·5–11·6)
Central Europe					
Moldova	4	2001–2010	59 906	9·7 (8·4–10·7)	10·7 (10·2–11·3)
Switzerland	8	1995–2013	243 638	7·6 (6·2–8·8)	10·4 (8·6–12·9)
France	18	2000–10	1 197 555	8·4 (4·7–10·9)	12·6 (10·6–16·2)
Southern Europe					
Spain	50	1990–2010	3 470 738	10·6 (5·8–15·4)	15·5 (10·9–21·6)
Portugal	2	1985–2012	966 814	8·4 (8·0–8·8)	15·9 (14·8–17·0)
South Africa					
South Africa	38	1997–2013	6 304 094	14·3 (6·8–19·1)	17·9 (12·4–22·8)

Data show average community-specific daily diurnal temperature range (range) and mean temperature (range). Countries are arranged in order of latitude within each region.

Table 1: **Descriptive statistics by country**

The second hypothesis assumed that the DTR mortality risk might increase due to a warming climate, on the basis of previous studies that found that a higher DTR mortality risk was associated with higher temperatures.[2,4,7] We hypothesised that the positive interaction between DTR and the long-term average temperature might continue in the future, and that DTR-related mortality would be influenced by the expected gradual increases of moderate and warm days because of rises in average temperature under climate change. Hence, in this study, it is referred to as the projection with an interactive effect with long-term average temperature.

We quantified the modifying effect of long-term average temperature on DTR mortality risk using the observed data and a linear mixed effect model. This model allowed us to simultaneously consider spatio-temporal variations in the DTR mortality risk, long-term average temperature, and other predictors. First, we estimated time-varying DTR mortality risks by adding a linear interaction term between the DTR basis and time in the first-stage model.[4] Then, we derived lag-cumulative, community-specific coefficients and the corresponding variances at the mid-points for 5-year periods (July 1, 1987, for 1985–89; July 1, 1992, for 1990–94 etc, until July 1, 2012, for 2010–14) within the study period of each community. Community-specific average temperatures during the same 5-year periods were also calculated as a predictor of interest. Additionally, potential covariates (country indicators, time trend, and average DTR) were considered to determine the best model. The final model was selected via goodness-of-fit tests (appendix p 27). Finally, we estimated the association between DTR mortality risk and long-term average temperature (a fixed coefficient of average temperature), using the linear mixed model with the community-specific random intercepts, with random slopes of average temperature, and with the overall and community-specific year trend adjustment. Additional information about the linear mixed effect model is presented in the appendix (p 7).

Season-specific and sensitivity analyses

To examine whether the distribution of DTR and DTR-related mortality risk differed according seasonal characteristics, we did stratified analyses for the warm (4 warmest months), cold (4 coldest months), and moderate (remainder of the year) seasons. The monthly mean temperature for each community was applied to divide these three seasons. We examined the distribution of DTR in the study periods and estimated the season-specific DTR mortality risk using an interactive term between the DTR basis and seasons (as an indicator variable) in the first stage model. We also did sensitivity analyses to examine the consistency of the results.

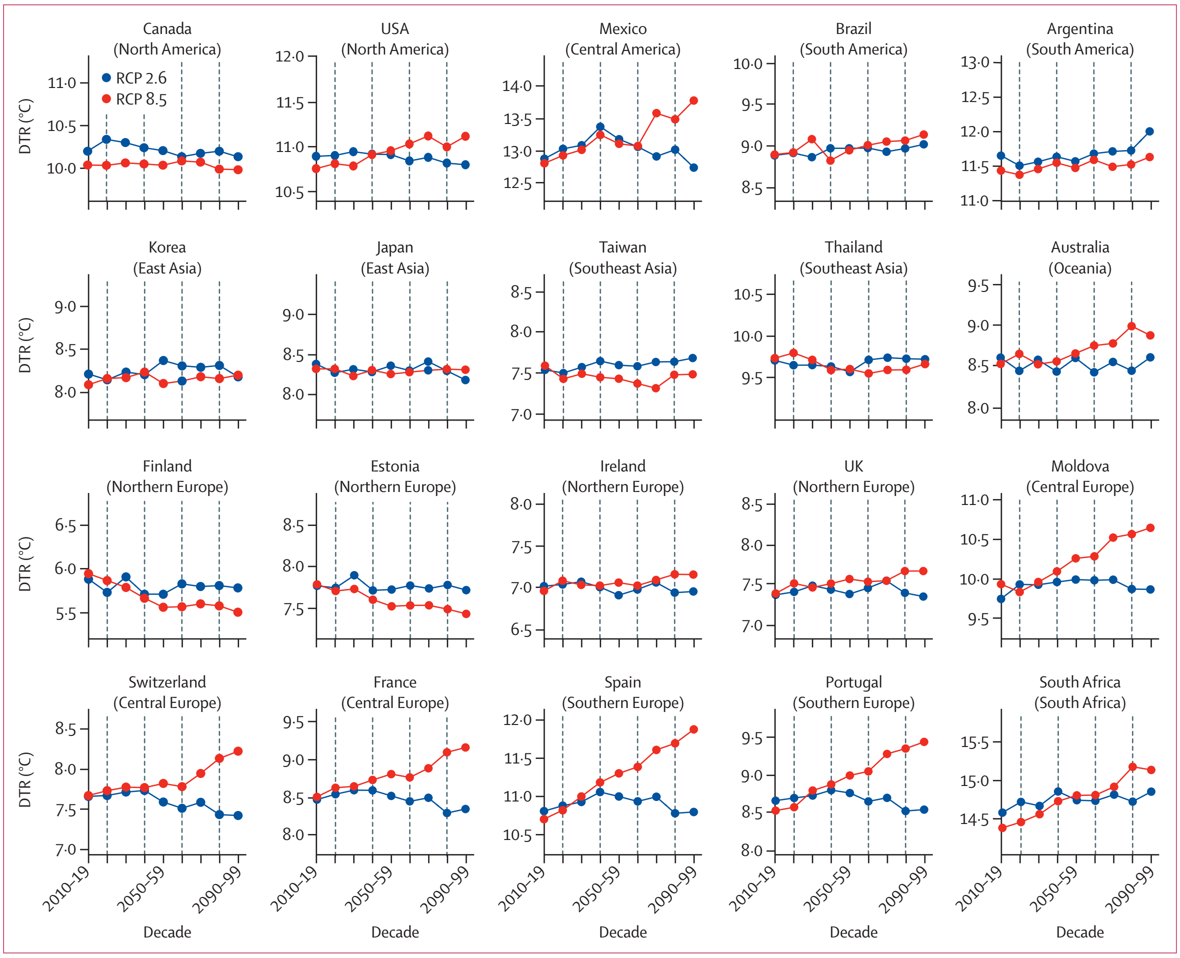

Figure 1: **Decadal trend of projected average DTR by RCP and country or region during 2010–99**
Data are mean country or region-specific DTR as GCM-ensemble. All countries are arranged in order of latitudes within each region. DTR=diurnal temperature range. RCP=representative concentration pathway. GCM=general circulation model.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the datasets and the final responsibility for the decision to submit for publication.

Results

A sample size of 93 886 489 deaths in 445 communities in 20 countries or regions was used in this study. The distribution of DTR varied among the countries and regions in the current period, with mean values ranging from 6·1°C (no range available) in Finland to 14·3°C (range 6·8–19·1) in South Africa (table 1). The geographical distributions of the 445 communities and the corresponding average values of DTR are shown in the appendix (p 10). The average DTR was generally higher in the warm and moderate seasons, except for in four countries (Mexico, Thailand, Australia, and South Africa), which exhibited a milder cold season than other countries (appendix p 11).

For clarity and brevity of interpretation, the most stringent mitigation scenario (RCP 2.6) and the unmitigated scenario (RCP 8.5) are displayed as the main results. Figure 1 shows the projected average DTR for decades within 2010–99 according to country for these two scenarios. Generally, in RCP 2.6, a reduced or roughly constant DTR was projected over time in most countries and regions. By contrast, the DTR changes for RCP 8.5 varied considerably by country and region; DTR was projected to increase in most countries (by –0·4 to 1·6°C), and a notable increase was projected in the USA, Mexico, south-central Europe, and South Africa, whereas a decreasing trend was projected in tropical and subtropical countries and regions (Thailand and Taiwan), and in countries at high latitudes (Canada, Estonia, and Finland). The increase in DTR was projected to be more prominent in the warm or moderate seasons than in cold season in most countries, showing an increasing trend in DTR (except for Mexico and South Africa), and the decline in the cold season was observed in countries that showed a decreasing DTR trend

	Representative concentration pathway 2.6			Representative concentration pathway 8.5		
	2020–29	2050–59	2090–99	2020–29	2050–59	2090–99
North America						
Canada	7·8 (3·2–11·4)	8·4 (3·9–12·0)	8·2 (3·7–11·9)	7·9 (3·7–11·5)	9·8 (5·6–13·3)	12·9 (8·8–16·3)
USA	16·1 (9·8–26·0)	16·6 (10·5–26·3)	16·4 (10·2–26·5)	16·1 (9·6–26·1)	17·8 (11·6–27·2)	20·4 (14·6–29·5)
Central America						
Mexico	18·8 (16·9–20·7)	19·2 (17·2–21·1)	19·0 (17·1–20·9)	18·7 (16·8–20·6)	20·3 (18·3–22·2)	22·7 (20·6–24·7)
South America						
Brazil	25·0 (18·1–28·0)	25·3 (18·3–28·3)	25·3 (18·4–28·4)	25·2 (18·4–28·1)	26·4 (19·8–29·8)	28·7 (21·8–32·7)
Argentina	18·3 (18·0–18·8)	18·8 (18·5–19·2)	18·9 (18·5–19·3)	18·4 (18·1–18·8)	19·4 (19·1–19·9)	21·2 (20·9–21·7)
East Asia						
South Korea	14·4 (13·3–15·6)	15·0 (13·8–16·1)	14·8 (13·7–15·9)	14·5 (13·4–15·6)	16·1 (15·0–17·1)	18·6 (17·6–19·4)
Japan	16·1 (10·0–23·7)	16·6 (10·5–24·0)	16·3 (10·5–23·9)	16·0 (10·0–23·7)	17·6 (11·8–24·8)	19·8 (14·5–26·4)
Southeast Asia						
Taiwan	24·3 (23·5–25·3)	24·6 (23·8–25·7)	24·5 (23·8–25·6)	24·3 (23·5–25·4)	25·5 (24·7–26·6)	27·3 (26·5–28·5)
Thailand	27·9 (25·3–29·9)	28·1 (25·5–30·1)	28·2 (25·6–30·2)	28·1 (25·7–30·0)	29·4 (26·9–31·3)	31·6 (29·3–33·4)
Oceania						
Australia	18·6 (16·3–20·8)	18·9 (16·6–21·1)	18·9 (16·4–21·2)	18·9 (16·7–20·8)	19·9 (17·6–21·9)	21·9 (19·6–23·7)
Northern Europe						
Finland	7·9 (7·9–7·9)	8·1 (8·1–8·1)	7·9 (7·9–7·9)	7·7 (7·7–7·7)	9·4 (9·4–9·4)	12·2 (12·2–12·2)
Estonia	7·4 (6·9–7·7)	7·6 (7·1–7·9)	7·4 (6·9–7·7)	7·3 (6·8–7·7)	9·0 (8·5–9·3)	11·7 (11·3–12·0)
Ireland	10·9 (10·4–11·5)	11·0 (10·5–11·6)	10·8 (10·3–11·5)	11·0 (10·5–11·6)	11·7 (11·3–12·3)	13·4 (13·0–13·9)
UK	11·0 (10·2–12·4)	11·2 (10·4–12·6)	10·9 (10·1–12·3)	11·1 (10·2–12·4)	12·0 (11·1–13·4)	13·9 (12·9–15·3)
Central Europe						
Moldova	11·8 (11·3–12·3)	12·3 (11·8–12·8)	12·1 (11·5–12·6)	11·8 (11·2–12·3)	13·3 (12·8–13·8)	15·8 (15·3–16·4)
Switzerland	11·1 (9·3–13·7)	11·4 (9·6–14·0)	11·2 (9·4–13·8)	11·2 (9·4–13·8)	12·5 (10·7–15·1)	15·0 (13·1–17·7)
France	13·1 (11·3–16·9)	13·4 (11·4–17·1)	13·2 (11·2–17·0)	13·2 (11·4–16·8)	14·4 (12·4–18·2)	16·7 (14·5–20·5)
Southern Europe						
Spain	16·2 (11·6–22·1)	16·5 (12·0–22·5)	16·4 (11·7–22·5)	16·2 (11·6–22·2)	17·7 (13·1–23·3)	20·2 (15·5–24·9)
Portugal	16·6 (15·7–17·5)	16·9 (16·0–17·9)	16·8 (15·9–17·8)	16·7 (15·8–17·7)	18·0 (17·1–19·0)	20·2 (19·3–21·1)
South Africa						
South Africa	18·4 (12·9–22·9)	18·7 (13·2–23·2)	18·7 (13·2–23·3)	18·5 (13·1–23·1)	20·0 (14·3–24·4)	22·4 (16·1–26·8)

Data are mean country-specific or region-specific temperature (range) as general circulation model-ensemble. Countries are arranged in order of latitude within each region.

Table 2: **Temporal trends of projected average temperature by representative concentration pathway and country or region**

(appendix p 12). Community-specific DTR changes for the two RCP scenarios between 2010–19 and 2090–99 were generally consistent with those in figure 1 (appendix p 13). Additional results for all RCP scenarios are in the appendix (p 14).

Concerning temporal trends of the projected average temperature for the two RCP scenarios, for RCP 8.5, in all countries and regions a steep, continuous increase in average temperatures is projected to occur, whereas the increase is expected to diminish for RCP 2.6 (table 2). The projected average temperatures for all four RCP scenarios from 2010–19 to 2020–99 are in the appendix (p 15).

Figure 2 shows the country-specific decadal projections of DTR-related excess mortality per unit increase in DTR from the current period to 2090–99 for the two RCP scenarios, with and without the interactive effect with long-term average temperature. The excess deaths currently attributable to DTR were estimated to be 0·2–7·4% (appendix p 28). The DTR mortality risk was generally higher in the moderate and warm seasons for all countries and regions, except for Mexico, Australia, Ireland, and South Africa (appendix p 29). Assuming no interactive effect with long-term average temperature, the results corresponded to future DTR projections. Specifically, the effects of DTR on mortality during the future period were nearly analogous with those of the current period under RCP 2.6. Under RCP 8.5, the future effects of DTR seemed to increase in 14 (70%) of 20 countries and regions. In addition, the projected increase in excess mortality in 2090–99 compared with the current period was highest in Spain (0·45%), Portugal (0·37%), and Mexico (0·36%), and lowest in Finland (–0·24%), Estonia (–0·07%), and Canada (–0·04%).

In the linear mixed model with the assumption of an interactive effect with long-term average temperature, we estimated 0·05% additional DTR mortality risk per 1°C increase in average temperature. The distribution of

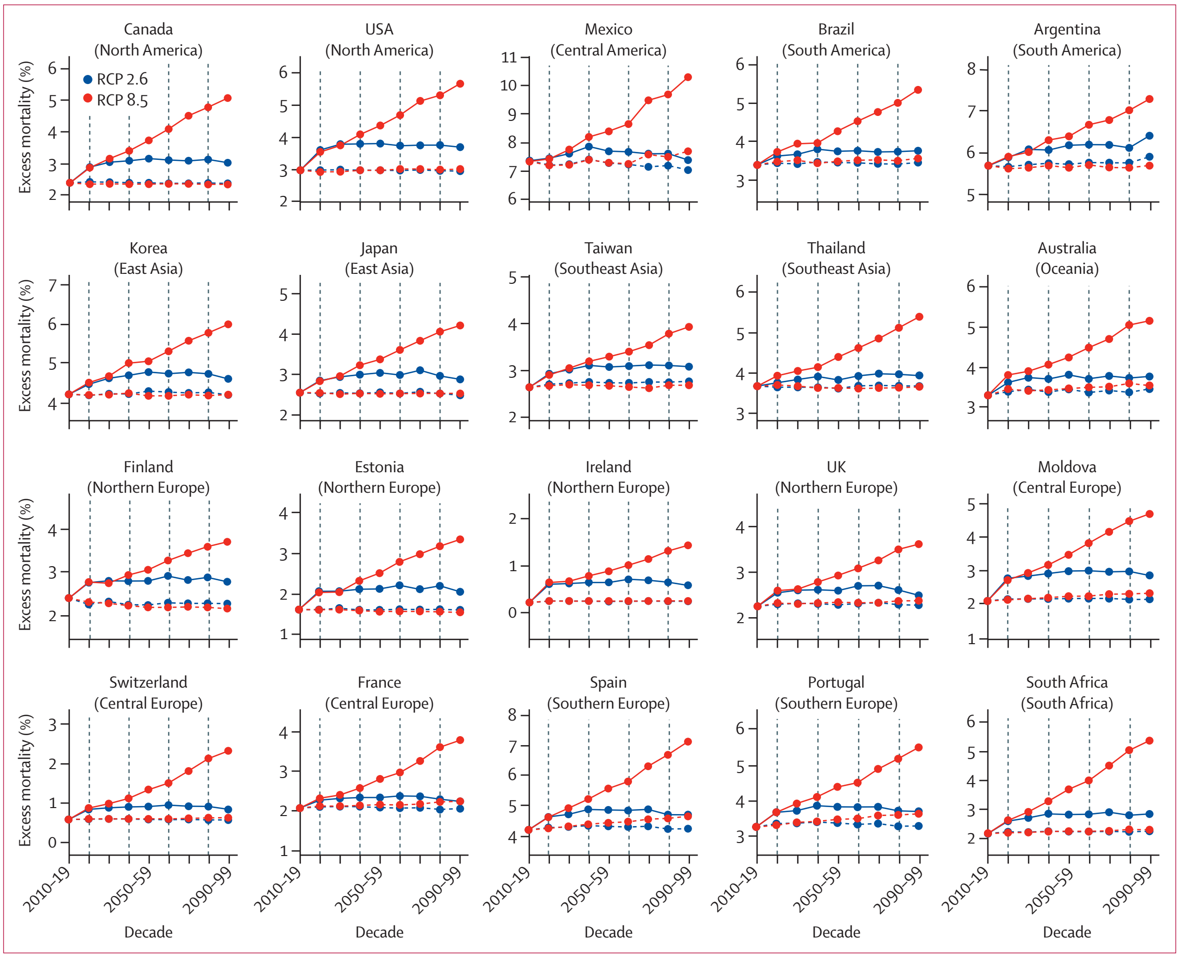

Figure 2: **Excess mortality attributed to DTR by decade in 20 countries and regions for four climate change scenarios**
Solid lines indicate the estimates with an interactive effect with long-term average temperature on DTR-related mortality risk, and dashed lines represent estimates without. All countries are arranged in order of latitudes within each region. Estimates are reported as GCM-ensemble average decadal fractions. DTR=diurnal temperature range. RCP=representative concentration pathway. GCM=general circulation model.

the coefficient of average temperature is shown in the appendix (p 16). Under the assumption of an interactive effect with long-term average temperature, the future DTR-related excess mortality for all RCP scenarios were projected to be considerably higher in almost all countries and regions than those without the interactive effect; DTR-related excess deaths are projected to increase in all countries or regions by 1·4–10·3% in 2090–99 (figure 2). The projected increase of DTR-related effect was most evident under RCP 8.5 in all countries and regions, ranging from 1·2% in Ireland to 3·2% in South Africa in 2090–99 compared with the current period. The appendix shows the corresponding country-specific excess deaths due to DTR with 95% eCI (appendix pp 17–21) and the percentage change in the projected excess deaths due to DTR compared with those in the current period (appendix pp 22–26).

The community-specific changes of DTR-related excess deaths under RCP 8.5 showed results consistent with figure 2 for the comparison of 2090–99 with the current period, with and without the interactive effect with long-term average temperature (figure 3). In addition, our results were generally robust to sensitivity analyses (appendix p 30).

Discussion

We assessed the potential impact of DTR on mortality for 445 communities in 20 countries or regions under different climate change scenarios. In most of the countries and regions, the projected average values of DTR were shown to increase under the unmitigated scenario (RCP 8.5), whereas the highest mitigation scenario (RCP2.6) showed a constant or weak decreasing trend. We also found that an increase in long-term average temperature was closely associated with an increase in the DTR mortality risk. Therefore, the projected effect of DTR on mortality increased substantially when considering the interactive effect with rising average temperatures under climate change, compared with no interactive effect. This increasing pattern was the

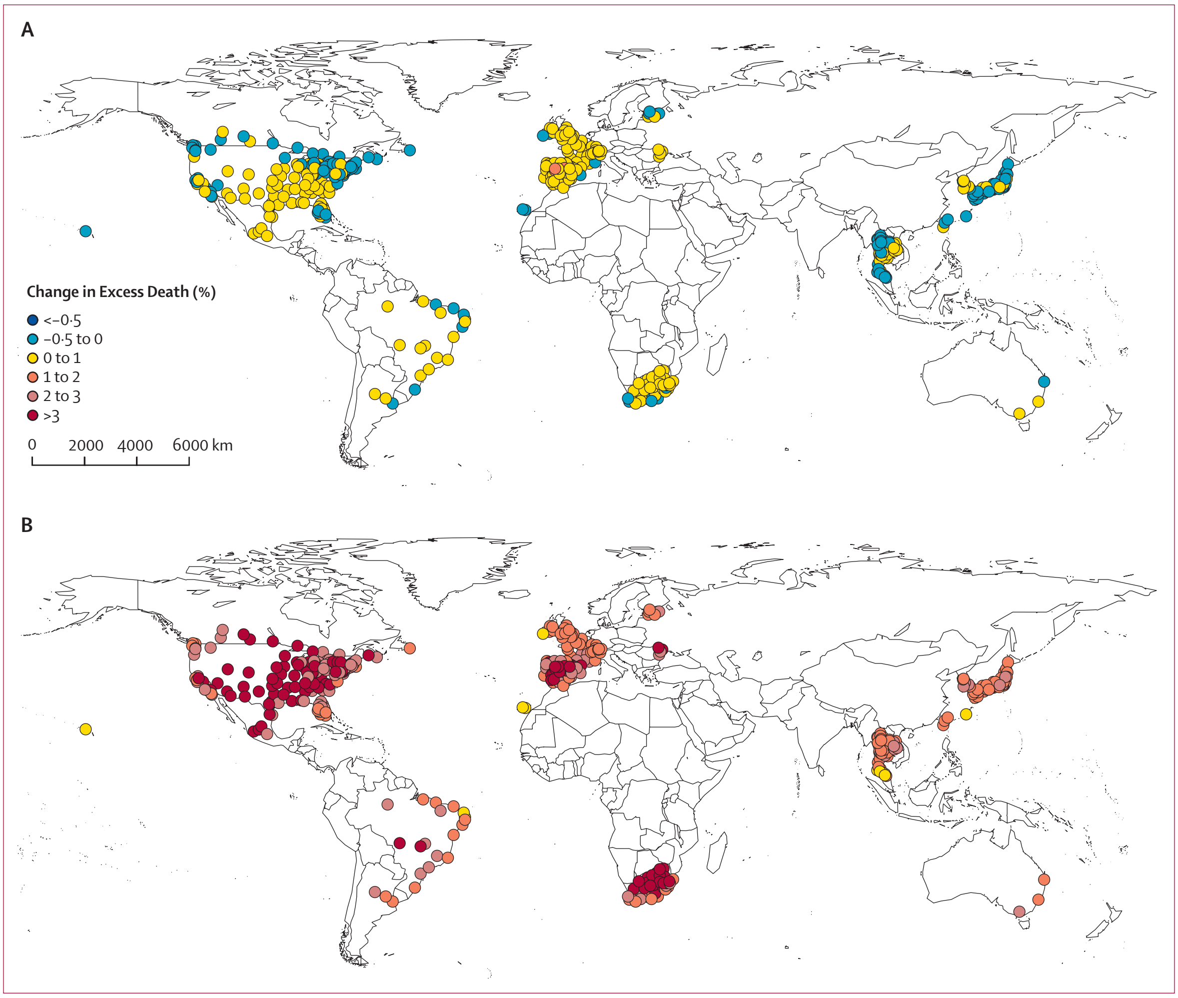

Figure 3: **Community-specific differences in excess mortality attributed to DTR in 2090–99 compared with the current period under RCP 8.5**
(A) Results without an interactive effect with long-term average temperature on DTR-related mortality risk. (B) Results with the interactive effect with long-term average temperature on DTR-related mortality risk. The current period is the study period for each county. DTR=diurnal temperature range. RCP=representative concentration pathway.

most prominent in South Africa, Mexico, Spain, and the USA.

These results are consistent with those of previous studies, showing that the DTR-related mortality risk was generally higher in warmer temperatures.[2,4,7] Several biological mechanisms could explain this relationship; both heat and sudden temperature changes could disrupt normal circulation and the immune system, affecting heart rate, blood pressure, blood cholesterol levels, and oxygen uptake.[24–26] In addition, heat can increase the risk of mortality from renal diseases because of electrolyte and water imbalances.[7,27] In other words, heat-related stress aggravates health conditions, which could make people more vulnerable to the effects of DTR. Furthermore, we showed that higher DTR-related effects on mortality are projected when the interactive effect with long-term average temperature is considered. These results were consistent with those of previous studies suggesting that warming temperatures might amplify the effect of DTR on mortality under climate change.[2,7] Additionally, through the season-specific analyses, we found that the DTR mortality risk was generally higher in the warm or moderate seasons than in the cold season, except in countries with mild cold seasons and high average DTRs. Further, the increase in future DTR was projected to be more prominent in the warm or moderate seasons than in cold seasons in most countries and regions. Therefore, we can infer that the future mortality burden due to DTR might be more pronounced in warm and moderate seasons than in cold seasons.

DTR is related to multiple meteorological factors. Hence, changes in future DTR should be discussed comprehensively. First, a decrease in atmospheric aerosols and cloud cover could decrease the downward long-wave radiation and elevate the daytime surface solar radiation, which could lead to a greater increase in maximum temperature than that in minimum temperature.[8,10] A study[15] projecting future DTR using the Coupled Model Intercomparison Project Phase 5 also suggested that future DTR might be associated with changes in several meteorological variables, such as clouds, the hydrological cycle, and longwave and shortwave radiations in these regions. In addition, because all RCP scenarios assume stringent emission controls on aerosols,[28] this can affect changes in the DTR under the scenario models.

Several limitations of this study should be acknowledged. First, our projection results for the different climate-change scenarios include only the effects of the changing climate, but do not consider other possible factors, such as adaptation and sociodemographic changes, which could affect the impact of DTR on mortality under climate change. Thus, our results should be interpreted as potential effects under hypothetical scenarios considering certain strict assumptions, and future work should consider sociodemographic changes by using the shared socioeconomic pathways that work in harmony with RCPs. Second, although previous studies have suggested a novel index that can measure the effects of temperature variability within and between days on mortality,[29] we could not consider the index because we focused on DTR and its lagged effects. Third, because this study did not cover large areas of the world (eg, Russia and India), our results might be biased towards countries with large numbers of observations. Therefore, the findings in this study should not be interpreted as globally representative. Additionally, our estimates are affected by substantial uncertainty, owing to variability in climate models and the potential imprecision in the statistical estimates. We could not consider a finer spatial resolution than the current climate data (0·5°×0·5°) due to data limitations, and this should be supplemented in further studies. Further, the location-specific interactive effect with long-term average temperature was not considered, because of modelling and interpretation complexities. Finally, this study could not consider non-external deaths, relative humidity, and seasonal viral infections (eg, influenza) for all countries because of limited data, which could cause potential bias in our results. Future studies should address these limitations by expanding the datasets and study population.

Despite these limitations, our findings could have important implications for future DTR studies and relevant public health policies. The main contribution of this study is to provide quantitative projections of the mortality burden due to DTR for the 20 countries and regions. Our results show that the future effects of DTR on mortality could increase in most countries under the unmitigated climate scenario. This result implies the necessity of preparing international action plans for managing changes in the future DTR and temperature. In addition, our findings suggest that the projected DTR effects were heterogeneous among countries and regions. This result indicates that region-specific interventions would be required, along with international policies.

Contributors

WL conceived of the study idea, designed the research, analysed the data and wrote the manuscript. YK, FS, and KP reviewed and revised the manuscript. FS collected climate scenario materials. FS, AG, EL, and BA provided advice regarding statistical modelling and relevant results. RP and KP reviewed the parts of the manuscript related to meteorological science. All other authors contributed to the data collection, overall research, and amendments of the manuscript. HK supported and counselled all processes of this study.

Declaration of interests

All authors declare no competing interests.

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