Seasonality of mortality under climate change: a multicountry projection study

*Lina Madaniyazi, Ben Armstrong, Aurelio Tobias, Malcolm N Mistry, Michelle L Bell, Aleš Urban, Jan Kyselý, Niilo Ryti, Ivana Cvijanovic, Chris Fook Sheng Ng, Dominic Roye, Ana Maria Vicedo-Cabrera, Shilu Tong, Eric Lavigne, Carmen Íñiguez, Susana das Neves Pereira da Silva, Joana Madureira, Jouni J K Jaakkola, Francesco Sera, Yasushi Honda, Antonio Gasparrini, Masahiro Hashizume, on behalf of the Multi-Country Multi-City Collaborative Research Network**

Summary

Background Climate change can directly impact temperature-related excess deaths and might subsequently change the seasonal variation in mortality. In this study, we aimed to provide a systematic and comprehensive assessment of potential future changes in the seasonal variation, or seasonality, of mortality across different climate zones.

Methods In this modelling study, we collected daily time series of mean temperature and mortality (all causes or non-external causes only) via the Multi-Country Multi-City Collaborative (MCC) Research Network. These data were collected during overlapping periods, spanning from Jan 1, 1969 to Dec 31, 2020. We projected daily mortality from Jan 1, 2000 to Dec 31, 2099, under four climate change scenarios corresponding to increasing emissions (Shared Socioeconomic Pathways [SSP] scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). We compared the seasonality in projected mortality between decades by its shape, timings (the day-of-year) of minimum (trough) and maximum (peak) mortality, and sizes (peak-to-trough ratio and attributable fraction). Attributable fraction was used to measure the burden of seasonality of mortality. The results were summarised by climate zones.

Findings The MCC dataset included 126 809 537 deaths from 707 locations within 43 countries or areas. After excluding the only two polar locations (both high-altitude locations in Peru) from climatic zone assessments, we analysed 126 766 164 deaths in 705 locations aggregated in four climate zones (tropical, arid, temperate, and continental). From the 2000s to the 2090s, our projections showed an increase in mortality during the warm seasons and a decrease in mortality during the cold seasons, albeit with mortality remaining high during the cold seasons, under all four SSP scenarios in the arid, temperate, and continental zones. The magnitude of this changing pattern was more pronounced under the high-emission scenarios (SSP3-7.0 and SSP5-8.5), substantially altering the shape of seasonality of mortality and, under the highest emission scenario (SSP5-8.5), shifting the mortality peak from cold seasons to warm seasons in arid, temperate, and continental zones, and increasing the size of seasonality in all zones except the arid zone by the end of the century. In the 2090s compared with the 2000s, the change in peak-to-trough ratio (relative scale) ranged from 0·96 to 1·11, and the change in attributable fraction ranged from 0·002% to 0·06% under the SSP5-8.5 (highest emission) scenario.

Interpretation A warming climate can substantially change the seasonality of mortality in the future. Our projections suggest that health-care systems should consider preparing for a potentially increased demand during warm seasons and sustained high demand during cold seasons, particularly in regions characterised by arid, temperate, and continental climates.

Funding The Environment Research and Technology Development Fund of the Environmental Restoration and Conservation Agency, provided by the Ministry of the Environment of Japan.

Lancet Planet Health 2024; 8: e86–94

*Collaborators are listed at the end of the Article

School of Tropical Medicine and Global Health, Nagasaki University, Nagasaki, Japan (L Madaniyazi PhD, Prof M Hashizume PhD); **Department of Public Health Environments and Society, London School of Hygiene & Tropical Medicine, London, UK** (Prof B Armstrong PhD, M N Mistry PhD, Prof A Gasparrini PhD); **Institute of Environmental Assessment and Water Research, Spanish Council for Scientific Research, Barcelona, Spain** (A Tobias PhD); **Department of Economics, Ca' Foscari University of Venice, Venice, Italy** (M N Mistry); **School of the Environment, Yale University, New Haven, CT, USA** (Prof M L Bell PhD); **Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czech Republic** (A Urban PhD, J Kyselý PhD); **Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic** (A Urban, J Kyselý); **Center for Environmental and Respiratory Health Research, University of Oulu, Oulu, Finland** (N Ryti PhD, Prof J J K Jaakkola PhD); **Medical Research Center Oulu, Oulu University Hospital and University of Oulu, Oulu, Finland** (N Ryti, Prof J J K Jaakkola); **Department of Public Health, University of Helsinki, Helsinki, Finland** (N Ryti); **Barcelona Institute for Global Health, Barcelona, Spain** (I Cvijanovic PhD); **Department of Global Health Policy, Graduate School of Medicine, The University of Tokyo, Tokyo, Japan** (C F S Ng PhD, Prof M Hashizume); **Climate Research Foundation, Madrid, Spain** (D Roye PhD); **Spanish Consortium for Research and Public Health (CIBERESP),**

Introduction

The seasonal variation, or pattern, in mortality (hereafter referred to as seasonality of mortality) is a well documented phenomenon, usually exhibiting a sinusoidal shape with higher mortality in cold seasons than in warm seasons. Although several risk factors can contribute to this seasonality, temperature has been identified as a key driver, especially in temperate and continental climate zones.[1]

Both low and high temperatures can increase mortality risk.[2,3] With the warming climate, mortality due to cold is projected to decrease, whereas heat-related mortality is expected to increase in most areas.[4] Thus, it is crucial to gather evidence on whether the warming climate will alter the seasonality of mortality and, if so, to what extent. However, to date, very few studies have explored this topic. We are aware of only one study[5] in which the authors projected maximum monthly mortality progressively shifting from winter to summer under climate change scenarios in Europe. A systematic and comprehensive global scale assessment is needed to

Instituto de Salud Carlos III, Madrid, Spain (D Roye, C Íñiguez PhD); Institute of Social and Preventive Medicine, University of Bern, Bern, Switzerland (A M Vicedo-Cabrera PhD); Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland (A M Vicedo-Cabrera); National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China (Prof S Tong PhD); School of Public Health and Social Work, Queensland University of Technology, Brisbane, QLD, Australia (Prof S Tong); School of Epidemiology and Public Health, Faculty of Medicine, University of Ottawa, Ottawa, ON, Canada (Prof E Lavigne PhD); Environmental Health Science and Research Bureau, Health Canada, Ottawa, ON, Canada (Prof E Lavigne); Department of Statistics and Computational Research, Universitat de València, València, Spain (C Íñiguez); Department of Epidemiology, Instituto Nacional de Saúde Dr Ricardo Jorge, Lisbon, Portugal (S d N P da Silva MSc); Environmental Health Department, National Institute of Health, Porto, Portugal (J Madureira PhD); EPIUnit, Instituto de Saúde Pública, Universidade do Porto, Porto, Portugal (J Madureira); Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional, Porto, Portugal (J Madureira); Finnish Meteorological Institute, Helsinki, Finland (Prof J J K Jaakkola); Department of Statistics, Computer Science and Applications "G Parenti", University of Florence, Florence, Italy (F Sera PhD); Center for Climate Change Adaptation, National Institute for Environmental Studies, Tsukuba, Japan (Prof Y Honda PhD)

Correspondence to: Dr Lina Madaniyazi, School of Tropical Medicine and Global Health, Nagasaki University, Nagasaki 852-8523, Japan lina.madaniyazi@nagasaki-u.ac.jp

For more on the **MCC** see http://mccstudy.lshtm.ac.uk/

Research in context

Evidence before this study

The seasonality of mortality is a well documented phenomenon, typically characterised by higher mortality in cold seasons than in warm seasons. Temperature is a key factor contributing to this seasonal variation. With global warming, there is an ongoing discussion about if and how the increasing temperature will impact the seasonality of mortality in the future. We did a search on PubMed, Scopus, and Google Scholar to identify original research articles published before Feb 8, 2023 that projected the seasonality of mortality under climate change. The search terms used were "seasonality" AND "mortality" AND "climate change". We found only one study that had projected the impact of climate change on seasonality of mortality. This study was restricted to Europe and reported the maximum monthly mortality changes. However, to our knowledge, no study to date has provided a comprehensive analysis of future changes in the seasonality of mortality at a global scale.

Added value of this study

Our analysis provides a comprehensive and systematic assessment of the impact of climate change on the seasonality of mortality across more than 700 locations in four major climate zones (arid, continental, temperate, and tropical) at a global scale. In particular, we assessed the changes in seasonality of mortality under several climate change scenarios by comparing the shape of fitted seasonal curves (ie, rise and fall of mortality throughout the year), timing of seasonality (ie, the day-of-year with maximum [peak] and minimum [trough] mortality), and size of seasonality (ie, peak-to-trough ratio and attributable fraction representing the amplitude and impact, respectively).

Implications of all the available evidence

Our analysis indicates that the warming climate would increase mortality in warm seasons and decrease mortality in cold seasons in the future, albeit with mortality remaining high in cold seasons, in arid, temperate, and continental zones. This changing pattern was pronounced in high-emission scenarios, altering the shape of seasonality of mortality and, under the highest emission scenario, shifting the mortality peak from cold seasons to warm seasons in arid, temperate, and continental zones. The size of seasonality was increased by the end of the century under the high-emission scenarios, except for the arid zone. The evidence produced in this study provides new information on the health impacts of climate change and can contribute to the development of climate and public health policies, such as policies addressing potential fluctuations in health-care demands under a warming climate.

understand the impact of a warming climate on seasonality across different climate zones. Questions also remain on whether climate change will impact the size of seasonality, and if so, to what extent. Investigation of this topic is crucial for the development of climate change-informed public health policies; for example, policies on the allocation of health-care resources in different seasons in the future.

In this study, we project the impact of climate change on seasonality of mortality on a global scale, covering four climate zones. Specifically, we examined the changes in seasonality of mortality between the present and future by comparing its shape (ie, rise and fall in mortality throughout the year), timings (the day-of-year of the peak and trough), and size (ie, amplitude and impact).

Methods

Data collection

We collected daily time series of observed mean temperature and mortality from either all causes or, when those data were not available, non-external causes only (International Classification of Diseases [ICD]: codes A00–R99 for the ICD 10th Revision, and codes 001–799 for the ICD 9th Revision), via the Multi-Country Multi-City (MCC) Collaborative Research Network. The data covers 707 locations (ie, cities, provinces, prefectures, or regions) across 43 countries or areas in largely overlapping periods from Jan 1, 1969, to Dec 31, 2020, with varying periods of 2 years to 50 years in length. The study locations were characterised by five Köppen–Geiger climate zones: arid, continental, polar, temperate, and tropical zones.[6]

We obtained modelled data on daily mean temperature from Jan 1, 1969 to Dec 31, 2099, under the Shared Socioeconomic Pathway (SSP) scenarios within Phase 6 of the Coupled Model Intercomparison Project.[7,8] We selected four emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), corresponding to different socioeconomic development pathways and increasing atmospheric greenhouse gas concentrations. These four scenarios describe a range of changes in climate, from mild (SSP1-2.6) to extreme (SSP5-8.5). Specifically, SSP1-2.6 prioritises sustainability with aggressive emissions reduction, SSP2-4.5 takes a moderate approach to addressing climate change, SSP3-7.0 emphasises economic growth with less environmental focus, and SSP5-8.5 prioritises economic growth with minimal emission control.[7] The data under each scenario includes five simulated sets of data from five general circulation models (GCMs) from the database of the Inter-Sectoral Impact Model Intercomparison Project,[9] in which the data are bias-corrected and downscaled to $0·5°\times0·5°$ spatial resolution for each GCM.[10] We extracted the modelled data for each MCC location by linking each location's GPS coordinates with the corresponding GCM grid cell from the simulations in 1969–2099. To preserve the trend and variability of the original data in the observed series, we recalibrated the modelled temperature series using the observed daily mean temperature series.[11] We calculated the difference in the annual mean temperature averaged across the five GCMs and all the locations between the years 2099 and 2000 under each scenario.

Statistical analysis

Our analysis proceeded in two steps. First, we projected the daily mortality from 2000 to 2099 under each climate change scenario for each location. Then, we assessed the seasonality of the projected mortality and compared it between decades. A detailed description of the analytical framework and statistical methods, partly described in previous work,[1,12] is provided in the appendix (pp 1–3).

We fitted a quasi-Poisson regression model to the observed daily mortality time series. We modelled a non-linear and delayed exposure–lag–response association between observed temperature and mortality, by applying a cross-basis function with 21 days for lag, as previously described.[2,13] We modelled the baseline seasonality (that remaining after temperature effects were modelled) using a cyclic spline of day-of-year ranging from 1 to 365 days (starting from Jan 1 to Dec 31 for locations in the northern hemisphere and July 1 to June 30 of the following year for locations in the southern hemisphere, and removing Feb 29 from the datasets) with four degrees of freedom. We modelled the long-term trend in the observed daily mortality time series using a natural cubic spline of the date with two degrees of freedom per decade.

We obtained the model parameters from the fitted quasi-Poisson regression model, fixed the long-term trend at a baseline value (eg, value on Jan 1, 2000), replaced the observed temperature series with modelled temperature series under climate change scenarios, and projected the daily mortality from 2000 to 2099 for each location and all combinations of GCMs and SSPs (five GCMs for each of the four SSPs: 20 outputs for each location). The baseline value of the long-term trend differed across locations due to variations in the observation periods at each location. By using the model parameters from the fitted regression model, we assumed the baseline seasonality and temperature–mortality dependence did not change between 2000 and 2099, so that the only changes in mortality were those due to changes in temperature. For the seasonality assessment in the next step, we calculated the daily mean mortality for each day from 2000 to 2099, averaged across five GCMs under each SSP for each location.

We assessed the future overall seasonality from the projected daily mortality by following methods for estimating seasonality used in previous studies.[1,12] In brief, we used a cyclic spline with four degrees of freedom for the day-of-year. From the fitted seasonal curve, we summarised the seasonality of mortality by describing its shape (ie, rise and fall in mortality), identifying its timing of the peak and trough (ie, the day-of-year with the highest and lowest mortality, respectively), and estimating its size by using the peak-to-trough ratio and the fraction of deaths attributable to seasonality (attributable fractions).[12] The peak-to-trough ratio is the ratio of the maximum mortality estimate at the peak day to the minimum mortality estimate at the trough day. 95% CIs for peak-to-trough ratio were obtained from the variance matrix of the fitted cyclic spline coefficients. The attributable fraction estimates the fraction by which mortality would be reduced in a counterfactual scenario in which mortality risk never increases above its seasonal trough (ie, the burden of seasonality of mortality). The 95% empirical confidence intervals (eCIs) for peak and trough timings and attributable fraction were estimated via Monte Carlo simulations.[12]

See Online for appendix

We assessed the future seasonality in each location by decade. The estimates from location-specific seasonality assessment were summarised with a multivariate meta-analysis[14] of the fitted cyclic spline coefficients to obtain mean seasonal patterns for each climate zone (location nested within the country or area as random effects) and country or area (location as a random effect), respectively. We then compared seasonal shapes, peak and trough timings, and sizes between decades. We reported the change in size between decades, using the ratio of peak-to-trough ratio and the absolute difference in attributable fraction. We report 95% CIs for the ratio of peak-to-trough ratio, and 95% eCIs for the difference in attributable fraction. Further details on the calculations are provided in the appendix (p 2). We excluded two high-altitude locations from Peru when summarising results by climate zones, as they were the only locations in our dataset characterised as having a polar climate. These two locations were, however, included in country-specific summary results for Peru. When describing the results, we use cold seasons (Oct 1 to March 31 for locations in the northern hemisphere, and April 1 to Sept 30 for locations in the southern hemisphere) and warm seasons (remaining months for each hemisphere) to represent the months with generally low and high temperatures, respectively.

As a sensitivity analysis, we repeated the whole analysis after restricting the observed series to the data since Jan 1, 2000, as previous studies suggested a reduced peak-to-trough ratio and some changes in temperature–mortality association over time.[15–18] Several locations in our dataset had data over a long period. We chose 2000 as the cutoff year to encompass all the locations in our sensitivity analysis while also restricting the observed series to the most recent decades.[19]

We did all analyses using R (version 4.2.2 for macOS), using the packages dlnm and mixmeta.

Results

The MCC dataset included 126 809 537 deaths from 707 locations within 43 countries or areas. We removed the only two polar locations (both in Peru) when obtaining modelled estimates for climate zones; thus, 126 766 164 deaths were analysed from 705 locations, aggregated in four climate zones (table). The daily mean temperature was heterogeneous across locations between and within climate zones (figure 1). The highest mean temperature was observed in the tropical zone, whereas the continental zone showed the largest variation (table). Across the 707 locations from 2000 to 2099, the annual mean temperature was projected to increase by 1·35°C, 2·73°C, 4·26°C, and 5·55°C, under the scenarios of SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively.

Figure 2 shows the shape of mortality seasonality by climate zone for each decade during 2000–99 under the four SSP scenarios. The shape of seasonality showed high mortality in the cold seasons and low mortality in the warm seasons at the beginning of the century in four climate zones, although the pattern is less evident in the tropical zone. In arid, temperate, and continental zones, the high mortality in cold seasons was projected to decrease throughout the century, albeit remaining high, whereas the low mortality in the warm seasons started to increase under all the scenarios. This changing pattern was most pronounced under the high-emission scenarios (SSP3-7.0 and SSP5-8.5), leading to a substantial change in the seasonal shape. The highest mortality was projected to occur in the warm seasons, followed by a second peak in the cold seasons in temperate, continental, and arid zones by the end of the century under the highest emission scenario (SSP5-8.5). In the tropical zone, the seasonal shape was also projected to change, generally becoming pronounced with time under all the scenarios, although the magnitude of change was small under the low-emission scenarios (SSP1-2.6 and SSP2-4.5). Similar patterns were projected when restricting the observed time series to the data since 2000 (results not shown).

Timings of the peak and trough (ie, day-of-year) were also projected to change, with a minimal change under the low-emission SSP scenarios except for the tropical zone, but notable shifts under the high-emission scenarios (appendix pp 4–7). However, the 95% eCIs of the projected peaks and troughs were generally wide. One of the noteworthy changes was projected in the temperate zone under SSP5-8.5: between the 2000s and 2090s, the peak in the temperate zone was projected to shift from day-of-year 18 (95% eCI 14–21) in the cold season to day-of-year 214 (212–215) in the warm season. The trough was projected to shift from day-of-year 256 (239–263) in the warm season to day-of-year 299 (295–302) in the cold season.

Figure 3 shows the changes in peak-to-trough ratio and attributable fraction by decade compared with 2000–09 in each climate zone under the four SSP scenarios. Projected sizes by decade under the SSPs are listed in the appendix (pp 8–11). The peak-to-trough ratio and attributable fraction generally decreased towards the middle of the century and remained constant thereafter

	Number of locations	Study period	Temperature, °C	Total deaths
Tropical	100	1973–2019	26·8°C (2·83)	6 567 145
Arid	50	1973–2016	18·6°C (8·04)	5 078 282
Temperate	438	1972–2020	14·2°C (8·17)	95 150 371
Continental	117	1969–2018	9·4°C (10·70)	19 970 366
Total	705*	1969–2020	14·3°C (9·40)	126 766 164

Temperature, presented as mean (SD), was calculated by averaging the daily mean location-specific temperatures across all locations during their respective study periods within each climate zone. Total deaths are from either all causes (available for 554 locations) or, when those data were not available, non-external causes only (available for 151 locations). *Two high-altitude locations in Peru are in the polar climate zone, which were excluded in climatic zone assessment but included when summarising results for Peru; the total number of deaths in these two locations was 43 373.

Table: Descriptive statistics by climate zone

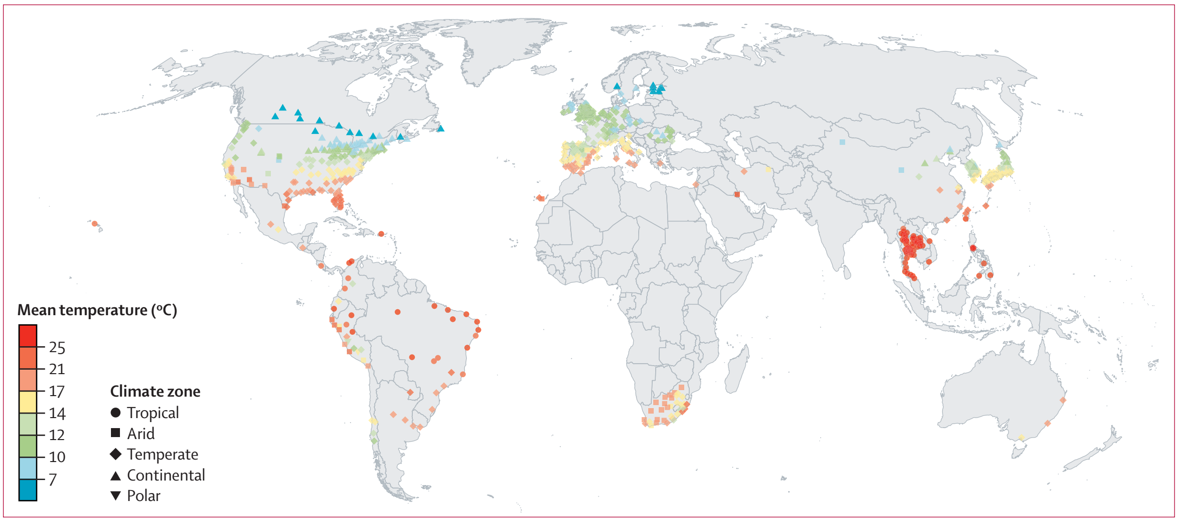

Figure 1: **The average of daily mean temperatures of the 707 locations included in the analysis**
The locations represent cities, provinces, prefectures, or regions from five climate zones. The colours represent different levels of mean temperature by averaging the daily mean temperature in each location during their respective study periods. The shapes represent five climate zones.

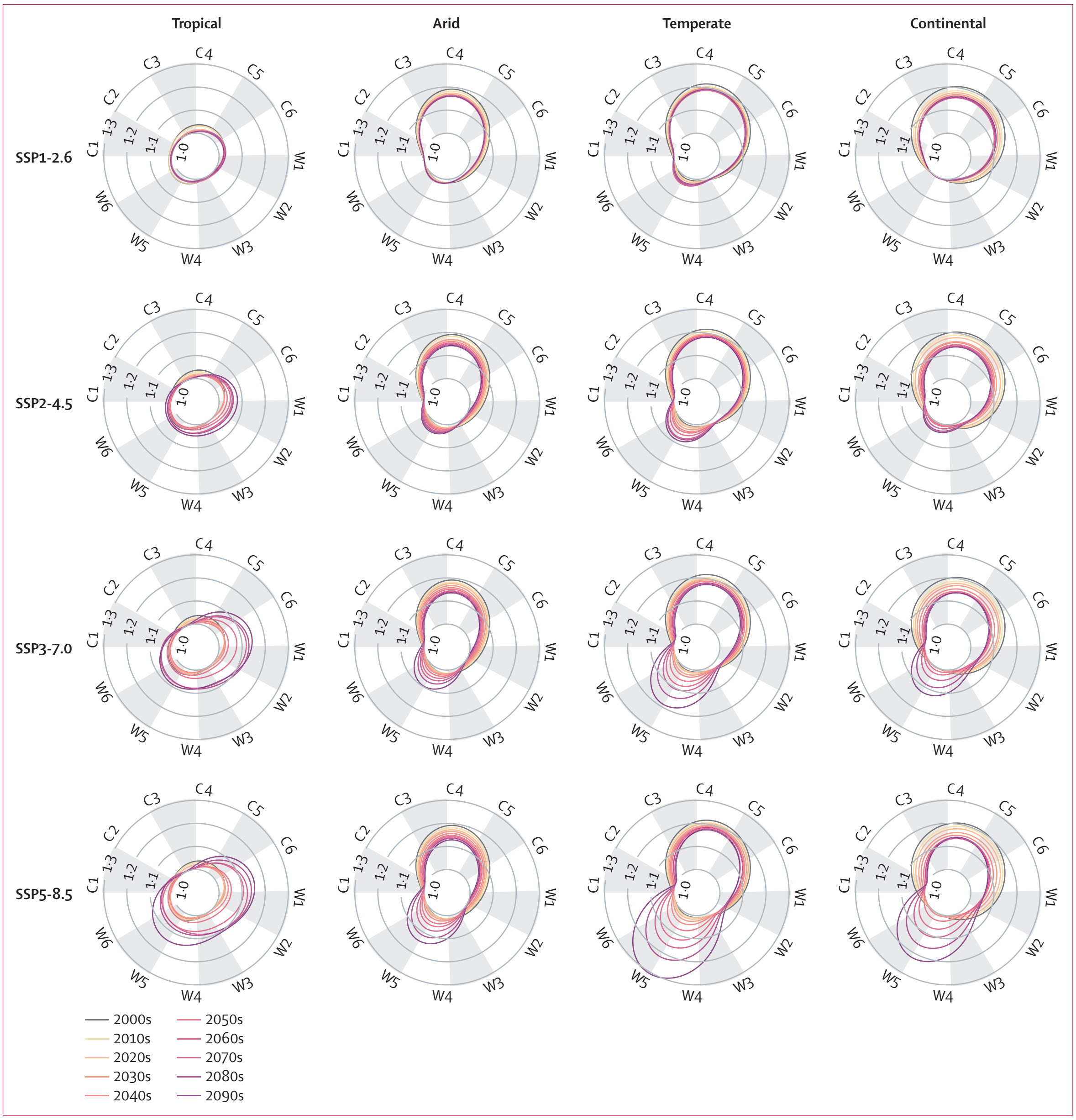

Figure 2: **Shape of seasonality of mortality in four climate zones from the 2000s to 2090s**

Seasonality was computed as the relative risk of mortality estimates on each day-of-year (*i*) to minimum mortality estimates on the trough day for four climate zones: relative risk=mortality estimate at day-of-year$_i$/minimum mortality estimate at the trough. The circles labelled 1·0–1·3 indicate relative risk. C1–C6 represents the months in the cold season (ie, October to March for locations in the northern hemisphere, and April to September for locations in the southern hemisphere), and W1–W6 represent the remaining months in the warm season for each hemisphere. The grey line represents the shape of seasonality in the 2000s, and the sequential colours represent the shape of seasonality from the 2010s to the 2090s. SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 represent the four emission scenarios.[7] SSP=Shared Socioeconomic Pathway.

under the lowest emission scenario (SSP1-2.6). However, this trend was generally reversed under the high-emission scenarios after the mid-century, with increasing peak-to-trough ratio or attributable fraction (or both) at the end of the century for all the climate zones except the arid zone. Compared with estimates for the 2000s, increases were projected in both peak-to-trough ratio and attributable fraction in the 2090s in the tropical, temperate, and continental zones under SSP5-8.5. The tropical zone was projected to have the most substantial increase, followed by the temperate zone. In the tropical zone, peak-to-trough ratio was projected to increase from 1·04 (95% CI 1·00 to 1·08) in the 2000s to 1·16 (1·05 to 1·27) in the 2090s, with a relative increase of 1·11 (95% CI 1·01 to 1·23), and attributable fraction was projected to increase from 0·02% (95% eCI 0·01 to 0·04)

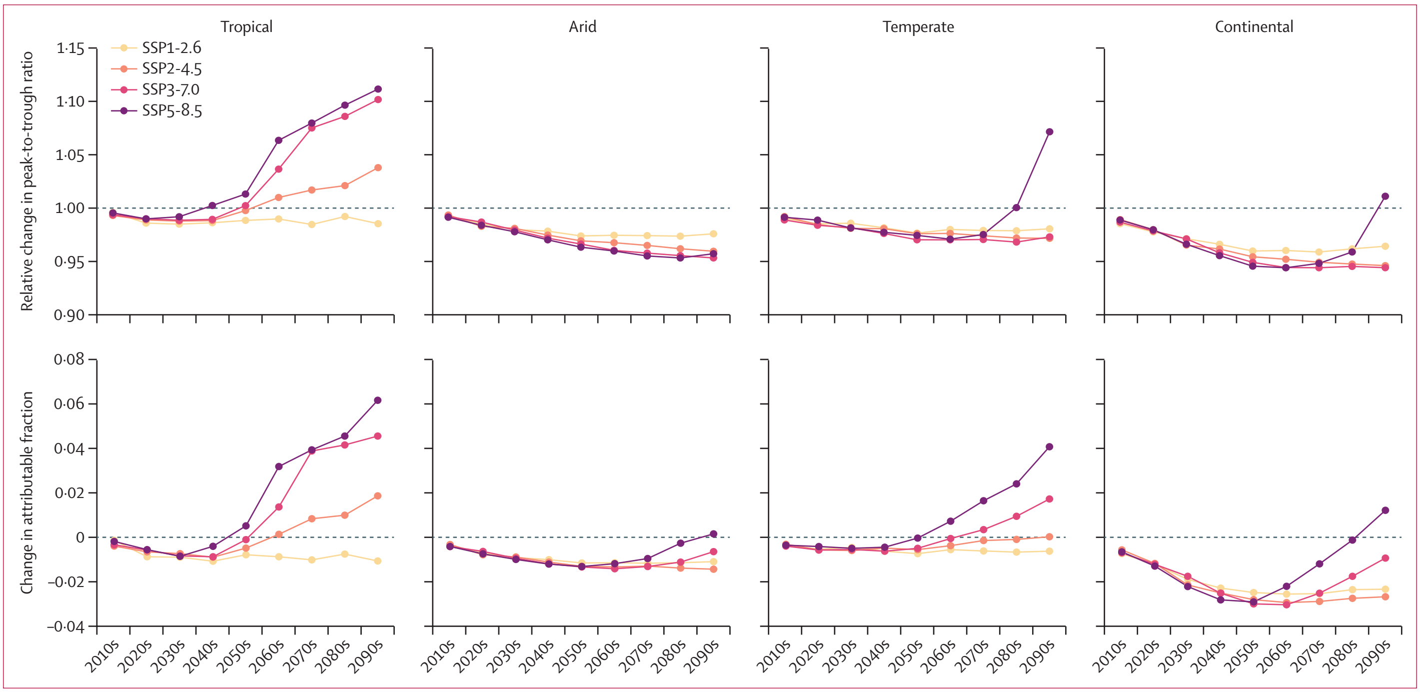

Figure 3: **Temporal changes in the size of seasonality of mortality by climate zone**
Difference in the size of seasonality of mortality by decade compared with the 2000s in four climate zones. Change in peak-to-trough ratio and attributable fraction was calculated as the ratio of peak-to-trough ratio and the absolute difference in attributable fraction by decade compared with the 2000s. SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 represent the four emission scenarios.[7] SSP=Shared Socioeconomic Pathway.

in the 2000s to 0·08% (0·04 to 0·15) in the 2090s, reflecting a 0·06% (95% eCI 0·01 to 0·12) rise. In the temperate zone, peak-to-trough ratio was projected to increase from 1·22 (95% CI 1·18 to 1·26) in the 2000s to 1·31 (1·18 to 1·44) in the 2090s, with a relative increase of 1·07 (95% CI 0·96 to 1·19), and attributable fraction was projected to increase from 0·07% (95% eCI 0·06 to 0·08) in the 2000s to 0·11% (0·08 to 0·14) in the 2090s, reflecting a 0·04% (95% eCI 0·01 to 0·07) increase. Conversely in the arid zone, a reduction in peak-to-trough ratio and a negligible difference in attributable fraction was projected under SSP5-8.5 between the 2000s and 2090s: peak-to-trough ratio was projected to decrease from 1·19 (95% CI 1·11 to 1·29) in the 2000s to 1·14 (0·96 to 1·36) in the 2090s, representing a relative decrease of 0·96 (95% CI 0·79 to 1·16), and attributable fraction was projected to remain similar, from 0·06% (95% eCI 0·04 to 0·09) in the 2000s to 0·06% (0·03 to 0·11) in the 2090s, reflecting a 0·00% (95% eCI –0·05 to 0·05) difference.

Results on the shape and size of seasonality of mortality by decade for each country or area are presented in the appendix (pp 12–50). In general, a similar pattern of increasing mortality in warm seasons and reducing mortality in cold seasons was projected for the shape of seasonality, except for Ireland and South Africa, where a marginal change, particularly in the warm seasons, was projected under the high-emission scenarios (appendix pp 12–34). Notably, some countries within the same climate zone showed variations in the shape of seasonality. For instance, the Philippines, Thailand, and Viet Nam, all located in the tropical climate zone, displayed some disparities in projected seasonal curves under all four SSP scenarios (appendix pp 12–34). In addition, the changes in the size of seasonality showed similar patterns across most countries as observed for the size of seasonality by climate zones, with the exception of a few countries (appendix pp 35–50). For example the UK (temperate climate zone) in northern Europe, Japan and South Korea (temperate and continental climate zones) in east Asia, Mexico (arid and temperate climate zones) in North America, and South Africa (arid and temperate climate zones) in Africa, showed a constant reduction in both peak-to-trough ratio and attributable fraction during the century under the high-emission scenarios (appendix pp 35–50).

Discussion

To the best of our knowledge, this study represents the first global investigation of the future impact of climate change on seasonality of mortality. The study used data from more than 700 locations, encompassing highly diverse populations across various climate zones. Our findings indicate that a warming climate might substantially alter the seasonality of mortality in the future, with the mortality peak potentially shifting from cold to warm seasons under the highest emission scenario in the arid, temperate, and continental zones by the end of the century. Furthermore, the size of the seasonality was projected to increase by the end of the century in most locations except the arid zone under high-emission scenarios.

Although the seasonality of mortality throughout the year has changed in several regions since the 1800s,[20,21] the current pattern almost everywhere is higher mortality in cold seasons than in warm seasons.[1] Temperature is a key driver of this pattern.[1,15,22] It has been hypothesised that, under climate change, increasing temperature could alter seasonality in the future;[23] however, evidence is scarce. To our knowledge, only one study in Europe has investigated the impact of climate change on the seasonality of mortality, and projected a change in maximum monthly mortality from winter to summer.[5] Our projections showed an increase in mortality in warm seasons and a decrease in cold seasons under all the SSP scenarios applied, albeit with mortality remaining high in cold seasons in arid, temperate, and continental zones. This trend intensified from low-emission to high-emission scenarios and reshaped seasonality under the highest emission scenarios throughout the century, shifting the peak from cold to warm seasons and increasing the impact of seasonality (ie, attributable fraction), especially during the second half of the century, with different climate zones being differentially affected by these changes. This overall changing pattern reflects the impact of increasing temperature on mortality under low-emission and high-emission scenarios: a previous study projected a reduction in cold-related mortality and an increase in heat-related mortality under both low-emission and high-emission scenarios, whereby a steep rise in heat-related mortality outweighed a reduction in cold-related deaths under the highest emission scenario.[4] This change could result in a substantial increase in mortality during warm seasons and a reduction during cold seasons across most regions, as projected for respiratory mortality in Spain.[24]

Our results show some geographical differences. In particular, the mortality in cold seasons was projected to remain high relative to a trough in spring or autumn in places with temperate, continental, and arid climates (figure 2), suggesting the reduction in cold-related deaths under a warming climate might not diminish the mortality in cold seasons by very much in these zones. This might be due to the strong baseline seasonality of mortality (ie, seasonal variation in mortality after the effects of temperature are removed) in these zones, driven by other seasonal risk factors, such as infectious diseases, air pollutants, and human behaviours. However, our projections in the tropical zone showed a different pattern, in which mortality was projected to decrease marginally in some of the cold season, but to increase in other parts of the cold season as well as during the warm season (figure 2). The seasonality of mortality in tropical climates is less pronounced than in other zones (ie, smaller peak-to-trough ratio),[1] and thus might be easily reshaped by the increasing heat-related mortality and decreasing cold-related deaths under a warming climate.

Some assumptions and limitations should be acknowledged. Seasonality of mortality is driven by a group of factors, including environmental, social, and demographic variables.[25,26] In our analysis, we assumed a constant baseline seasonality and considered only changes in temperature to project daily mortality patterns from 2000 to 2099. This approach allowed for isolation of the effect of a warming climate, but ignored contributions from the other seasonal factors (eg, rainfall in tropical zones). In addition, we assumed a constant effect of temperature on mortality and did not consider the potential adaptation of the population to increasing temperature. This assumption may have led to an overestimation of heat-related mortality in warm seasons. When a full adaptation to increasing temperature occurs, the seasonality of mortality will not change unless the baseline seasonality shifts. However, adaptation poses a multifaceted challenge that warrants dedicated research in the future. Our results for the climate zones and countries or areas included might not be fully representative, as some zones and countries or areas had low or no data inclusion. Specifically, a substantial portion of Africa and Asia (except for South Africa and east Asia) lacked representation due to data scarcity. Additionally, our projection of daily mortality is affected by considerable uncertainty, because of temperature variability in the climate models and the imprecision in the estimated temperature-mortality association. The pooled seasonality results for climate zones, particularly tropical zones, might also have some uncertainty due to divergent seasonal patterns across locations within the same climate zone. Furthermore, we acknowledge that the finding of increasing mortality peaks in two seasons on average in tropical climates is puzzling and deserves more research. Finally, the quality of our daily mortality data might exhibit variability across time and locations, given the extensive time span and broad geographical coverage of the dataset.

In this study, we considered the seasonal changes in mortality under different climate change scenarios, across multiple locations globally, covering highly diverse populations from four major climate zones. Our findings reveal three key insights. Firstly, under high-emission climate scenarios, mortality peaks might shift to the warm seasons, which could pose challenges for health-care resource allocation. Secondly, in regions characterised by temperate, continental, and arid climates, cold-season mortality was projected to persist at elevated rates, creating a dual challenge for health-care systems. Lastly, without stricter climate action, some areas, especially those with tropical and temperate climates, might experience a heavier seasonal mortality burden (ie, increasing attributable fraction) in the future than at present, suggesting that resource allocation would need to adjust accordingly. In summary, our study suggests that health-care systems should consider the potential need to prepare for increased demand during warm seasons and sustained high demand during cold seasons, particularly in regions with temperate, continental, and arid climates. These findings warrant careful consideration for policy planning.

Multi-Country Multi-City (MCC) Collaborative Research Network

Argentina Rosana Abrutzky (Universidad de Buenos Aires, Facultad de Ciencias Sociales, Instituto de Investigaciones Gino Germani, Buenos Aires). *Australia* Yuming Guo, Shanshan Li (Climate, Air Quality Research Unit, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC). *Brazil* Micheline de Sousa Zanotti Stagliorio Coelho (Department of Pathology, Faculty of Medicine, University of São Paulo, São Paulo), Samuel Osorio (Department of Environmental Health, University of São Paulo, São Paulo), Paulo Hilario Nascimento Saldiva (INSPER, São Paulo). *Chile* Patricia Matus Correa (Department of Public Health, Universidad de los Andes, Santiago), Nicolás Valdés Ortega (Centro Interdisciplinario de Cambio Global, Pontificia, Universidad Católica de Chile, Santiago). *China* Haidong Kan (Department of Environmental Health, School of Public Health, Fudan University, Shanghai). *Estonia* Ene Indermitte, Hans Orru (Institute of Family Medicine and Public Health, University of Tartu, Tartu). *France* Mathilde Pascal (Santé Publique France, Department of Environmental and Occupational Health, French National Public Health Agency, Saint Maurice). *Germany* Veronika Huber (Helmholtz Zentrum München, Institute of Epidemiology, Munich), Alexandra Schneider (Institute of Epidemiology, Helmholtz Zentrum München – German Research Center for Environmental Health, Neuherberg). *Greece* Antonis Analitis, Klea Katsouyanni (Department of Hygiene, Epidemiology and Medical Statistics, Medical School, National and Kapodistrian University of Athens, Athens). *Iceland* Hanne Krage Carlsen (Centre of Public Health, University of Iceland, Reykjavík). *Iran* Fatemeh Mayvaneh, Alireza Entezari (Faculty of Geography and Environmental Sciences, Hakim Sabzevari University, Sabzevar). *Ireland* Patrick Goodman (Technological University Dublin, Dublin). *Israel* Raanan Raz (Braun School of Public Health and Community Medicine, The Hebrew University of Jerusalem). *Italy* Fiorella Acquaotta (Department of Earth Sciences, University of Torino, Turin), Francesca de'Donato, Paola Michelozzi (Department of Epidemiology, Lazio Regional Health Service, ASL Roma 1, Rome). *Japan* Yoonhee Kim (Department of Global Environmental Health, Graduate School of Medicine, University of Tokyo, Tokyo), Xerxes Seposo (Department of Hygiene, Graduate School of Medicine, Hokkaido University, Sapporo). *Mexico* Magali Hurtado Diaz, César De la Cruz Valencia (Department of Environmental Health, National Institute of Public Health, Cuernavaca, Morelos). *Moldova* Ala Overcenco (National Agency for Public Health of the Ministry of Health, Labour and Social Protection, Chișinău). *Netherlands* Danny Houthuijs (National Institute for Public Health and the Environment, Centre for Sustainability and Environmental Health, Bilthoven). *Norway* Shilpa Rao (Norwegian Institute of Public Health, Oslo). *Peru* Gabriel Carrasco-Escobar (Health Innovation Laboratory, Institute of Tropical Medicine "Alexander von Humboldt", Universidad Peruana Cayetano Heredia, Lima). *Romania* Iulian-Horia Holobaca (Faculty of Geography, Babeș -Bolyai University, Cluj-Napoca). *South Korea* Ho Kim (Graduate School of Public Health, Seoul National University, Seoul), Whanhee Lee (School of Biomedical Convergence Engineering, College of Information and Biomedical Engineering, Pusan National University, Yangsan). *Sweden* Bertil Forsberg (Department of Public Health and Clinical Medicine, Umeå University, Umeå). *Switzerland* Martina S Ragettli (Swiss Tropical and Public Health Institute, Allschwill). *Taiwan* Yue Leon Guo (Environmental and Occupational Medicine, National Taiwan University [NTU] College of Medicine and NTU Hospital, Taipei), Shih-Chun Pan (National Institute of Environmental Health Science, National Health Research Institutes, Zhunan). *UK* Ariana Zeka (Institute for Global Health, University College London, London). *USA* Barrak Alahmad, Antonella Zanobetti, Joel Schwartz (Department of Environmental Health, Harvard T H Chan School of Public Health, Harvard University, Boston, MA), Noah Scovronick (Department of Environmental Health. Rollins School of Public Health, Emory University, Atlanta, GA). *Uruguay* Valentina Colistro (Department of Quantitative Methods, School of Medicine, University of the Republic, Montevideo). *Viet Nam* Tran Ngoc Dang (Department of Environmental Health, Faculty of Public Health, University of Medicine and Pharmacy at Ho Chi Minh City, Ho Chi Minh City), Do Van Dung (Department of Environmental Health, Faculty of Public Health, University of Medicine and Pharmacy at Ho Chi Minh City, Ho Chi Minh City).

Contributors

LM, AT, and MH designed the study. LM and BAr developed the statistical methods. LM took the lead in drafting the manuscript and interpreting the results. DR contributed to the data visualisation. All authors provided the data and contributed to the interpretation of results and the submitted version of the manuscript. LM, BAr, AT, and MH accessed and verified the data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data used in our study were obtained from the MCC Collaborative Research Network under a data-sharing agreement and cannot be made publicly available. Researchers can refer to collaborators of the Network, who are listed as coauthors of this Article (primary contact: Antonio Gasparrini, Antonio.Gasparrini@lshtm.ac.uk), for information on accessing the data for each country. The R code is available on request, and a reproducible example is publicly available on the personal GitHub website of the first author (https://github.com/LinaMadaniyazi).

Acknowledgments

This study was primarily supported by the Environment Research and Technology Development Fund (grant number JPMEERF20231007) of the Environmental Restoration and Conservation Agency, provided by the Ministry of the Environment of Japan. MH was supported by the Japan Science and Technology Agency as part of the Strategic International Collaborative Research Program (grant number JPMJSC20E4). AG was supported by the UK Medical Research Council (grant number MR/V034162/1) and the EU's Horizon 2020 research project Exhaustion (grant number 820655). AU and JK were supported by the Czech Science Foundation (project 22–24920S). JJKJ was supported by the Academy of Finland (grant number 310372; Global Health Risks Related to Atmospheric Composition and Weather Consortium). FS was supported by the Italian Ministry of University and Research, Department of Excellence project 2023–2027, Rethinking Data Science—Department of Statistics, Computer Science and Applications—University of Florence.

Editorial note: The Lancet Group takes a neutral position with respect to territorial claims in published maps, figures, and institutional affiliations.

References

1 Madaniyazi L, Armstrong B, Chung Y, et al. Seasonal variation in mortality and the role of temperature: a multi-country multi-city study. *Int J Epidemiol* 2022; **51:** 122–33.

2 Gasparrini A, Guo Y, Hashizume M, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 2015; **386:** 369–75.

3 Zhao Q, Guo Y, Ye T, et al. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet Health* 2021; **5:** e415–25.

4 Gasparrini A, Guo Y, Sera F, et al. Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health* 2017; **1:** e360–67.

5 Ballester J, Robine J-M, Herrmann FR, Rodó X. Long-term projections and acclimatization scenarios of temperature-related mortality in Europe. *Nat Commun* 2011; **2:** 358.

6 Peel MC, Finlayson BL, Mcmahon TA. Updated world map of the Köppen–Geiger climate classification. *Hydrol Earth Syst Sci Discuss* 2007; **4:** 439–73.

7 Riahi K, van Vuuren DP, Kriegler E, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob Environ Change* 2017; **42:** 153–68.

8 O'Neill BC, Tebaldi C, van Vuuren DP, et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 2016; **9:** 3461–82.

9 Lange S, Büchner M. ISIMIP3b bias-adjusted atmospheric climate input data (v1.1). 2021. https://doi.org/10.48364/ISIMIP.842396.1 (accessed June 20, 2022).

10 Lange S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1·0). *Geosci Model Dev* 2019; **12:** 3055–70.

11 Vicedo-Cabrera AM, Sera F, Gasparrini A, Gasparrini A. Hands-on tutorial on a modeling framework for projections of climate change impacts on health. *Epidemiology* 2019; **30:** 321–29.

12 Madaniyazi L, Tobias A, Kim Y, Chung Y, Armstrong B, Hashizume M. Assessing seasonality and the role of its potential drivers in environmental epidemiology: a tutorial. *Int J Epidemiol* 2022; **51:** 1677–86.

13 Gasparrini A, Armstrong B, Kenward MG. Distributed lag non-linear models. *Stat Med* 2010; **29:** 2224–34.

14 Sera F, Armstrong B, Blangiardo M, Gasparrini A. An extended mixed-effects framework for meta-analysis. *Stat Med* 2019; **38:** 5429–44.

15 Madaniyazi L, Chung Y, Kim Y, et al. Seasonality of mortality under a changing climate: a time-series analysis of mortality in Japan between 1972 and 2015. *Environ Health Prev Med* 2021; **26:** 69.

16 Gasparrini A, Guo Y, Hashizume M, et al. Temporal variation in heat–mortality associations: a multicountry study. *Environ Health Perspect* 2015; **123:** 1200–07.

17 Lee W, Choi HM, Lee JY, Kim DH, Honda Y, Kim H. Temporal changes in mortality impacts of heat wave and cold spell in Korea and Japan. *Environ Int* 2018; **116:** 136–46.

18 Chung Y, Noh H, Honda Y, et al. Temporal changes in mortality related to extreme temperatures for 15 cities in northeast Asia: adaptation to heat and maladaptation to cold. *Am J Epidemiol* 2017; **185:** 907–13.

19 Liu C, Chen R, Sera F, et al. Ambient particulate air pollution and daily mortality in 652 cities. *N Engl J Med* 2019; **381:** 705–15.

20 Momiyama M, Katayama K. A medico-climatological study in the seasonal variation of mortality in the United States of America (II)—signs of "deseasonality " seen in mortality. *Pap Meteorol Geophys* 1967; **18:** 209–32.

21 Rolden HJA, Rohling JHT, van Bodegom D, Westendorp RGJ. Seasonal variation in mortality, medical care expenditure and institutionalization in older people: evidence from a Dutch cohort of older health insurance clients. *PLoS One* 2015; **10:** e0143154.

22 Madaniyazi L, Ng CFS, Seposo X, et al. Role of temperature, influenza and other local characteristics in seasonality of mortality: a population-based time-series study in Japan. *BMJ Open* 2021; **11:** e044876.

23 Ebi KL, Mills D. Winter mortality in a warming climate: a reassessment. *Wiley Interdiscip Rev Clim Change* 2013; **4:** 203–12.

24 Achebak H, Devolder D, Ingole V, Ballester J. Reversal of the seasonality of temperature-attributable mortality from respiratory diseases in Spain. *Nat Commun* 2020; **11:** 2457.

25 Stewart S, Keates AK, Redfern A, McMurray JJV. Seasonal variations in cardiovascular disease. *Nat Rev Cardiol* 2017; **14:** 654–64.

26 Barnett AG, Dobson AJ. Analysing seasonal health data. Berlin: Springer, 2010.