Environment International 193 (2024) 109050

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

The reciprocal relation between rising longevity and temperature-related mortality risk in older people, Spain 1980–2018

Simon J LLOYD [a,*], Erich STRIESSNIG [b,*], José Manuel ABURTO [c], Hicham ACHEBAK [d], Shakoor HAJAT [e], Raya MUTTARAK [f], Marcos QUIJAL-ZAMORANO [a], Constanza VIELMA [a], Joan BALLESTER [a]

[a] *Climate and Health Programme, ISGlobal, Barcelona, Spain*
[b] *Department of Demography, University of Vienna, Vienna, Austria*
[c] *Department of Population Health, London School of Hygiene and Tropical Medicine, UK, Leverhulme Centre for Demographic Science, University of Oxford, UK, Interdisciplinary Centre on Population Dynamics, University of Southern Denmark, UK*
[d] *National Institute of Health and Medical Research (Inserm), Paris. 75013, France*
[e] *Centre on Climate Change and Planetary Health, London School of Hygiene and Tropical Medicine, London, UK. WC1E 7HT*
[f] *Department of Statistical Sciences "Paolo Fortunati", University of Bologna, Bologna, Italy*

ARTICLE INFO

Keywords:
Longevity
Heat-related mortality
Cold-related mortality
Climate change
Older people
Spain

ABSTRACT

Temperature-related mortality mostly affects older people and is attributable to a combination of factors. We focussed on a key non-temperature factor – rising longevity – and aimed to quantify its reciprocal relation with temperature-related mortality risk in Spain over 1980–2018.

We obtained average annual temperature-attributable deaths among people aged 65y+, by sex and age group, for different temperature ranges (extreme cold, moderate cold, moderate heat, and extreme heat), from a previous study. Combining this with population and mortality data as well as life table information, we used: (i) a counterfactual approach to assess the contribution of rising longevity to changes in the absolute risk of temperature-related mortality, and (ii) decomposition to assess the contribution of changes in temperature-related mortality to changes in longevity and its variation (lifespan inequality).

Rising longevity led to considerable declines in the absolute risk of temperature-related mortality in females and males across the entire temperature range. For extreme heat, it accounted for about a 30% decrease in absolute risk (half of the total decrease over the study period). For moderate and extreme cold, it accounted for about a 20% fall in absolute risk (a quarter of the total fall). In the opposite direction, changing patterns of temperature-related deaths contributed to higher life expectancy (accounting for > 20% of the total rise in both females and males) but also higher lifespan inequality amongst older people. Most of the influence (about 80%) was via moderate cold, but declines in risk at both moderate and extreme heat led to small rises in life expectancy.

Our study points to the benefits of adopting risk-reduction strategies that aim, not only at modifying hazards and reducing exposure, but that also address socially-generated vulnerability among older people. This includes ensuring that lifespans lengthen primarily through increases in years lived in good health.

Abbreviations: AF, Attributable Fraction; AN, Attributable Number; AR, Absolute Risk; BLUPs, Best Linear Unbiased Predictors; CI, Confidence Interval; DLNM, Distributed Lag Non-Linear Model); ERF, Exposure Response Function; INE, Instituto Nacional de Estadística (Spanish Institute of Statistics); LE, Life Expectancy; LI, Lifespan Inequality; MMT, Minimum Mortality Temperature; MMTP, Minimum Mortality Temperature Percentile; NUTS, Nomenclature of Territorial Units for Statistics; PAF, Population Attributable Fraction; RR, Relative Risk; SD, Standard Deviation.

[*] Corresponding authors.

E-mail addresses: simon.climate.health@gmail.com (S.J. LLOYD), erich.striessnig@univie.ac.at (E. STRIESSNIG), jose.aburto@lshtm.ac.uk (J.M. ABURTO), hicham.achebak@iserm.fr (H. ACHEBAK), shakoor.hajat@lshtm.ac.uk (S. HAJAT), raya.muttarak@unibo.it (R. MUTTARAK), marcos.quijal@isglobal.org (M. QUIJAL-ZAMORANO), constanza.vielma@isglobal.org, constanza.vielma@isglobal.org (C. VIELMA), joan.ballester@isglobal.org (J. BALLESTER).

https://doi.org/10.1016/j.envint.2024.109050
Received 7 May 2024; Received in revised form 12 September 2024; Accepted 2 October 2024

1. Introduction

Temperature-related mortality accounts for about 10% of deaths globally (Zhao et al., 2021), mostly affecting older people (Ebi et al., 2021). By convention, deaths are attributed to temperature if they are associated with daily average temperatures either below ("cold") or above ("heat") a statistically identified optimum at which risk is lowest (known as the Minimum Mortality Temperature, MMT) (Gasparrini et al., 2015b). At present, most temperature-related deaths (about 90%) are associated with cold conditions (Zhao et al., 2021), but the heat-attributable proportion is rising and, if climate change-driven warming continues unabated, may dominate before the end of the century (Gasparrini et al., 2017; Quijal-Zamorano et al., 2021). Notably, most temperature-related deaths occur at moderate temperatures rather than during extreme conditions (Gasparrini et al., 2015a). That is, while extreme heat poses a rapidly growing threat (Ballester et al., 2023) and may eventually compromise human survivability in some locations (Vecellio et al., 2023), most temperature-related deaths currently occur during "normal" conditions rather than in the face of intense but transitory hazards (Gasparrini et al., 2015a; Marí-Dell'Olmo et al., 2019).

In general, any death is ultimately due to a combination of factors (direct and indirect; down- and upstream) (Bambra, 2016; Krieger, 2011), and temperature-related mortality poses no exception (Arbuthnott et al., 2018; Lloyd et al., 2023). Such a multi-causal perspective is implicit in the epidemiological measures used to assess the mortality impacts of temperature; i.e. Population Attributable Fraction (PAF) and Attributable Number (AN). Rather than quantifying deaths exclusively caused by temperature, these measures capture the expected reduction in deaths if exposure to non-optimal temperatures were avoided (Krieger, 2017). But these same deaths could be averted by addressing any of their modifiable non-temperature contributors.

For instance, a wide range of factors have been shown to influence the relative risk (RR) of mortality at non-optimal temperatures, including years of education, national income per capita, access to air conditioning, and demographics (Achebak et al., 2023; Benmarhnia et al., 2015; Chung et al., 2018; Sera et al., 2019b). More generally, an analysis of 10 countries over 25 years concluded that non-temperature attenuation mechanisms made a large contribution to observed reductions for heat-related (but not cold-related) deaths (Vicedo-Cabrera et al., 2018). Specific mechanisms were not assessed in the study, but the authors suggested it was likely they included improved health care and infrastructure changes.

Two major global trends with significant implications for temperature-related mortality are rising longevity (i.e. longer lifespans) and population ageing (i.e. changing population structure) (Harrington and Otto, 2023; Lloyd et al., 2024b; United Nations Department of Social and Economic Affairs, 2023). These processes are linked but distinct. A number of studies have focussed on population ageing, with both historical analyses and projections showing that rising numbers and proportions of older people (combined with rising temperatures) contribute to increasing impacts (i.e. the number of temperature-related deaths) (Chen et al., 2024; de Schrijver et al., 2022; Huang et al., 2023; Lloyd et al., 2024a; Park et al., 2020). While this highlights an important challenge, it may inadvertently divert attention from the potential benefits of rising longevity: as survivorship amongst older people increases, there may be a concomitant decline in the absolute risk (AR) of temperature-related mortality.

To investigate this, we shifted perspectives and aimed to quantify the contribution of rising longevity to changes in the risk of temperature-related mortality amongst older people in Spain over recent decades. Additionally, we assessed how changing patterns of temperature-related mortality have impacted on longevity.

Rising longevity is arguably the most remarkable achievement of the modern era, resulting from a range of improvements including in public health, medical care, nutrition, education, wealth, and health-related behaviours (Riley, 2001). The particular combination of tactics adopted to improve survival has differed by country (and often within-countries) and over time. That is, longevity, captures the combined influence of social progress in multiple but varying arenas, with the ultimate effect being increased survivorship in different age groups.

Until about 1950, most gains in higher income countries were due to reduced death rates at younger ages. Since then, rises in longevity have largely been driven by falling mortality rates in people aged 65y+ (Aburto et al., 2020; Oeppen and Vaupel, 2002). Given this, and because most temperature-related deaths occur at higher ages (Ebi et al., 2021), our study focuses specifically on people aged 65y+, thus helping to fill the research gap on older people and climate change (World Health Organization, 2022). Moreover, our investigation may provide insights into whether rising temperatures are already undermining social progress, while potentially opening new windows to look at the health implications of ongoing climate and social change under various scenarios.

To capture the influence of rising longevity on temperature-related mortality, we represent longevity as declines in underlying mortality rates in older people (i.e. we use age-/sex-specific all-cause mortality rates). As noted above, the tendency of the latter to fall is a hallmark characteristic of the late stage of the health transition (Riley, 2001). For instance, in high life expectancy countries, about 58% of the rise in longevity between 1975 and 1990 was due to increased survival in people aged 65y+; this rose to 79% for the 1990 to 2007 period (Christensen et al., 2009).

To capture the influence of temperature-related mortality on longevity, in the second part of our study we reverse the perspective to quantify the impact of temperature-related mortality on life expectancy (LE) at 65y, as well as "lifespan inequality" (LI) in people aged 65y+ (Permanyer and Scholl, 2019; van Raalte et al., 2018). LE is a measure of average lifespan and always rises if lives are saved. LI is a measure of variation in the age at death; as a consequence, the influence of lives saved on LI depends on their age pattern (Aburto et al., 2020; van Raalte et al., 2018). Specifically, the direction of influence depends on a moving threshold age, which tends to be close to LE at the youngest age in the population (for instance, if the population of interest includes all ages, the threshold age will be close to LE at birth). When deaths are averted below the threshold age, LI declines. However, when they are averted above the threshold, LI rises. LI matters because, for one, it is a measure of uncertainty around age at death at the individual level (van Raalte et al., 2018). Additionally, and more importantly for our analysis, changes in LI can be seen as an indicator of how equally distributed health improvements are at the population level.

Our analysis focused on Spain, a country that has achieved one of the highest life expectancies in the world while experiencing a rapid rise in temperatures (0.33 °C per decade) (Achebak et al., 2019; Lloyd et al., 2024a; Zueras and Rentería, 2020). Based on age- and sex-specific temperature-attributable mortality estimates for people aged 65y+ over 1980 to 2018, we used: (i) a counterfactual approach to quantify the contribution of rising longevity (represented as falling underlying all-cause mortality rates) to changes in the AR of temperature-related mortality; and, (ii) state-of-the-art demographic decomposition methods to calculate the contribution of changes in temperature-related mortality to changes in longevity and its variation (represented as remaining LE at 65y and LI amongst people aged 65y+, respectively). Throughout the analysis, we separate the influence of extreme cold, moderate cold, moderate heat, and extreme heat. We refer to these different exposures as "temperature ranges".

2. Methods

2.1. Study design and population

Our study utilized existing estimates of temperature-attributable mortality – i.e. attributable numbers, ANs – for Spain (Lloyd et al., 2024a). The ANs had been derived for females and males aged 65y+, split into five age groups, for both non-standardized and age/sex standardized populations, for the period 1980 to 2018. They were available for extreme cold, moderate cold, moderate heat, and extreme heat.

In brief, for the analysis of the influence of rising longevity on temperature-related mortality risk, we adopted a counterfactual approach. For the factual, we used the standardized ANs as they controlled for changes in population structure while retaining the influence of rising longevity. We also generated a counterfactual, in which longevity did not rise over the study period. We did this by re-calculating the ANs while holding underlying mortality rates constant at 1980 levels. Next, based on the factual and counterfactual, we calculated the fall in AR over the study period for “fixed longevity” and “rising longevity” scenarios. Finally, we used the between-scenario differences to estimate the change in AR attributable to rising longevity.

For the analysis of the influence of temperature-related mortality on longevity, we used the non-standardized ANs (i.e. estimates of the actual number of deaths). We first disaggregated these into single years of age using standard methods (Rizzi et al., 2015). We then combined them with population and all-cause mortality data (which were also available from the original study), and calculated the numbers of deaths that were not attributable to temperature (i.e. as total deaths minus ANs). This gave us a dataset that included population counts, deaths by temperature range, and deaths not attributable to temperature, by sex and single years of age, for each year in the study. We used this dataset to generate yearly life tables. Finally, we produced survival curves and used state-of-the-art demographic decomposition methods to calculate the contribution of changes in ANs to changes in remaining LE at age 65y and LI amongst people aged 65y+ over the study period (Aburto et al., 2022) (For a schematic diagram, see Fig S1).

Throughout the study, we adopt a “period” rather than “cohort” perspective. In any given year, the population is composed of multiple cohorts, with each of latter having different life expectancies. We assume, however, that the experience of a population in a given period gives a reasonable approximation of the likely longitudinal experience of a cohort. This is a widely used approach in demography, largely because it is not possible to calculate cohort life expectancies until the entire cohort has died out. While this will have some influence on our results, we expect this will be minimal, particularly because we only include people aged 65y+ (which limits the number of cohorts in any period).

2.2. Data sources

We obtained average annual temperature-attributable deaths (ANs) for Spain, in non-standardized and age/sex-standardized (to the standard of the year 2000) populations, from a previous analysis (Lloyd et al., 2024a). The ANs had been derived from 15 year time periods, which moved in annual steps over 1980 to 2018, centred on 1987 (i.e. 1980 to 1994) to 2011 (i.e. 2004 to 2018). The ANs were available by sex for the following age groups: 65–72.5y, 72.5-80y, 80-85y, 85-90y, and 90y+ . Additionally, they were split by temperature range based on standard definitions (Gasparrini et al., 2015b): extreme cold (0th to 2.5th temperature percentile), moderate cold (2.5th to the minimum mortality temperature percentile (MMTP)), moderate heat (MMTP to the 97.5th temperature percentile), and extreme heat (97.5th to 100th temperature percentile).

The ANs had been calculated using standard methods. In brief, distributed lag non-linear models (DLNM) and multivariate random effect meta-analysis (Gasparrini et al., 2012, 2010; Sera et al., 2019a)) were applied to daily mortality counts and daily mean temperatures to generate temperature-mortality exposure–response functions (ERFs) (The ERFs are available in Appendix B of the original paper). This was done by sex and age group for moving 15-year time periods (as described above) in 13 regions covering mainland Spain plus the Balearic Islands. The regions were based on the Spanish “Autonomous Communities” (which correspond to NUTS 2 regions under the European Union’s Nomenclature of Territorial Units for Statistics (NUTS) (European Commission, 2023)). Smaller Autonomous Communities were aggregated into larger ones.

Next, average annual ANs for each time period, in each region, for each temperature range, were calculated (Gasparrini and Leone, 2014). These were then smoothed over rolling 5-year periods and summed to give (non-standardized) national totals. Finally, the ANs were age/sex-standardized relative to the year 2000 by re-scaling the estimates using the ratio of the age group-specific population in 2000 to the population in any given year. This approach adjusted the population structure but did not change underlying mortality rates. Of note, the standardized ANs were derived specifically because they allowed the calculation of change in AR over time. In the present study, we use the standardized ANs for the same purposes (see Section 2.3.2).

From the same study, we obtained regional-level lifetables in quarter year of age steps (i.e. 65.00y, 65.25y, 65.50y, … etc), for each year from 1980 to 2018. These had been generated from complete life tables (i.e. single year of age steps) (Instituto Nacional de Estadistica, 2023a) using spline-based penalized composite link models (Rizzi et al., 2015). We also obtained all-cause mortality data for Spain covering 1980 to 2018, in the form of microdata (i.e. individual deaths) and as daily mortality counts by sex and age group (Instituto Nacional de Estadistica n.d. (2023)). Finally, we obtained national-level annual population counts by sex for single years of age for each year over the same period (Instituto Nacional de Estadistica, 2023b).

2.3. The influence of rising longevity on temperature-related mortality risk

To estimate the influence of rising longevity on the absolute risk of temperature-related mortality, we used the following counterfactual approach.

2.3.1. Generating the counterfactual

For the factual, we used the sex/age group-specific ANs for the standardized population, where the population size had been adjusted but underlying mortality rates remained unchanged. Hence, they include the influence of rising longevity. We also generated counterfactual standardized ANs in which we removed the influence of rising longevity; i.e. we held mortality rates constant at 1980 levels (the first year in the study period).

We generated the counterfactual as follows. First, we obtained the underlying mortality rates for 1980 from the regional life tables. We did this by sex, based on the central age for each age group (i.e. 68.75y, 76.25y, 82.5y, 87.5y, 92.5y). Then, we extracted the corresponding mortality rates from the life tables for 1981 to 2018, and calculated mortality rate ratios as:

$\frac{mortality\ \ rate_{region,age\ \ group,sex,1980}}{mortality\ \ rate_{region,age\ \ group,sex,year}}$(i.e. in 1980, ratio = 1).

Next, we used the mortality rate ratios to adjust the regional sex/age group-specific, daily all-cause death counts (i.e. we multiplied the daily death count by the ratio before rounding to the nearest integer). Finally, we used these adjusted death counts to calculate the counterfactual, standardized ANs at the national-level, using the same method as for the factual ANs (Lloyd et al., 2024a). Of note, both the factual and the counterfactual ANs retain the influence of changes over time in the temperature distribution (e.g. due to climate change) and the ERFs (i.e. RR).

2.3.2. Calculating the influence of rising longevity on AR

We next used the factual and counterfactual ANs to generate “fixed longevity” and “rising longevity” scenarios. The scenarios were based on identical ERFs and temperature patterns. Thus, we used the difference between the scenarios to estimate the contribution of rising longevity to risk reduction.

The fixed longevity scenario used the counterfactual ANs for the first and last time periods (i.e. 1980 to 1994, and 2004 to 2018, respectively).

The rising longevity scenario also used the counterfactual ANs for the first time period, but then allowed underlying mortality rates to decline by using the factual ANs for the last time period.

We adopted this approach – in which both scenarios used the counterfactual ANs for the first time period – to ensure a common baseline (i.e. for which mortality rates were held at 1980 levels over the period 1980 to 1994). Consequently, the change seen in the rising longevity scenario is slightly larger than the actual change over the study period. This is because, in the real world, mortality rates tended to fall in each subsequent year within the first time period. The actual change is shown in Tables S1 (A-D), as "Change" in the columns for the standardized population.

We calculated change in AR in the fixed longevity scenario as:

$$\Delta AR\%^{fl}_{i,j,k} = \left[\left(AN^{Last\ time\ period,cf}_{i,j,k} - AN^{First\ time\ period,cf}_{i,j,k}\right)/AN^{First\ time\ period,cf}_{i,j,k}\right] \times 100\%$$

Where, *fl* stands for fixed longevity, and *cf* stand for counterfactual; *i* is age group, *j* is sex, and *k* is temperature range.

The equivalent calculation for the rising longevity scenario was:

$$\Delta AR\%^{rl}_{i,j,k} = \left[\left(AN^{Last\ time\ period,f}_{i,j,k} - AN^{First\ time\ period,cf}_{i,j,k}\right)/AN^{First\ time\ period,cf}_{i,j,k}\right] \times 100\%$$

Where, *rl* stands for rising longevity, and stands for *f* is factual.

The reason these calculations give change in AR is as follows. Risk is a probability, where the numerator is the number of deaths and the denominator is the population at risk. In standardized ANs, the denominator (i.e. the population at risk) is held constant over time, but the numerator (i.e. the number of deaths, or AN) changes. This means the percent change in AN in the final time period compared to the first time period equals the percent change in AR.

Finally, we estimated the contribution of rising longevity to AR reduction by calculating the absolute and relative between-scenario differences in the percent change in AR:

Absolute:. $-\left(\Delta AR\%^{rl}_{i,j,k} - \Delta AR\%^{fl}_{i,j,k}\right)$

Relative:. $\dfrac{\left(\Delta AR\%^{rl}_{i,j,k} - \Delta AR\%^{fl}_{i,j,k}\right)}{\Delta AR\%^{rl}_{i,j,k}}$

Throughout this part of the analysis, we calculated all point estimates by simple addition or subtraction and estimated confidence intervals (CIs) using standard Monte Carlo simulations. For the latter, for each of the estimates of interest, we simulated 1000 draws based on the point estimate and standard deviation (SD), then added or subtracted the resulting vectors as required, and finally calculated the 2.5th and 97.5th centiles.

2.4. *The impact of temperature-related mortality on longevity*

For this part of the analysis, we used decomposition methods from demography to calculate the contribution of changes in temperature-related mortality to changes in remaining LE at 65y and LI amongst people aged 65y+ (For a schematic of our approach, see Fig S1). In essence, this approach decomposes the total change in LE and LI over the study period into contributions by age and "cause" (i.e. temperature range), for each annual time-step during the study period. This means that the decomposed contributions sum to the total change observed over the study period.

We used the sex/age group-specific non-standardized ANs, which give estimates of the actual number of deaths. We first disaggregated these into single years of age (65y to 110y) using spline-based penalized composite link models as implemented in the R package "ungroup" (Rizzi et al., 2015). Next, we aggregated the all-cause mortality microdata into annual total death counts by single years of age and sex. We then combined the latter with the disaggregated ANs based on the middle year of each time period (i.e. 1987 to 2011 in single year steps). From this, we calculated annual deaths that were not attributable to temperature by subtracting temperature-attributable deaths from total deaths. The resulting death counts for each cause were then rounded to the nearest integer. Finally, we merged in population data (This allowed the calculation of mortality rates, which are required for the construction of life tables (Preston et al., 2001)).

The resulting dataset was then used to construct life tables based on all-cause mortality rates for single years of age for 65y to 100y+ using standard demographic methods (piece-wise constant hazard model for single years of age from 65y to 100y) (Aburto et al., 2022; Chiang, 1960).

Next, we used decomposition to calculate the contribution of temperature-related mortality to changes in longevity. While the full technical details of the method are outlined in the original paper (Aburto et al., 2022), in brief, the approach disentangles the influence of age- and cause-specific effects over time on change in remaining LE and LI using linear integral decomposition (Horiuchi et al., 2008). We have included sample code with this paper (Appendix B). The method decomposes each yearly change in LE and LI – that is, change between any two consecutive years – by age and cause. For instance, from 2000 to 2001 a given total change in LE at 65y+ is decomposed into contributions due to extreme cold, moderate cold, moderate heat, extreme heat, and all other causes for males aged 65y. The same is done for 66y, then 67y, and so on, for all age/sex/cause combinations for all yearly time steps. The yearly changes are additive such that, for example, if all the yearly contributions to changes in LE were summed, it would equal the total change in LE between the first to last year of the study. We utilized this additivity in our results by: combining the contributions by single years of age into five-year age groups; and, by combining yearly contributions into three time periods (1987 to 1995, 1995 to 2005, and 2005 to 2011).

In the study, we measure LI as the standard deviation (SD) of the age-at-death distribution (For a description, see Text S1) (Aburto et al., 2022). The higher the value of the SD, the greater the degree of lifespan inequality.

3. RESULTS

3.1. *Demographics and temperature attributable deaths*

Over the study period (1980 to 2018), the size of the Spanish population aged 65y+ more than doubled, increasing from 2.4 to 4.7 million for females, and from 1.6 to 3.5 million for males. Remaining LE at 65y rose from 17.7y to 23.1y in females (+5.4y), and 14.6y to 19.2y in males (+4.6y).

The temperature distribution shifted upwards over the study period (Fig S2). During 1980 to 1994, the median daily temperature was 14.3°C; this increased to 15.5°C for 2004 to 2018. The corresponding 99th percentiles were 26.5°C and 27.1°C. (Temperatures are population-weighted averages for the regions included in the study.)

Table 1 shows the average annual number of temperature-attributable deaths (i.e. ANs) for the first and last time periods in the non-standardized population. Additionally, ratios comparing ANs at different temperature ranges are shown. (ANs by age group and sex for the first and last time periods, for the non-standardized and standardized populations are shown in Tables S1 (A-D).).

Over the study period, the total AN fell in both females and males. The patterns, however, differed significantly by temperature range. There were considerable reductions in cold-related mortality in both sexes, with the bigger declines for moderate compared to extreme cold. In contrast, heat-related mortality increased in females and males, with greatest rises for moderate heat. Age group patterns (Table S1(A, B)) show that, for moderate heat, there were relatively small rises in deaths below age 85y for both sexes (with small declines in 72.5-80y females and 80-85y males), and larger rises in people aged 85y+ (1449 in

Table 1
Average annual temperature-related deaths (ANs)[a] in the first and last time periods, and ratios comparing ANs, by temperature range.

	Females			Males		
AN	**First**	**Last**	**Change**[b]	**First**	**Last**	**Change**[b]
Extr Heat	1053 (1006 to 1096)	1204 (1168 to 1235)	151 (95 to 208)	509 (461 to 552)	569 (536 to 603)	60 (7 to 114)
Mod Heat	1448 (1314 to 1582)	2896 (2473 to 3329)	1448 (999 to 1871)	580 (489 to 672)	998 (802 to 1189)	418 (197 to 631)
Mod Cold	11,499 (10,697 to 12,249)	5819 (5065 to 6565)	−5680 (−6708 to −4645)	12,113 (11,479 to 12,738)	8589 (7349 to 9765)	−3524 (−4883 to −2134)
Extr Cold	1500 (1442 to 1552)	800 (728 to 870)	−700 (−789 to − 608)	1359 (1312 to 1405)	942 (856 to 1023)	−417 (−516 to −326)
All[c]	15,500 (14,706 to 16,282)	10,719 (9817 to 11,587)	−4781 (−5960 to −3734)	14,561 (13,966 to 15,255)	11,098 (9884 to 12,370)	−3463 (−4889 to −2027)
Ratios[d]						
Mod: Extr, Heat	1.4 (1.2 to 1.5)	2.4 (2.0 to 2.8)		1.1 (1.0 to 1.3)	1.8 (1.4 to 2.1)	
Mod: Extr, Cold	7.7 (7.1 to 8.2)	7.3 (6.2 to 8.5)		8.9 (8.4 to 9.5)	9.1 (7.8 to 10.7)	
Mod: Extr, All	5.1 (4.7 to 5.4)	4.3 (3.9 to 4.8)		6.8 (6.4 to 7.2)	6.3 (5.5 to 7.2)	
Cold: Heat	5.2 (4.8 to 5.6)	1.6 (1.4 to 1.9)		12.4 (11.2 to 13.7)	6.1 (5.1 to 7.2)	

[a] ANs are for the non-standardized population and are shown as point estimate and 95% CI.

[b] "Change" is the absolute difference in AN between the first and last time period; positive numbers indicate an increase over time.

[c] "All" is total AN for all temperature ranges.

[d] Ratios (shown as point estimate and 95% CI) are calculated as AN for the first term divided by AN for the second term. For example, "Mod:Extr, Heat" is AN for moderate heat in that time period divided by AN for extreme heat in the same time period.

females; 397 in males). For extreme heat, ANs declined in people aged < 85y and increased in people aged 85y+ (366 for females; 143 for males).

The ratios in Table 1 show the relative contributions of deaths at different temperature ranges changed over the study period. Combining cold and heat deaths shows there was decline in the ratio of deaths attributable to moderate vs extreme temperatures over the study period (although the 95% CIs overlap), but mortality at moderate temperatures remained dominant. For cold deaths, the moderate to extreme ratios were fairly stable over time. For heat, however, the ratios rose over the study period (with no overlap of the 95% CIs). There was also a clear shift in the ratio of cold- to heat-related deaths (with no overlap of the 95% CIs) due to a relative rise in heat-related deaths.

3.2. The influence of rising longevity on temperature-related mortality risk

Fig. 1 shows the percent change in AR of temperature-related mortality in the first compared to the last time period (as point estimates) for the fixed and rising longevity scenarios (For the numbers underlying the figure, including the 95% CIs, see Table S2). The absolute and relative differences between scenarios (as point estimates and 95% CIs)) are shown in Table 2 and may be interpreted as the change in AR attributable to rising longevity.

For moderate heat, change in absolute risk in males aged 90y+ were relatively large. Consequently, we truncated the bars and have labelled them with their actual values. The figure shows the point estimates; 95% CIs are available in Table S2.

In the rising longevity scenario (Fig. 1, blue bars; Table S2), AR decreased over the study period for all the temperature ranges and age groups (with the exception of 90y+ males at moderate heat). The magnitude of the reduction was greatest for cold, with similar changes for both extreme and moderate cold. In females for all ages combined, AR fell by 79% (95% CI: 77% to 81%) and 79% (95% CI: 76% to82%) for extreme and moderate cold, respectively. The corresponding falls in males were 73% (95% CI: 70% to 75%) and 71% (95% CI: 67% to 76%), respectively. For extreme heat, AR more than halved; decreasing by 63% (95% CI: 61% to 65%) in females for all ages combined, and 55% (95% CI: 50% to 60%) in males. The smallest falls were seen for moderate heat: 35% (95% CI: 24% to 46%) in females for all ages combined, and 27% (95% CI: 6% to 44%) in males (The age group-specific estimates for moderate heat had wide uncertainty intervals; see Table S2). In the fixed longevity scenario (Fig. 1, pink; Table S2), the declines in AR were considerably smaller than in the rising longevity scenario, and there was an increase in risk for moderate heat: 20% (95% CI: 0% to 41%) in females for all ages combined; 21% (95% CI: −6% to 52%) in males.

The absolute differences between the percent change in AR in the moving and fixed longevity scenarios show that rising longevity made considerable contributions to risk reduction at all temperature ranges (Table 2). By far the largest influence was for moderate heat although the 95% CI were wide, particularly for males. Based on the point estimates, rising longevity turned potential increases in risk for moderate heat (i.e. as seen in the fixed longevity scenario) into decreases. For extreme heat, rising longevity accounted for about a third of the absolute reduction in both females and males for all ages combined. The influence on cold was smallest but far from negligible, contributing to absolute risk reductions in the order of 20% for all ages combined.

The relative contributions of rising longevity to falls in AR were of greater magnitude (Table 2). For cold for all ages combined, the relative contributions at both extreme and moderate cold were about 25% in both females and males. For extreme heat, in both females and males the relative contributions for all ages combined were about 50%. The contributions for moderate heat, where there was a shift from a rise (fixed longevity scenario) to a fall (rising longevity scenario) in AR, were >150% but again had wide uncertainty intervals.

Table 2 shows no strong patterns by age group but tendencies were evident for extreme temperatures in males. For extreme cold, rising longevity made a decreasing contribution to AR reduction as age rose. Conversely, for extreme heat, the contribution of rising longevity increased with age. That is, rising longevity brought the greatest benefits to the younger old males for extreme cold but to the older old males for extreme heat.

3.3. The impact of temperature-related mortality on longevity

Fig. 2 shows survival curves for people aged 65y+ for selected years, including the contributions of temperature-related mortality and all other causes of death. Over time, the probability of surviving increased at all ages (for instance, the red dotted lines show probability of survival at 75y and 85y). The influence of temperature-related mortality increased with age (i.e. the non-grey part of the curve widens with age) but fell over time (i.e. the non-grey part of the curve narrows in each subsequent time period), mostly due to changes in deaths attributable to moderate cold (green). The influence of moderate (blue) and extreme heat (orange) was relatively small but persistent over time. The survival curves show that cold had a stronger effect on survival in males compared to females, but that heat had a bigger influence on females than males.

Each survival curve also shows remaining LE at 65y LI for people aged 65y+ (as standard deviation) for the centre year of the time period. The red dotted lines indicate the probability of surviving at 75y and 85y.

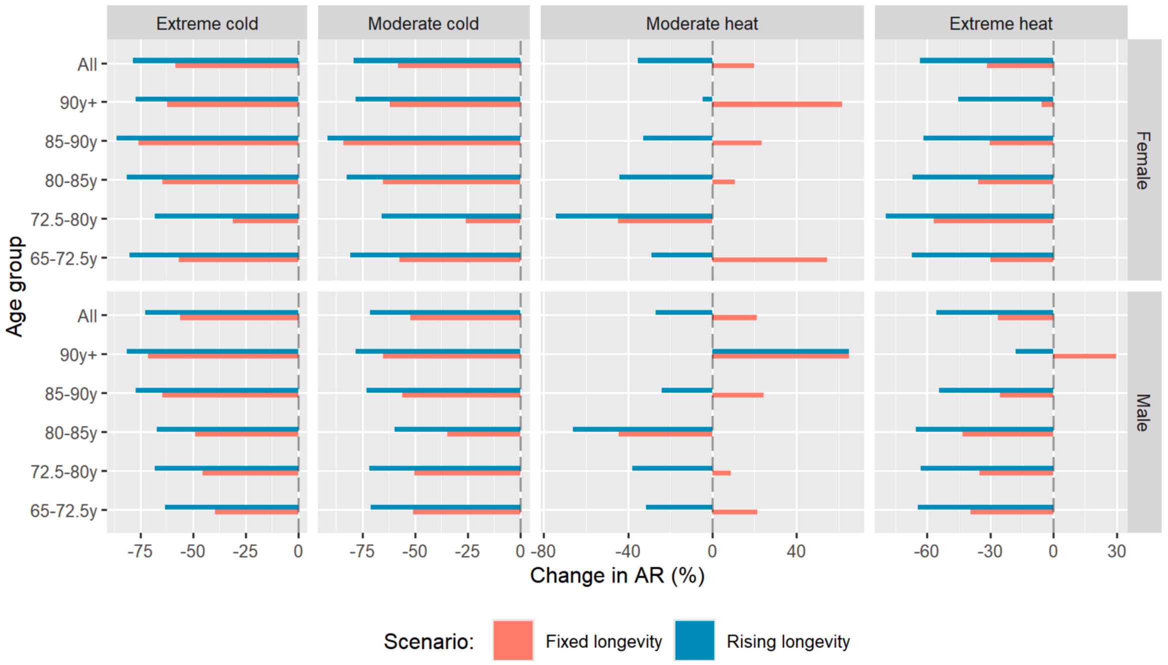

Fig. 1. Percent change in absolute risk of temperature-related mortality over the study period in the fixed longevity and rising longevity scenarios, by temperature range, sex, and age group.

Table 2
Absolute and relative differences in percent change in AR between the fixed and rising longevity scenarios, by temperature range, sex, and age.

		Extreme Cold		Moderate Cold		Moderate Heat		Extreme Heat	
Sex	**Age**	**Abs diff**	**Rel diff**	**Abs diff**	**Rel diff**	**Abs diff**	**Rel diff**	**Abs diff**	**Rel diff**
Female	**65–72.5y**	23% (−1% to 50%)	29% (−1% to 62%)	**23%** **(11% to 59%)**	29% (−13% to 73%)	83% (−145% to 306%)	290% (−505% to 1064%)	**37%** **(14% to 61%)**	**56%** **(21% to 91%)**
	72.5-80y	**37%** **(27% to 47%)**	**54%** **(40% to 69%)**	**40%** **(19% to 59%)**	**61%** **(29% to 90%)**	**30%** **(11% to 48%)**	**40%** **(14% to 64%)**	**23%** **(14% to 31%)**	**28%** **(18% to 40%)**
	80-85y	**17%** **(9% to 36%)**	**21%** **(11% – 31%)**	**17%** **(9% to 26%)**	**21%** **(10% to 32%)**	**55%** **(20% to 88%)**	**125%** **(46% to 199%)**	**31%** **(24% to 39%)**	**47%** **(35% to 57%)**
	85-90y	**11%** **(3% to 18%)**	**12%** **(3% to 20%)**	**7%** **(0% to 14%)**	**8%** **(0% to 16%)**	**56%** **(9% to 102%)**	**171%** **(27% to 311%)**	**32%** **(24% to 40%)**	**51%** **(38% to 65%)**
	90y+	**15%** **(8% to 23%)**	**20%** **(10% to 30%)**	**16%** **(5% to 26%)**	**21%** **(6% to 33%)**	**66%** **(12% to 123%)**	**1455%** **(263% to 2686%)**	**40%** **(27% to 53%)**	**88%** **(60% to 116%)**
	All	**20%** **(16% to 25%)**	**26%** **(20% to 32%)**	**21%** **(14% to 29%)**	**27%** **(17% to 26%)**	**55%** **(32% to 77%)**	**156%** **(89% to 217%)**	**32%** **(28% to 37%)**	**50%** **(44% to 58%)**
Male	**65–72.5y**	**24%** **(0% to 48%)**	**38%** **(0% to 76%)**	20% (−9% to 49%)	28% (−13% to 69%)	53% (−125% to 223%)	168% (−396% to 708%)	25% (−1% to 51%)	39% (−2% to 79%)
	72.5-80y	**23%** **(12% to 33%)**	**33%** **(18% to 48%)**	**21%** **(13% to 31%)**	**30%** **(17% to 43%)**	47% (−2% to 104%)	123% (−6% to 273%)	**28%** **(10% to 45%)**	**44%** **(15% to 72%)**
	80-85y	**18%** **(7% to 30%)**	**27%** **(11% to 45%)**	**25%** **(0% to 51%)**	**42%** **(1% to 85%)**	22% (−7% to 53%)	33% (−11% to 80%)	**22%** **(9% to 35%)**	**34%** **(13% to 54%)**
	85-90y	**13%** **(6% to 20%)**	**17%** **(7% to 26%)**	**17%** **(1% to 34%)**	**23%** **(1% to 47%)**	49% (−19% to 115%)	202% (−77% to 477%)	**29%** **(10% to 48%)**	**53%** **(19% to 88%)**
	90y+	**10%** **(1% to 19%)**	**12%** **(1% to 23%)**	**13%** **(5% to 31%)**	17% (−6% to 13%)	122% (−104% to 332%)	−110% (94% to −299%)	**48%** **(7% to 88%)**	**266%** **(40% to 493%)**
	All	**17%** **(11% to 22%)**	**23%** **(16% to 30%)**	**19%** **(11% to 28%)**	**27%** **(15% to 39%)**	**48%** **(13% to 83%)**	**179%** **(50% to 309%)**	**29%** **(21% to 38%)**	**52%** **(37% to 69%)**

"Abs diff" is absolute difference; "Rel diff" is relative difference. Numbers are shown as point estimate with 95% CI in brackets. Results where the 95% CI does not cross 0 are shown in bold.

3.3.1. The influence of temperature-related mortality on LE at 65y

Fig. 2 shows LE at 65y in the first and last time periods (i.e. centred on 1987 and 2011), as well for two intermediate time periods (centred on 1995 and 2005). From the first to last time period, remaining LE rose by 3.55y in females and 2.93y in males, with the rate of increase rising over time. Fig. 3A shows the contribution of temperature-related mortality to these changes in LE during three periods covering 1987–1995, 1995–2005, and 2005–2011. In total, changing patterns of temperature-related mortality resulted in gains of 0.74y (21% of the total rise) in females and 0.69y (24% of the total rise) in males. Over time, however, the contribution of temperature-related mortality declined: in females, from 0.23y to 0.12y in the first and last periods, respectively; in males, from 0.27y to 0.08y.

The majority of the influence of temperature-related mortality was due to changes for moderate cold: 80% for females; 87% for males. Of note, Fig. 3A shows that the declines in moderate cold deaths were not

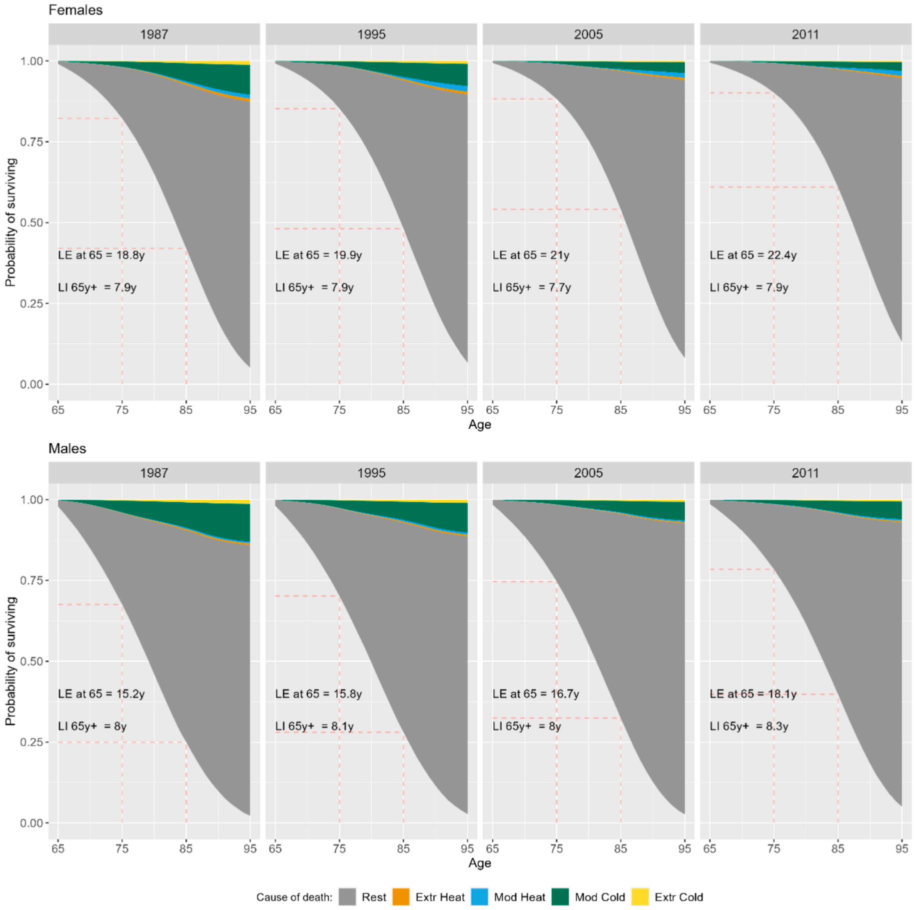

Fig. 2. Probability of surviving for people aged 65y+, showing temperature-related mortality by temperature range and all other causes of death, for time periods centred on 1987, 1995, 2005 and 2011, by sex.

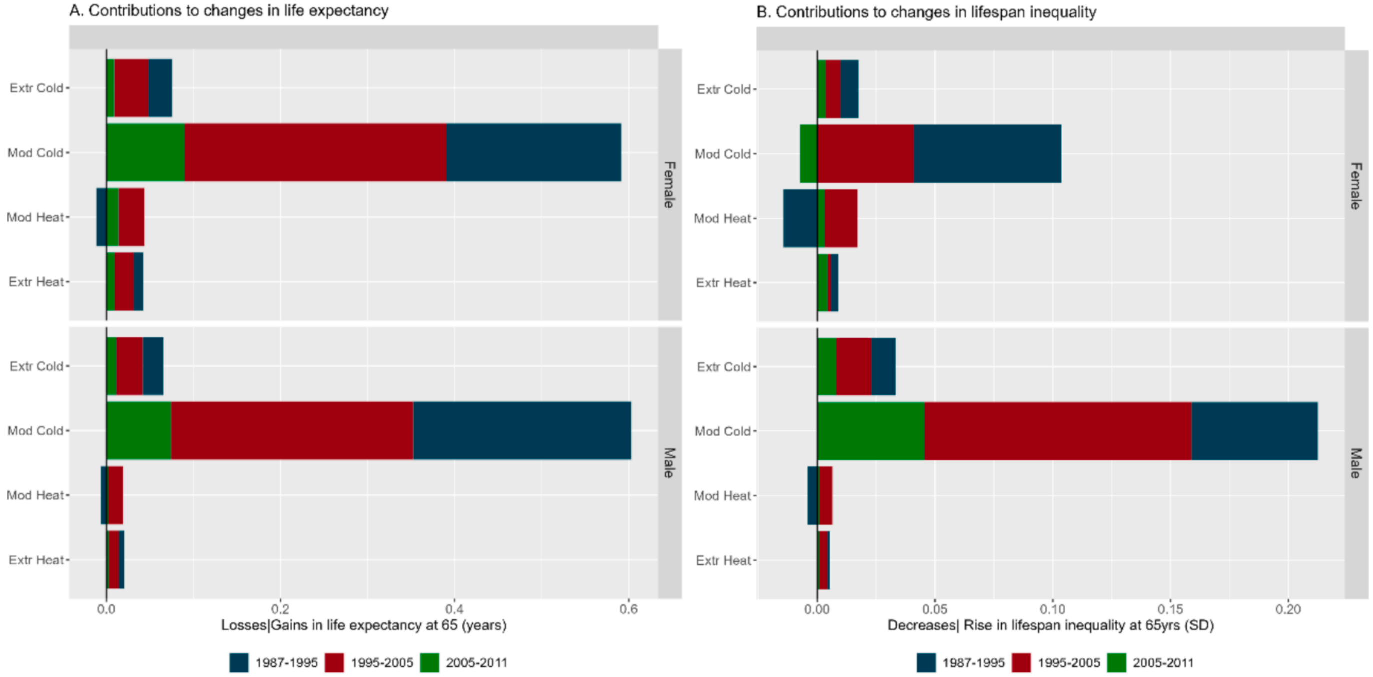

Fig. 3. Contributions of temperature-related mortality to changes in (A) life expectancy and (B) lifespan inequality, at 65yrs of age, during periods based on time periods centred on 1987–1995, 1995–2005, and 2005–2011, by sex and temperature range.

the result of reclassification as extreme cold or moderate heat deaths (i.e. there was no compensatory increase in negative contributions at these temperature ranges). The magnitude of the gains in LE due to changes in moderate cold deaths declined over time.

For heat, the percent contributions to the overall effect of temperature-related mortality on LE at 65y were, for moderate heat: 4% in females and 1% in males; for extreme heat: 5% in females and 3% in males. That is, although climate change is driving temperature increases, changes in heat-related mortality patterns have – at least so far – contributed to net gains (albeit small) in remaining LE in older people. Considering contributions by period: changes in moderate-heat deaths led to small reductions in remaining LE in the first period, small gains in the second period, and considerably smaller gains in the third period; changes in extreme heat-deaths led to gains in remaining LE in all periods.

Fig. 4A shows contributions to gains in LE by age group, which were similar across all four temperature ranges. The biggest contributions were due to changes in temperature-related mortality in females aged 80-89y (44% of the total) and males aged 70-79y (48% of the total). For moderate and extreme cold, all age groups contributed to gains, with the exceptions of the oldest groups in the first period and 80-85y males in the last period. For extreme heat, almost all contributions were positive, with occasional very small negative contributions. For moderate heat, contributions by age group were mostly positive, but there were more negative contributions than for other temperature ranges. The latter were mostly in the first period – for females aged 80y+ and males aged 70y+ – but also for males aged 90y+ in the middle and final time period.

3.3.2. The influence of temperature-related mortality on LI amongst people aged 65y+

Over the study period, LI was stable in females (change = -0.02y from the first to last time period) but rose in males (change = 0.27y), finishing at 7.9y and 8.3y in females and males, respectively (Fig. 2). Considering temperature-related mortality (Fig. 3B), the total contributions were 0.13y in females and 0.25y in males, with most of the influence due to moderate cold (77% and 84% in females and males, respectively). That is, temperature-related mortality drove LI upwards. Fig. 3B also shows that contributions tended to be smaller in the most recent period (green) compared to the two earlier periods (blue and red) for all temperature ranges except extreme heat.

Age group-specific contributions were small, but the patterns are of interest (Fig. 4B). As noted in the introduction, deaths averted below a moving threshold age will decrease LI, while deaths averted above the threshold will increase inequality. Given this, for both moderate and extreme cold, the patterns suggest that age-group specific contributions were almost all through the aversion of deaths, with the moving threshold lying somewhere from 76y-84y in females, and from 70y-79y in males. As also noted in the introduction, the threshold tends to lie close to the remaining LE at the youngest age in the population of interest: here, the expected age at death at 65y in females was 83.8y in the first time period and 87.4y in the last time period; for males, the ages were 80.2y and 83.1y, respectively (Fig. 2; calculated as: 65 + remaining LE)). The patterns also show that the overall net positive contribution to LI is being driven by deaths avoided at the oldest ages. At these ages, however, the size of the positive contribution has tended to decline over time (i.e. green compared to blue or red), suggesting a decline in the relative number of deaths averted amongst the oldest.

For extreme heat, the age patterns were broadly similar to those seen for cold, and the threshold age was visible in the plots. (Fig. 4B). However, two differences were evident in the most recent period, both suggesting a rise in deaths. Firstly, there was a small positive contribution for the youngest females; secondly, contributions were negative or neutral in males aged 90y+ . For moderate heat, there were no systematic patterns by age, and the threshold age was not visible. This suggests there were contributions due to increasing deaths both below and above the threshold age. For instance, in the most recent periods, deaths in people aged 90y+ contributed to declines in LI, suggesting (a small part of) inequality reduction is being driven by a relative rise in deaths of fragile older people.

4. Discussion

Our study assessed the reciprocal relation between rising longevity and temperature-related mortality in Spain over the period 1980 to 2018. This is particularly germane as Spain is among the world's leading nations for both population ageing and temperature increases due to global warming. We found that, firstly, rising longevity led to considerable declines in the absolute risk (AR) of temperature-related mortality for both heat and cold. Secondly, the results showed that changes in the patterns of temperature-related deaths contributed to rises in life expectancy (LE) but increases in lifespan inequality (LI) amongst older people. Most of the influence on LE was due to declines in deaths attributable to moderate cold, but changes at both moderate and extreme heat also led to (small) gains.

To our knowledge, this is the first assessment to quantify the bidirectional relationship between temperature-related mortality and longevity. Previous studies have focussed on the associated process of population ageing, linking structural changes in populations to increases in the number of temperature-related deaths, particularly for heat (Chen et al., 2024; de Schrijver et al., 2022; Huang et al., 2023; Lloyd et al., 2024a; Park et al., 2020). These (and related) studies draw attention to important challenges (Harrington and Otto, 2023). At the same time, although such studies do sometimes account for declines in susceptibility (i.e. relative risk, RR), they give limited attention to the changing characteristics of older people and how this may influence AR (Lloyd et al., 2024b). Central amongst these characteristics is rising longevity (Lloyd et al., 2024a; Sanderson and Scherbov, 2019): our results demonstrate the importance of considering this.

Over the study period, the Spanish population aged 65y+ doubled but the total number of temperature-related deaths fell. This was entirely due to large falls in cold-attributable deaths. The number of heat-attributable deaths rose, particularly for moderate heat. In terms of risk, however, the AR of temperature-related mortality fell at all temperature ranges and for all age groups (except for 90y+ males for moderate heat). Overall (i.e. for all age groups combined), the relative fall in AR was about 70% to 80% for both moderate and extreme cold; about 55% to 65% for extreme heat; and, about 25% to 35% for moderate heat (Fig. 1, rising longevity scenario; Tables S1 (A-D)).

These observed declines in AR are likely to be due to a range of (overlapping) processes, including changes in individual physiology and behaviour, population-level targeted adaptation, general improvements in social welfare, and alterations to the built environment (Arbuthnott et al., 2016). However, rather than attempt to identify specific actions that contributed to risk reduction, we focussed on the influence of the more general process of rising longevity, which is the culmination of social progress in various arenas (Riley, 2001). We found that a large proportion of the declines in AR could be accounted for by rising longevity, with a similar influence in females and males. For extreme heat, it accounted for about half of the total fall in AR (Table 2); in absolute terms, this was about a 30% reduction. For both extreme and moderate cold, rising longevity accounted for about a quarter of the total decline in AR, a decline of about 20% in absolute terms (Table 2).

For moderate heat, rising longevity turned potential 20% relative rises in AR into declines of about 30%, although uncertainties were wide (Table S2). These potential rises in risk in the fixed longevity scenario may have been due to changes in the hazard, exposure, or vulnerability. Regardless of the mechanism, our results suggest that general social progress more than offset them. This is important because, not only has the ratio of moderate to extreme heat deaths risen over time (Table 1), but moderate heat is a "normal" occurrence that is unlikely to be perceived as risky (Margolis, 2021). Here, vulnerability reduction via

Fig. 4. Contributions of temperature-related mortality to changes in (A) life expectancy and (B) lifespan inequality, at 65y of age, for periods based on time periods centred on 1987–1995, 1995–2005, and 2005–2011, by age group, sex and temperature range.

generalized rather than heat-targeted actions play a key role: our results show the potentially large benefits this can bring.

Our approach to assessing change in risk differs to previous studies. Assessment of historical declines in risk have tended to focus on shifts in RR or percent of deaths attributable to temperature (i.e. Attributable Fractions) (Achebak et al., 2019; Arbuthnott et al., 2016; Pascal et al., 2023). Similarly, projection studies typically account for future risk reduction by adjusting the ERFs, via changes in RR or the MMT (Gosling et al., 2017; Lee et al., 2019; Wan et al., 2024; Wang et al., 2022). In contrast, our results show the large declines in AR due to rising longevity are independent of changes in the ERFs; that is, we allowed RR to change identically over time in both the fixed and rising longevity scenarios (For changes in RR at the 99th temperature centile over the study period, see Fig. 2 in Lloyd et al (2024a)). The implication is that, if the purpose of a study is to assess changes in the actual risk of death (i.e. AR), tracking RR alone may significantly underestimate the risk reducing potential of general social progress (Lloyd et al., 2023; Pascal et al., 2023), including via rising longevity. To avoid this, we suggest future historical and projection studies should explicitly consider changes in both susceptibility (as RR) and population characteristics (as AR, including the influence of changes in underlying mortality rates).

Looking in the other direction, our results for the influence of changes in temperature-related mortality on longevity have three interrelated implications. Firstly, declines in temperature-related mortality accounted for about a fifth to a quarter of the total rise in longevity over the study period (Fig. 2; Fig. 3A). In terms of age, almost half of the contribution was due to AR reductions in females aged 80-89y and males aged 70-79y. This age pattern partly reflects the ages at which risk reduction has been most successful. But, it also arises because the magnitude of the effect risk reduction has on LE varies by age. Here, the rule of thumb is: a given percent reduction in risk reduction will bring the greatest gains in LE when achieved in groups aged close to LE of the population (Vaupel, 1986). Our findings appear to reflect this rule. In terms of temperature range, most of the contribution (>80%) was associated with moderate cold, but deaths were not simply shifted to heat: changes for both moderate and extreme heat also led to (small) increases in LE.

Thus, the combined influences of heat and population ageing have – so far – been insufficient to undermine ongoing rises in longevity. At the same time, the magnitude of the positive influence of changes in temperature-related mortality fell over time. This, alongside evidence that recent temperature rises have had large mortality impacts on older people (Ballester et al., 2023), suggests that heat-related mortality may soon begin to undermine general social progress. We suggest future studies should monitor this: threats to ongoing rises in longevity in older people potentially provide a powerful motivation for tackling climate change and its impacts.

Secondly, even as it contributed to rising longevity, changes in temperature-related mortality drove LI in older people upwards (although the magnitude of the effect was small). The results suggest the moving threshold age (i.e. below which lives saved contribute to reduced LI; above which lives saved contribute to increased LI (Aburto et al., 2020)) was somewhere in the range 75-85y for females and 70-79y for males. And, that the tendency to push LI upwards was due to the dominance of lives saved in "older" old people (i.e. people aged above the thresholds) (Fig. 4B). This suggest that an LI is perspective is useful for highlighting the need to take actions to protect both "younger" and "older" old people.

This leads to the third implication: LE- and LI-perspectives on temperature-related mortality potentially offer a lens onto health equity more generally. For instance, contributions to increases in both LE and LI may indicate that most gains have been amongst the "older" old. In general, this group tends to disproportionately represent the better-off (e.g. in terms of education and/or income), as they already have a survival advantage over the worse-off (Bramajo et al., 2023). Further, as temperatures rise, the better-off are also likely to be better positioned to take individual protective actions and to benefit more from collective actions (Mackenbach, 2020). That is, health inequities may increase not only due the effects of climate change, but also via the distribution of actions taken to avert its impacts. Monitoring only the temporal changes in risk and number of deaths may miss such possibilities; tracking influences on LE and LI may fill this gap, acting as indicators of whether inequities in risk are narrowing or widening.

Our study has several limitations. Firstly, when extracting underlying all-cause mortality rates to represent longevity and generate the counterfactual (Section 2.3.1), we made three assumptions: that the mortality rate at the central age in any age group gave a reasonable indication of the average mortality rate experienced by the entire age group; that if the overall mortality rate in a given age group in a given year were to change, this would have the same relative influence on daily mortality counts on all days during that year; and, that changes in mortality rates in one age group did not influence the mortality rates or size of the other age groups. While this approach is imperfect, we believe it is unlikely to bias the results in any particular direction and provides a reasonable and useful approximation.

Secondly, rising longevity and improvements in health and capabilities overlap but should be distinguished (Riley, 2001). A given pattern of survivorship may be associated with quite different patterns of health and, hence, vulnerability (Ebi et al., 2021). For instance, studies in Spain have found that, despite rising longevity, disease-free life expectancy has not improved in recent years due to persistently high prevalence of conditions such as hypertension, diabetes and coronary heart disease (Zueras and Rentería, 2021, 2020). Further, a recent cohort analysis has shown that declines in functioning and cognition in older people increased risk during heatwaves in China (Xi et al., 2024). Consequently, our quantitative findings are not generalizable across time or locations. Despite this, they clearly show the large benefits rising longevity can bring. Further, given the lack of improvement in disease-free life expectancy in Spain, our results are likely to be underestimates of the full potential benefits of rises in healthy longevity.

Related to the above, a third limitation is that our study does not assess either how gains in longevity were achieved or the resulting pattern of mortality. While we did not set out to assess either of these, they could be usefully explored in future work. We focussed on longevity in general as it could be represented by readily available data (i.e. age/sex-specific mortality rates). But, as improved survivorship can be driven by a range of processes, it may be useful ask: which of these processes also best protects populations and sub-groups from climate impacts? In terms of patterns of mortality, the ANs underlying our analysis only considered all-cause mortality. Deaths due to specific-causes, however, are evolving differentially over time and are likely to have different relations to both temperature and vulnerability (Achebak et al., 2019, 2018). Given this it would be useful to study the relations between means of increasing longevity, the resulting patterns of mortality, and the consequences for risk of temperature-related mortality.

Fourthly, most of the changes in temperature-related mortality over time were due to reductions in moderate cold deaths. There has been debate about whether such deaths are "caused" by low temperatures. A comprehensive assessment concluded that available evidence supports a causal relationship, but that the mechanisms are likely to be more direct at extremes and more indirect (e.g. via infectious disease) at moderate cold (Arbuthnott et al., 2018). In any case, all temperature-related deaths have multiple direct and indirect causes and may be averted by addressing any of their modifiable contributors. From the perspective of our study, it is unimportant that temperature itself may play a bigger role at extremes than more moderate temperatures; what matters is how longevity influences and is influenced by temperature-related deaths.

5. Conclusions

Rising longevity (longer lifespans) and population ageing (changed population structures) are linked but distinct processes occurring in many countries across the globe. While a number of studies have identified ageing as a potential threat driving rises in the number of temperature-related deaths, our study shows that rising longevity is driving the absolute risk of temperature-related mortality downwards. Additionally, so far, shifts in temperature-related mortality are not negatively impacting on longevity (although it is pushing lifespan inequality upwards).

Our findings point to the benefits of adopting a wide range of risk reduction strategies, spanning from targeted adaptation during extremes (i.e. by modifying the hazard and reducing exposure) (Casanueva et al., 2019) to general vulnerability reduction (Kelman, 2020). The latter includes ensuring that as lifespans lengthen, the number of years lived in good health also rises (World Health Organization, 2022). Vulnerability is a function not of climate but of conditions of everyday life (Ribot, 2014; Wisner et al., 2004): changing these conditions could play a large role in risk reduction. As Friel (2023) pointed out, “(g)ood social policies … are good climate-health adaptation policies.”.

CRediT authorship contribution statement

Simon J LLOYD: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Erich STRIESSNIG:** Writing – review & editing, Writing – original draft, Conceptualization. **José Manuel ABURTO:** Writing – review & editing, Methodology, Conceptualization. **Hicham ACHEBAK:** Writing – review & editing. **Shakoor HAJAT:** Writing – review & editing. **Raya MUTTARAK:** Writing – review & editing. **Marcos QUIJAL-ZAMORANO:** Writing – review & editing. **Constanza VIELMA:** Writing – review & editing. **Joan BALLESTER:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Acknowledgements

SL, HA, MQ-Z, CV, and JB gratefully acknowledge funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 865564 (European Research Council Consolidator Grant EARLY-ADAPT, https://www.early-adapt.eu/). SL acknowledges funding from the Swedish Research Council (FORMAS) under grant agreement No. 2022-01845 (project ADATES). CV acknowledges funding from the Ministry of Research and Universities of the Government of Catalonia (2021 SGR 01563). RM gratefully acknowledges funding from the EU’s Horizon 2020 research and innovation programme under grant agreement no 101002973 (European Research Council Consolidator Grant POPCLIMA, https://www.popclima.eu/). We acknowledge support from the grant CEX2018-000806-S funded by MCIN/AEI/ 10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Program.

Appendixes A and B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109050.

REFERENCES

Aburto, J.M., Tilstra, A.M., Floridi, G., Dowd, J.B., 2022. Significant impacts of the COVID-19 pandemic on race/ethnic differences in US mortality. Proc Natl Acad Sci U S A 119, e2205813119. https://doi.org/10.1073/pnas.2205813119.

Aburto, J.M., Villavicencio, F., Basellini, U., Kjærgaard, S., Vaupel, J.W., 2020. Dynamics of life expectancy and life span equality. Proceedings of the National Academy of Sciences 117, 5250–5259. https://doi.org/10.1073/pnas.1915884117.

Achebak, H., Devolder, D., Ballester, J., 2018. Heat-related mortality trends under recent climate warming in Spain: A 36-year observational study. PLoS Med 15, e1002617.

Achebak, H., Devolder, D., Ballester, J., 2019. Trends in temperature-related age-specific and sex-specific mortality from cardiovascular diseases in Spain: a national time-series analysis. Lancet Planet Health 3, e297–e306. https://doi.org/10.1016/S2542-5196(19)30090-7.

Achebak, H., Rey, G., Lloyd, S.J., Quijal-Zamorano, M., Fernando Méndez-Turrubiates, R., Ballester, J., 2023. Drivers of the time-varying heat-cold-mortality association in Spain: A longitudinal observational study. Environ Int 182, 108284. https://doi.org/10.1016/j.envint.2023.108284.

Arbuthnott, K., Hajat, S., Heaviside, C., Vardoulakis, S., 2016. Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. Environmental Health 15, S33. https://doi.org/10.1186/s12940-016-0102-7.

Arbuthnott, K., Hajat, S., Heaviside, C., Vardoulakis, S., 2018. What is cold-related mortality? A multi-disciplinary perspective to inform climate change impact assessments. Environ Int 121, 119–129. https://doi.org/10.1016/j.envint.2018.08.053.

Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R., Pegenaute, F., Herrmann, F., Robine, J., Basagaña, X., Tonne, C., Antó, J., Achebak, H., 2023. Heat-related mortality in Europe during the summer of 2022. Nat Med 29, 1857–1866. https://doi.org/10.1038/s41591-023-02419-z.

Bambra, C., 2016. Health Divides: Where You Live Can Kill You. Policy Press, Bristol.

Benmarhnia, T., Deguen, S., Kaufman, J.S., Smargiassi, A., 2015. Review Article: Vulnerability to Heat-related Mortality: A Systematic Review, Meta-analysis, and Meta-regression Analysis. Epidemiology 26, 781–793. https://doi.org/10.1097/EDE.0000000000000375.

Bramajo, O., Permanyer, I., Blanes, A., 2023. Regional inequalities in life expectancy and lifespan variation by educational attainment in Spain, 2014–2018. Popul Space Place 29, e2628.

Casanueva, A., Burgstall, A., Kotlarski, S., Messeri, A., Morabito, M., Flouris, A.D., Nybo, L., Spirig, C., Schwierz, C., 2019. Overview of Existing Heat-Health Warning Systems in Europe. Int J Environ Res Public Health 16, 2657. https://doi.org/10.3390/ijerph16152657.

Chen, K., de Schrijver, E., Sivaraj, S., Sera, F., Scovronick, N., Jiang, L., Roye, D., Lavigne, E., Kyselý, J., Urban, A., Schneider, A., Huber, V., Madureira, J., Mistry, M.N., Cvijanovic, I., Armstrong, B., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Abrutzky, R., Tong, S., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Correa, P.M., Ortega, N.V., Kan, H., Osorio, S., Orru, H., Indermitte, E., Jaakkola, J.J.K., Ryti, N., Pascal, M., Katsouyanni, K., Analitis, A., Mayvaneh, F., Entezari, A., Goodman, P., Zeka, A., Michelozzi, P., de’Donato, F., Hashizume, M., Alahmad, B., Diaz, M.H., De la Cruz Valencia, C., Overcenco, A., Houthuijs, D., Ameling, C., Rao, S., Carrasco-Escobar, G., Seposo, X., da Silva, S.P., Holobaca, I.H., Acquaotta, F., Kim, H., Lee, W., Íñiguez, C., Forsberg, B., Ragettli, M.S., Guo, Y.-L.L., Pan, S.-C., Li, S., Colistro, V., Zanobetti, A., Schwartz, J., Dang, T.N., Van Dung, D., Carlsen, H.K., Cauchi, J.P., Achilleos, S., Raz, R., Gasparrini, A., Vicedo-Cabrera, A.M., Network, M.C.C.C.R, 2024. Impact of population aging on future temperature-related mortality at different global warming levels. Nat Commun 15, 1796. https://doi.org/10.1038/s41467-024-45901-z.

Chiang, C., 1960. A stochastic study of the life table and its applications. II. Sample variance of the observed expectation of life and other biometric functions. Hum Biol 32, 221–238.

Christensen, K., Doblhammer, G., Rau, R., Vaupel, J.W., 2009. Ageing populations: the challenges ahead. The Lancet 374, 1196–1208. https://doi.org/10.1016/S0140-6736(09)61460-4.

Chung, Y., Yang, D., Gasparrini, A., Vicedo-Cabrera, A.M., Ng, C.F.S., Kim, Y., Honda, Y., Hashizume, M., 2018. Changing Susceptibility to Non-Optimum Temperatures in Japan, 1972–2012: The Role of Climate, Demographic, and Socioeconomic Factors. Environ Health Perspect 126, 57002. https://doi.org/10.1289/EHP2546.

European Commission, 2023. NUTS - Nomenclature of Territorial Units For Statsitics [WWW Document]. URL https://ec.europa.eu/eurostat/web/nuts/background (accessed 27.6.23).

de Schrijver, E., Bundo, M., Ragettli, M., Sera, F., Gasparrini, A., Franco, O., Vicedo-Cabrera, A., 2022. Nationwide Analysis of the Heat- and Cold-Related Mortality Trends in Switzerland between 1969 and 2017: The Role of Population Aging. Environ Health Perspect 130, 37001. https://doi.org/10.1289/EHP9835.

Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R.S., Ma, W., Malik, A., Morris, N.B., Nybo, L., Seneviratne, S.I., Vanos, J., Jay, O., 2021. Hot weather and heat extremes: health risks. The Lancet 398, 698–708. https://doi.org/10.1016/S0140-6736(21)01208-3.

Friel, S., 2023. Climate change mitigation: tackling the commercial determinants of planetary health inequity. The Lancet 402, 2269–2271. https://doi.org/10.1016/S0140-6736(23)02512-6.

Gasparrini, A., Armstrong, B., Kenward, M.G., 2010. Distributed lag non-linear models. Stat Med 29, 2224. https://doi.org/10.1002/SIM.3940.

Gasparrini, A., Armstrong, B., Kenward, M.G., 2012. Multivariate meta-analysis for non-linear and other multi-parameter associations. Stat Med 31, 3821–3839. https://doi.org/10.1002/sim.5471.

Gasparrini, A., Guo, Y., Hashizume, M., Kinney, P.L., Petkova, E.P., Lavigne, E., Zanobetti, A., Schwartz, J.D., Tobias, A., Leone, M., Tong, S., Honda, Y., Kim, H., Armstrong, B.G., 2015a. Temporal Variation in Heat-Mortality Associations: A Multicountry Study. Environ Health Perspect 123, 1200–1207. https://doi.org/10.1289/EHP.1409070.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M.L., Guo, Y.-L.-L., Wu, C., Kan, H., Yi, S.-M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Honda, Y., Kim, H., Armstrong, B, 2015b. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet 386, 369–375. https://doi.org/10.1016/S0140-6736(14)62114-0.

Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A.M., Huber, V., Tong, S., de Sousa Zanotti Stagliorio Coelho, M., Nascimento Saldiva, P.H., Lavigne, E., Matus Correa, P., Valdes Ortega, N., Kan, H., Osorio, S., Kyselý, J., Urban, A., Jaakkola, J.J.K., Ryti, N.R.I., Pascal, M., Goodman, P.G., Zeka, A., Michelozzi, P., Scortichini, M., Hashizume, M., Honda, Y., Hurtado-Diaz, M., Cesar Cruz, J., Seposo, X., Kim, H., Tobias, A., Iñiguez, C., Forsberg, B., Åström, D.O., Ragettli, M.S., Guo, Y.L., Wu, C., Zanobetti, A., Schwartz, J., Bell, M.L., Dang, T.N., Van, D. Do, Heaviside, C., Vardoulakis, S., Hajat, S., Haines, A., Armstrong, B, 2017. Projections of temperature-related excess mortality under climate change scenarios. Lancet Planet Health 1, e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0.

Gasparrini, A., Leone, M., 2014. Attributable risk from distributed lag models. BMC Med Res Methodol 14, 55. https://doi.org/10.1186/1471-2288-14-55.

Gosling, S.N., Hondula, D.M., Bunker, A., Ibarreta, D., Liu, J., Zhang, X., Sauerborn, R., 2017. Adaptation to climate change: A comparative analysis of modeling methods for heat-related mortality. Environ Health Perspect 125, 1–14. https://doi.org/10.1289/EHP634.

Harrington, L.J., Otto, F.E.L., 2023. Underestimated climate risks from population ageing. NPJ Clim Atmos Sci 6, 70. https://doi.org/10.1038/s41612-023-00398-z.

Horiuchi, S., Wilmoth, J.R., Pletcher, S.D., 2008. A decomposition method based on a model of continuous change. Demography 2008 45:4 45, 785–801. https://doi.org/10.1353/DEM.0.0033.

Huang, Y., Li, C., Liu, D.L., Yang, J., 2023. Projection of temperature-related mortality among the elderly under advanced aging and climate change scenario. NPJ Clim Atmos Sci 6, 153. https://doi.org/10.1038/s41612-023-00487-z.

Instituto Nacional de Estadistica [WWW Document], n.d. 2023. URL www.ine.es (accessed 30.7.24).

Kelman, I., 2020. Disaster By Choice. Oxford University Press, Oxford.

Krieger, N., 2011. Epidemiology and the People's Health: Theory and Context. Oxford University Press, New York.

Krieger, N., 2017. Health Equity and the Fallacy of Treating Causes of Population Health as if They Sum to 100. Am J Public Health 107, 541–549. https://doi.org/10.2105/AJPH.2017.303655.

Lee, J.Y., Lee, W.-S., Ebi, K.L., Kim, H., 2019. Temperature-Related Summer Mortality Under Multiple Climate, Population, and Adaptation Scenarios. Int J Environ Res Public Health 16, 1026. https://doi.org/10.3390/ijerph16061026.

Lloyd, S.J., Quijal-Zamorano, M., Achebak, H., Hajat, S., Muttarak, R., Striessnig, E., Ballester, J., 2023. The Direct and Indirect Influences of Interrelated Regional-Level Sociodemographic Factors on Heat-Attributable Mortality in Europe: Insights for Adaptation Strategies. Environ Health Perspect 131, 087013. https://doi.org/10.1289/EHP11766.

Lloyd, S.J., Striessnig, E., Achebak, H., Hajat, S., Muttarak, R., Quijal-Zamorano, M., Rizzi, S., Vielma, C., Ballester, J., 2024a. Remeasuring the influence of ageing on heat-related mortality in Spain, 1980 to 2018. Environ Res 248, 118408. https://doi.org/10.1016/j.envres.2024.118408.

Lloyd, S.J., Striessnig, E., Muttarak, R., KC, S., Ballester, J, 2024b. Avoiding overestimates of climate risks from population ageing. NPJ Clim Atmos Sci 7, 88. https://doi.org/10.1038/s41612-024-00641-1.

Mackenbach, J.P., 2020. Health Inequalities: Persistence and Change in European Welfare States. Oxford University Press, Oxford.

Margolis, H.G., 2021. Heat Waves and Rising Temperatures: Human Health Impacts and the Determinants of Vulnerability 123–161. https://doi.org/10.1007/978-3-030-54746-2_7.

Marí-Dell'Olmo, M., Tobías, A., Gómez-Gutiérrez, A., Rodríguez-Sanz, M., García de Olalla, P., Camprubí, E., Gasparrini, A., Borrell, C., 2019. Social inequalities in the association between temperature and mortality in a South European context. Int J Public Health 64, 27–37. https://doi.org/10.1007/s00038-018-1094-6.

Instituto Nacional de Estadistica, 2023a. Life Tables. Results [WWW Document]. URL https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736177004&menu=resultados&secc=1254736195384&idp=1254735573002 (accessed 26.4.23).

Instituto Nacional de Estadistica, 2023b. Population figures. Results [WWW Document]. URL https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=Estadistica_C&cid=1254736176951&menu=resultados&idp=1254735572981 (accessed 26.4.23).

Oeppen, J., Vaupel, J.W., 2002. Broken Limits to Life Expectancy. Science (1979) 296, 1029–1031. https://doi.org/10.1126/science.1069675.

Park, C.E., Jeong, S., Harrington, L.J., Lee, M.I., Zheng, C., 2020. Population ageing determines changes in heat vulnerability to future warming. Environmental Research Letters 15. https://doi.org/10.1088/1748-9326/abbd60.

Pascal, M., Wagner, V., Corso, M., 2023. Changes in the temperature-mortality relationship in France: Limited evidence of adaptation to a new climate. Int J Biometeorol 1, 1–10. https://doi.org/10.1007/s00484-023-02451-1.

Permanyer, I., Scholl, N., 2019. Global trends in lifespan inequality: 1950–2015. PLoS One 14, e0215742.

Preston, S.H., Heuvline, P., Guillot, M., 2001. Demography. Measuring and Modeling Population Processes. Blackwell, Oxford.

Quijal-Zamorano, M., Martínez-Solanas, È., Achebak, H., Petrova, D., Robine, J.-M., Herrmann, F.R., Rodó, X., Ballester, J., 2021. Seasonality reversal of temperature attributable mortality projections due to previously unobserved extreme heat in Europe. Lancet Planet Health 5, e573–e575. https://doi.org/10.1016/S2542-5196(21)00211-4.

Ribot, J., 2014. Cause and response: vulnerability and climate in the Anthropocene. DOI: 10.1080/03066150.2014.894911 41, 667–705. https://doi.org/10.1080/03066150.2014.894911.

Riley, J.C., 2001. Rising Life Expectancy. Cambridge University Press, Cambridge.

Rizzi, S., Gampe, J., Eilers, P.H.C., 2015. Efficient estimation of smooth distributions from coarsely grouped data. Am J Epidemiol 182, 138–147. https://doi.org/10.1093/aje/kwv020.

Sanderson, W.C., Scherbov, S., 2019. Prospective Longevity: A New Vision of Population Aging. Harvard University Press, Cambridge, Massachusetts.

Sera, F., Armstrong, B., Blangiardo, M., Gasparrini, A., 2019a. An extended mixed-effects framework for meta-analysis. Stat Med 38, 5429–5444. https://doi.org/10.1002/sim.8362.

Sera, F., Armstrong, B., Tobias, A., Vicedo-Cabrera, A.M., Åström, C., Bell, M.L., Chen, B.-Y., de Sousa Zanotti Stagliorio Coelho, M., Matus Correa, P., Cruz, J.C., Dang, T.N., Hurtado-Diaz, M., Do Van, D., Forsberg, B., Guo, Y.L., Guo, Y., Hashizume, M., Honda, Y., Iñiguez, C., Jaakkola, J.J.K., Kan, H., Kim, H., Lavigne, E., Michelozzi, P., Ortega, N.V., Osorio, S., Pascal, M., Ragettli, M.S., Ryti, N.R.I., Saldiva, P.H.N., Schwartz, J., Scortichini, M., Seposo, X., Tong, S., Zanobetti, A., Gasparrini, A, 2019b. How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. Int J Epidemiol 48, 1101–1112. https://doi.org/10.1093/ije/dyz008.

United Nations Department of Social and Economic Affairs, 2023. World Social Report 2023: Leaving No One Behind In An Ageing World. New York.

van Raalte, A., Sasson, I., Martikainen, P., 2018. The case for monitoring life-span inequality. Science 1979 (362), 1002–1004. https://doi.org/10.1126/science.aau5811.

Vaupel, J.W., 1986. How Change in Age-specific Mortality Affects Life Expectancy. Popul Stud (NY) 40, 147–157. https://doi.org/10.1080/0032472031000141896.

Vecellio, D.J., Kong, Q., Kenney, W.L., Huber, M., 2023. Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance. Proceedings of the National Academy of Sciences 120, e2305427120. https://doi.org/10.1073/pnas.2305427120.

Vicedo-Cabrera, A.M., Sera, F., Guo, Y., Chung, Y., Arbuthnott, K., Tong, S., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Hilario Nascimento Saldiva, P., Goodman, P.G., Zeka, A., Hashizume, M., Honda, Y., Kim, H., Ragettli, M.S., Röösli, M., Zanobetti, A., Schwartz, J., Armstrong, B., Gasparrini, A, 2018. A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. Environ Int 111, 239–246. https://doi.org/10.1016/j.envint.2017.11.006.

Wan, K., Hajat, S., Doherty, R.M., Feng, Z., 2024. Integrating Shared Socioeconomic Pathway-informed adaptation into temperature-related mortality projections under climate change. Environ Res 118731. https://doi.org/10.1016/j.envres.2024.118731.

Wang, P., Tong, H.W., Lee, T.C., Goggins, W.B., 2022. Projecting future temperature-related mortality using annual time series data: An example from Hong Kong. Environ Res 212, 113351. https://doi.org/10.1016/j.envres.2022.113351.

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2004. At Risk, 2nd ed. Routledge, Abingdon.

World Health Organization, 2022. The UN Decade of Healthy Ageing 2021-2030 in a Climate-changing World. Geneva.

Xi, D., Liu, L., Zhang, M., Huang, C., Burkart, K.G., Ebi, K., Zeng, Y., Ji, J.S., 2024. Risk factors associated with heatwave mortality in Chinese adults over 65 years. Nat Med. https://doi.org/10.1038/s41591-024-02880-4.

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S.-C., Íñiguez, C., Ameling, C., De la Cruz Valencia, C., Åström, C., Houthuijs, D., Dung, D. V., Royé, D., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., De'Donato, F., Di Ruscio, F., Sera, F., Carrasco-Escobar, G., Kan, H., Orru, H., Kim, H., Holobaca, I.-H., Kyselý, J., Madureira, J., Schwartz, J., Jaakkola, J.J.K., Katsouyanni, K., Hurtado Diaz, M., Ragettli, M.S., Hashizume, M., Pascal, M., de Sousa Zanotti Stagliorio Coélho, M., Valdés Ortega, N., Ryti, N., Scovronick, N., Michelozzi, P., Matus Correa, P., Goodman, P., Nascimento Saldiva, P.H., Abrutzky, R., Osorio, S., Rao, S., Fratianni, S., Dang, T.N., Colistro, V., Huber, V., Lee, W., Seposo, X., Honda, Y., Guo, Y.L., Bell, M.L., Li, S, 2021. 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 5, e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4.

Zueras, P., Rentería, E., 2020. Trends in disease-free life expectancy at age 65 in Spain: Diverging patterns by sex, region and disease. PLoS One 15, e0240923.

Zueras, P., Rentería, E., 2021. Disease-free life expectancy has not improved in Spain. Perspectives Demogràfiques 1–4. https://doi.org/10.46710/ced. pd.eng.22.