# The impact of heat and cold on excess mortality and life expectancy in Europe, 2015–2024

Tamás Hajdu

KRTK-KTI WP 2025/11

September 2025

INSTITUTE OF ECONOMICS
ELTE CENTRE FOR ECONOMIC AND REGIONAL STUDIES
BUDAPEST, HUNGARY

ABSTRACT
This paper analyzes the effects of temperatures on mortality and life expectancy using data on 40 million deaths across 73 geographic regions in 28 European countries between 2015 and 2024. The findings indicate that both cold and hot temperatures increase mortality rates, with cold having a stronger overall effect. Heat-related mortality tends to be immediate, whereas cold-related effects are more delayed and prolonged. Climate emerges as a key moderator of these effects: cold-related mortality is higher in warmer regions, whereas heat-related mortality is higher in colder regions. The study also shows that recent shifts in the temperature distribution increased the number of deaths during the summer months but reduced mortality during spring, autumn, and winter, resulting in a net decrease of 869,000 deaths over the 2015–2024 period. This reduction corresponds to an average increase in life expectancy at birth of 0.20 years.

JEL codes: I10, I14, Q54
Keywords: temperature; climate change; life expectancy; mortality; Europe

Tamás Hajdu
ELTE Centre for Economic and Regional Studies
hajdu.tamas@krtk.elte.hu

# A hőmérséklet hatása a többlethalálozásra és a várható élettartamra Európában, 2015–2024

Hajdu Tamás

ÖSSZEFOGLALÓ

A tanulmány a hőmérséklet hatását vizsgálja a halálozásra és a várható élettartamra, 28 európai ország 73 földrajzi régiójában. Az elemzés 40 millió, 2015 és 2024 között bekövetkezett haláleset adatain alapul. Az eredmények azt mutatják, hogy mind a hideg, mind a meleg hőmérséklet növeli a halálozási rátát, de a hideg időjárásnak erősebb hatása van. A magas hőmérséklet által okozott halálozások általában azonnal következnek be, míg a hideg hőmérséklettel összefüggő hatások inkább késleltetve jelentkeznek és hosszabb ideig tartanak. A hőmérsékleti hatások erősségét az éghajlat jelentős mértékben befolyásolja: a hideg hőmérséklet által okozott halálozások száma magasabb a melegebb éghajlatú régiókban, míg a magas hőmérséklet által okozott halálozások száma jelentősebb a hidegebb régiókban. A tanulmány azt is kimutatja, hogy a hőmérsékleteloszlás közelmúltbeli változásai növelték a halálesetek számát a nyári hónapokban, azonban csökkentették a tavaszi, őszi és téli haláleseteket. Mindez összességében 869 000-el kevesebb halálesetet eredményezte a 2015–2024 közötti időszakban a vizsgált 28 országban. Ez a csökkenés átlagosan a születéskor várható élettartam 0,20 évvel történő növekedésének felel meg.

JEL kódok: I10, I14, Q54

Kulcsszavak: hőmérséklet; éghajlatváltozás; várható élettartam; halálozás; Európa

**The impact of heat and cold on excess mortality and life expectancy in Europe, 2015–2024**

Tamás Hajdu

Institute of Economics, ELTE Centre for Economic and Regional Studies
hajdu.tamas@krtk.elte.hu

## Abstract

This paper analyzes the effects of temperatures on mortality and life expectancy using data on 40 million deaths across 73 geographic regions in 28 European countries between 2015 and 2024. The findings indicate that both cold and hot temperatures increase mortality rates, with cold having a stronger overall effect. Heat-related mortality tends to be immediate, whereas cold-related effects are more delayed and prolonged. Climate emerges as a key moderator of these effects: cold-related mortality is higher in warmer regions, whereas heat-related mortality is higher in colder regions. The study also shows that recent shifts in the temperature distribution increased the number of deaths during the summer months but reduced mortality during spring, autumn, and winter, resulting in a net decrease of 869,000 deaths over the 2015–2024 period. This reduction corresponds to an average increase in life expectancy at birth of 0.20 years.

JEL codes: I10, I14, Q54

Keywords: temperature; climate change; life expectancy; mortality; Europe

**Acknowledgments**

I thank Gábor Hajdu for his helpful comments and suggestions. This work was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. I acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu).

## 1. Introduction

The relationship between ambient temperature and mortality has been extensively studied in the literature. Given the rapid pace of global warming – with record-high surface temperatures observed almost every year in recent human history – many studies have focused specifically on the mortality effects of heat (Basagaña et al., 2011; Gasparrini and Armstrong, 2011; Khatana et al., 2022; Schuster et al., 2025; Schwarz et al., 2025). However, several other studies that have examined the full temperature distribution have revealed a U-shaped effect, indicating that both extreme heat and cold increase the mortality risk (Barreca et al., 2016; Chen et al., 2018; Cohen and Dechezleprêtre, 2022; Conte Keivabu, 2022; Deschenes, 2022; Deschênes and Greenstone, 2011; García-Witulski et al., 2023; Gasparrini et al., 2015; Gould et al., 2025; Guo et al., 2014; Helo Sarmiento, 2023; Heutel et al., 2021; Martínez-Solanas et al., 2021; Masiero et al., 2022; Otrachshenko et al., 2017).

From a public policy perspective, it is vital to understand the mortality consequences of climate change. Projections of the future impacts typically combine estimates of the historical relationship between temperature and mortality with temperature projections from climate models. Several such studies have revealed substantial geographic variation in expected excess mortality. Many regions (especially in the Global South) are projected to experience large increases in mortality rates by the end of the century, however a number of regions in the Global North may benefit from a warming climate, mainly due to milder winters (Carleton et al., 2022; Gasparrini et al., 2017; Martínez-Solanas et al., 2021).

Other studies have focused on the recent mortality impacts of temperature exposure. These papers typically estimate the effects as the number of excess deaths resulting from deviations from a minimum mortality (optimal) temperature (Ballester et al., 2023; Gasparrini et al., 2015; Masselot et al., 2023). However, research that directly assesses the effects of recent changes in the temperature distribution – that is, the climate change already experienced – remains limited, especially at the continental or global level. Furthermore, the literature offers little insight into how recent temperature changes have influenced life expectancy, a key summary measure of overall mortality conditions.[1]

In this paper, I examine the relationship between temperature and mortality and estimate the impact of recent temperature changes on life expectancy in Europe. I utilize a large weekly dataset covering 40 million deaths between 2015 and 2024 across 73 geographic regions of 28

[1] One notable exception is the paper by Walkowiak et al. (2025). This paper directly examines the relationship between non-optimal temperatures and life expectancy.

European countries. A flexible empirical approach using temperature bins is applied to capture the nonlinear nature of the temperature–mortality relationship. The high-frequency (weekly) data allow for the analysis of short-run dynamics, while the broad spatial coverage makes it possible to investigate how climatic conditions shape the effects of heat and cold.

I find that an additional day with a daily mean temperature >25°C increases the number of deaths by 0.68 per 100,000 population over a five-week-long period, while an additional day with a mean temperature ≤−5°C leads to 1.45 additional deaths, relative to a reference temperature of 15–20°C. Within the 10–25°C range, mortality shows little variation. However, below 10°C, mortality rates increase approximately linearly as temperatures decline.

Similar to the studies using high-frequency data (Chen et al., 2018; Cohen and Dechezleprêtre, 2022; Deschênes and Moretti, 2009; Guo et al., 2014), I also find that the mortality effect of very high temperatures (>25°C) is strongest during the week of exposure and quickly dissipates, whereas the effect of very cold temperatures (≤−5°C) emerges with a one-week delay and gradually weakens over the following weeks.

The analysis also corroborates the previous finding that climate strongly influences temperature-related mortality (Barreca et al., 2015; Carleton et al., 2022; Conte Keivabu, 2022; Heutel et al., 2021). The effect of a day with a mean temperature above 25°C is much greater in colder climates (1.41 deaths per 100,000 population) than in warmer ones (0.52 deaths per 100,000 population). Conversely, the effect of a mean temperature at or below −5°C is more pronounced in warmer climates (3.32 deaths per 100,000 population) than in colder ones (0.88 deaths per 100,000 population).

This paper also estimates the number of excess deaths attributable to recent shifts in temperature distributions. Specifically, I evaluate the impact of temperature changes between 1950–1979 and 2015–2024. I find that across the 73 European regions included in this study, more deaths occurred during the summer, while fewer deaths occurred during the spring, autumn, and winter months of 2015–2024 than would have been expected under the temperature distribution of 1950–1979. Since the decline in mortality during the colder seasons outweighed the increase in summer mortality, the net effect of the temperature change is 869,333 fewer deaths. More precisely, these deaths were postponed – by at least a few months – due to climate change. Approximately 35% of this reduction occurred among individuals aged 60–79, and around 60% among those aged 80 and older. Converting these mortality changes into a summary measure of overall mortality conditions, I find that nearly all European regions experienced an increase in life expectancy at birth, with a population-weighted average gain of 0.20 years.

The remainder of the paper is organized as follows. Section 2 describes the data. Section 3 outlines the econometric models used to estimate the temperature effects and the methodology for calculating excess deaths and changes in life expectancy. Section 4 presents the results. Section 5 discusses their implications and summarizes the main findings.

## 2. Data

### *2.1. Deaths and population*

Data on deaths and population were drawn from Eurostat databases. The first database contains the number of weekly deaths by sex, five-year age group (from 0–4 to 90 years and older), and NUTS 2 region (Eurostat, 2025a). The second database contains the population size data by age, sex, and NUTS 2 region on January 1 each year (Eurostat, 2025b). This analysis used years between 2015 and 2024, and the sample was restricted to the countries and regions with complete age-specific death and population counts.[2] Smaller countries (those with a total area of less than 100,000 square kilometers) were not broken down into smaller geographical units; mortality rates are analyzed for the whole country. For larger countries, however, mortality rates were analyzed for NUTS 1 regions.[3]

In the original mortality dataset, calendar weeks are defined according to the ISO 8601 standard. According to this standard, each year consists of 52 or 53 complete weeks of seven days each. The first week of the year always includes January 4, but it can begin as early as December 29 of the previous year or as late as January 4. For this analysis, the data were restructured so that each day of the first and last weeks of the year belongs to the same year. In other words, the first week begins on January 1, and the last week of the year ends on December 31. The original weekly death counts were first distributed across the days of the given week (assuming that each day had the same number of deaths). Then, a new weekly dataset was created in which each year is divided into precisely 52 weeks, and the first calendar week contains the first seven days of the year (January 1-7). This approach means that the 52$^{nd}$ calendar week is eight days long (except in leap years, when it is nine days).

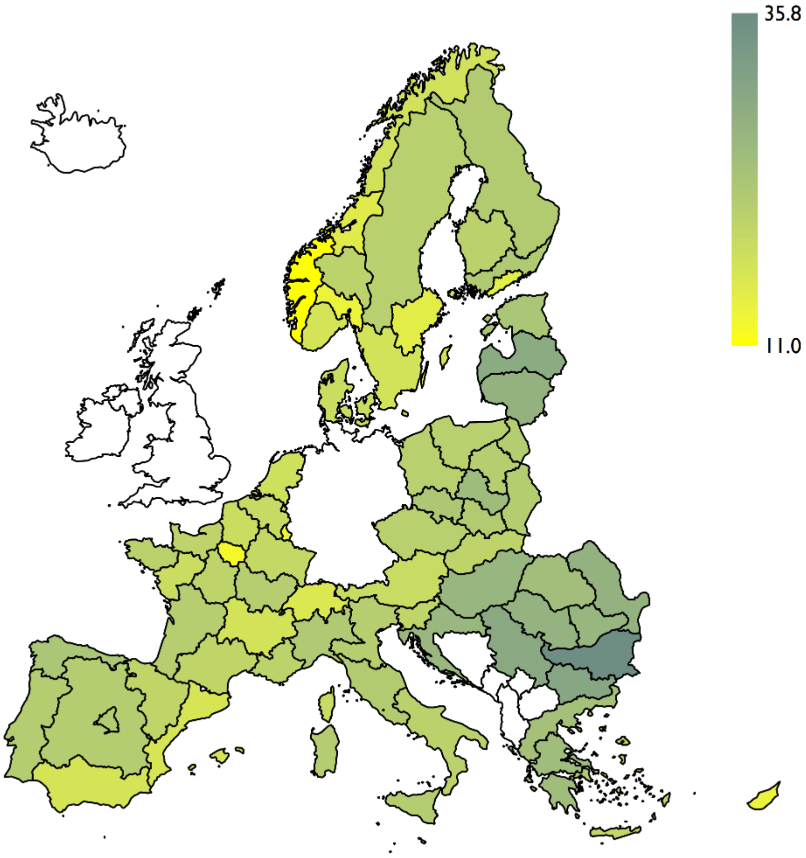
[2] Five French overseas regions were excluded from the sample (Guadeloupe, Martinique, Guyane, La Réunion, and Mayotte), as well as overseas Norwegian territories (Svalbard and Jan Mayen), the two autonomous regions of Portugal (the Azores and Madeira), the Canary Islands and two Spanish autonomous cities on the North African coast (Ceuta and Melilla).

[3] Finland and Norway were exceptions because one NUTS 1 region basically represents the whole country, so NUTS 2 regions were used.

From the death and population data, weekly mortality rates were calculated (number of deaths per 100,000 population) for each region-by-sex-by-age group. These weekly mortality rates served as the dependent variable of the empirical analysis.

A total of 73 geographic units from 28 countries[4] were included in the final dataset, which contains information on 40 million deaths (40,012,449). Fig. 1 illustrates the geographic coverage of the study and shows the average weekly total mortality rates.

**Fig. 1: Average weekly total mortality rates, 2015-2024**




Notes: Mortality rate = number of deaths per week per 100,000 population

*2.2. Weather*

Information on weather was drawn from the E–OBS 31.0e dataset provided by the Copernicus Climate Data Store (Copernicus Climate Change Service, Climate Data Store, 2025). The E–

[4] The following countries are included: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Greece, Hungary, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland.

OBS data are provided at a spacing of 0.25° × 0.25° in regular latitude/longitude coordinates (Cornes et al., 2018). The analysis primarily used data on daily average temperature and precipitation, but the main results will be shown using minimum and maximum temperatures.

The daily temperature conditions at each grid point were described by eight binary variables indicating the temperature range into which the daily mean temperature at that grid point fell: ≤−5°C, (−5,0]°C, (0,5]°C, (5,10]°C, (10,15]°C, (15,20]°C, (20,25°C], >25°C. Additionally, four precipitation variables showed the amount of precipitation: 0 mm, (0,5] mm, (5,10] mm, and >10 mm. Next, the grid-point-level weather variables were averaged by geographic unit (country or region). Defining the weather indicators at the grid point level first and then averaging them preserves within-region weather variations. This method captures the daily weather conditions of a region as accurately as possible.[5] Finally, the weekly number of days with different mean temperatures and precipitation levels was calculated by summing the daily data. The descriptive statistics are summarized in Table A1 (Supplementary Materials).

The E-OBS 31.0e dataset was also used to assess recent climate change. The temperature distribution of the years between 2015 and 2024 was compared to the temperature distribution observed in 1950–1979. First, the annual average number of days falling into the eight temperature categories (≤−5°C, …, >25°C) was calculated for 2015–2024, and these distributions were compared with the average annual temperature distribution during the period 1950–1979:

$$\Delta T_r^j = \overline{T}_{r,2015\text{-}2024}^j - \overline{T}_{r,1950\text{-}1979}^j \quad (1)$$

where the variable $\overline{T}$ denotes the average number of days per year at region *r* when the daily mean temperature falls into temperature category *j*, while ΔT represents the changes between 1950–1979 and 2015–2024.[6] These temperature changes were used for the calculation of the effect of recent climate change on excess deaths.

Fig. A1 in the Supplementary Materials depicts these changes in the annual temperature distribution for three climate regions. Climate regions were defined based on the average annual mean temperature between 2015 and 2024. The first group, the "cold climate group", includes regions with an average annual mean temperature <8.5°C. The second group, the "mild climate group", includes regions with an average annual mean temperature between 8.5°C and 12.5°C.

[5] For example, if on a given day the daily mean temperature in half of a region is 24°C, while in the other half of the region the daily mean temperature is 26°C, then this day will be recorded in the database with a value of 0.5 for the two upper temperature categories and 0 for the lower six temperature categories.

[6] To deal with the effects of leap years, each temperature distribution has been converted to 365-day years.

The third group, the "warm climate group", includes regions with an average annual mean temperature >12.5°C.

## 3. Methods

To describe the effect of temperature on mortality in Europe, first, the total mortality rate was regressed on temperature and precipitation with a simple linear model:

$$M_{rt} = \sum_j \sum_{b=0}^{4} \beta_b^j T_{r(t\text{-}b)}^j + \sum_k \sum_{b=0}^{4} \gamma_b^k P_{r(t\text{-}b)}^k + \rho_{rys} + \theta_{rw} + \mu_t + \varepsilon_{rt} \quad (2)$$

where M is the total mortality rate in geographic region *r* at time *t* (year *y*, season *s*, week *w*). $T^j$ stands for the number of days in the *j*-th temperature category to which individuals were exposed, while P denotes the amount of precipitation. Region-by-year-by-season[7] fixed effects (ρ) account for unobserved location-by-time-specific factors that influence the mortality rate. Region-specific, time-invariant seasonality was captured by region-by-week fixed effects (θ). Finally, time (year-by-week) fixed effects (μ) were also included to control time-varying factors that are common to all geographic regions in Europe.

The coefficient $\beta^j$ represents the effect of an additional day when the daily mean temperature falls into temperature category *j* on the mortality rate (relative to a day with a mean temperature of 15–20°C). Since exposure to heat and cold is likely to affect mortality rates not only immediately but also with some delay, four lags were introduced. In Eq. (2), the mortality rate at time *t* can be influenced by both the contemporaneous weather (b=0) and weather in the previous 4 weeks (b = 1, …, 4). The sum of the β coefficients ($\beta^j = \sum_{b=0}^{4} \beta_b^j$) can be interpreted as the cumulative effect of temperature in category *j* at time *t* over a five-week-long period.

Weighted regressions were estimated where the weights are the geographic regions' average population size between 2015 and 2024. Standard errors were clustered by region.

To check whether climate influences the effects of temperature, Eq. (2) was estimated separately for the three climate groups introduced in the previous section.

Total mortality rates were used to illustrate and explore some of the details of the relationship between temperature and deaths. However, understanding the impact of a warming climate on life expectancy at birth requires knowledge of age-specific effects. In order to ensure that the effects reflect climate-specific differences as accurately as possible, these age-specific temperature effects (from 0–4 to 90 years and older) were estimated separately for the three climate groups. Therefore, similar regressions to Eq. (2) were separately estimated for each

[7] Seasons are defined based on calendar weeks. Spring (weeks 9-21), summer (weeks 22-34), autumn (weeks 35-47), winter (weeks 48-52 and weeks 1-8).

climate-by-age "cell". From these estimations, climate- and age-specific cumulative temperature effects were obtained:

$$\beta^{j}_{ca} = \sum_{b=0}^{4} \beta^{j}_{cab} \quad (3)$$

where *c* denotes the climate group based on the regions' average annual mean temperature between 2015 and 2024 and *a* denotes the age groups (0–4, 5–9, …, 90–).

The excess death counts due to recent changes in the temperature distribution were calculated by utilizing the climate- and age-specific cumulative temperature coefficients from Eq. (3), the temperature changes from Eq. (1), and age-specific population figures:

$$\overline{D}^{E}_{ra} = \sum_{j} \beta^{j}_{ca} \, \Delta T^{j}_{r} \frac{\overline{NP}_{ra}}{100{,}000} \quad (4)$$

where $\overline{D}^{E}$ is the average number of excess deaths per year in 2015–2024 in age category *a* in region *r*[8], $\beta^{j}_{ca}$ is the cumulative effect for temperature category *j*, $\Delta T^{j}$ is the change in the annual number of days in temperature category *j* between 1950–1979 and 2015–2024, while $\overline{NP}$ is the average age-specific population size for the years 2015–2024.

By summing up the age- and region-specific excess death counts from Eq. (4), we obtain the total number of excess deaths per year in the 28 countries covered by the study. This is the annual number of deaths in an average year caused by changes in the temperature distribution between the periods of 1950–1979 and 2015–2024. Multiplying this number by ten gives us the total number of excess deaths that occurred between 2015 and 2024:

$$D^{E} = 10 \times \sum_{r} \sum_{a} \overline{D}^{E}_{ra} \quad (5)$$

Next, the excess death counts were used to calculate adjusted deaths for each age category. Adjusted deaths represent the number of deaths that would have been observed if the temperature distribution in the years 2015–2024 had been the same as it was in 1950–1979:

$$\overline{D}^{A}_{ra} = \overline{D}^{O}_{ra} - \overline{D}^{E}_{ra} \quad (6)$$

where $\overline{D}^{A}$ is the average number of adjusted deaths per year in 2015–2024. $\overline{D}^{O}$ is the average number of observed deaths per year in 2015–2024, while $\overline{D}^{E}$ is the average number of excess deaths per year in 2015–2024 from Eq. (4).

Life expectancies for each region were calculated using the observed ($D^{O}$) and adjusted ($D^{A}$) age-specific deaths following a standard approach (Preston et al., 2001). The difference between these life expectancies shows the changes due to the recent shift in the temperature distribution.

[8] It should be noted that climate groups are not included in the notation, as they are determined by the regions.

The uncertainty in the excess deaths and life expectancy estimates was quantified using 200 bootstrap samples.

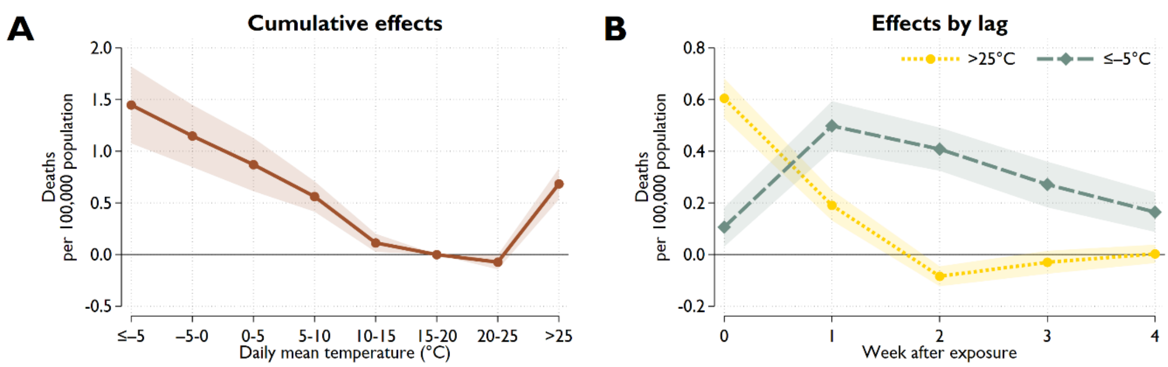
## 4. Results

### *4.1. The effects of temperature on the total mortality rate*

Panel A of Fig. 2 shows the cumulative effect of each temperature category on the total mortality rate, relative to a temperature of 15–20°C. A quasi-U-shaped relationship is observed. Both high and low temperatures increase mortality, but the effect of low temperatures is stronger. An additional day with a temperature >25°C results in 0.68 additional deaths per 100,000 population over a five-week-long period, whereas an additional day with a temperature ≤−5°C results in 1.45 additional deaths per 100,000 population. The other colder temperature categories below 10°C also have strong effects. However, there is not much difference between the effects of temperatures in the 10–25°C range.

Panel B of Fig. 2 indicates that the effect of heat (temperature category >25°C) is immediate. Most of the cumulative effect is due to the increase within the exposure week. Mortality is only slightly elevated the following week, and the effects are negligible thereafter. In contrast, the immediate effect of cold (temperature category ≤−5°C) is weak, but the delayed effects are stronger and last a few weeks. Fig. A2 in Supplementary Materials shows the estimated effects by lag for all temperature categories. The pattern is consistent: the effects are more long-lasting for cooler temperatures, while the immediate effects are dominant for warmer temperatures.

**Fig. 2: The effect of temperature on the total mortality rate**




Notes: (A) Cumulative effects for lags 0–4. (B) Estimates by lag. Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

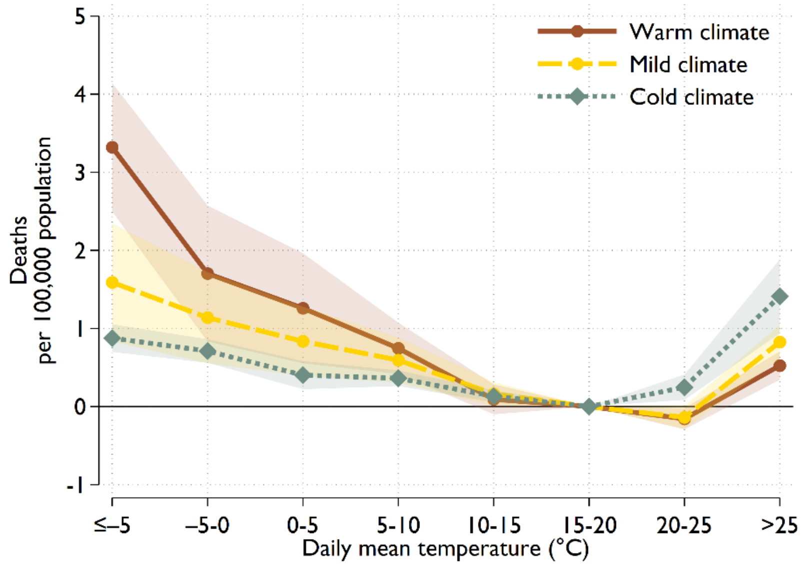
The sensitivity of the results was explored in several ways. First, it was demonstrated that including additional lags did not alter the results. Specifically, Fig. A3 in Supplementary Materials shows that exposure to temperatures of ≤−5°C or >25°C does not affect mortality rates five to six weeks later. Second, a falsification test was performed where the weather variables were replaced by observations exactly one year later. Since the weather in the distant future should have no backward effects, zero temperature coefficients were expected, and exactly this was found (Fig. A4, Supplementary Materials). Third, Table A2 in the Supplementary Materials summarizes the results of alternative model specifications. These include an unweighted estimation, the exclusion of precipitations, and experimenting with fixed effects. Fourth, it was shown that the baseline patterns are qualitatively similar when maximum or minimum temperatures are used instead of mean temperature (Fig. A5, Supplementary Materials). Finally, I showed that applying alternative clustering methods does not change the conclusions (Fig. A6, Supplementary Materials). The statistical significances were unaffected even when more conservative clustering methods were used.[9]

*4.2. Heterogeneity by climate*

I also examined whether climate influences the effects of temperature. As in Section 2.2 was described, regions were divided into three groups based on their average annual mean temperature between 2015 and 2024 (<8.5°C, 8.5°–12.5°C, >12.5°C). Separate regressions were then run for each group, and the results are summarized in Fig. 3. It is clear that climate strongly influences the effects of temperature. Cold-related mortality is higher in warmer regions, while heat-related mortality is higher in colder regions. For example, the effect of an additional ≤−5°C day is 3.32 deaths per 100,000 population in warm climate regions, 1.59 in mild climate regions, and 0.88 in cold climate regions. Conversely, the effect of an additional >25°C day is 0.52, 0.83, and 1.41 deaths per 100,000 population in cold, mild, and warm climate regions, respectively. These findings suggest that long-term adaptation may mitigate the effects of more frequently occurring extreme temperatures.

[9] Since a significant share of the death data for the most recent years was labeled as "provisional" in the Eurostat dataset, I also demonstrated that the main pattern remains unchanged when the analysis was restricted to the years 2015–2021 (Fig. A7, Supplementary Materials).

**Fig. 3: The temperature effects by climate**




Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

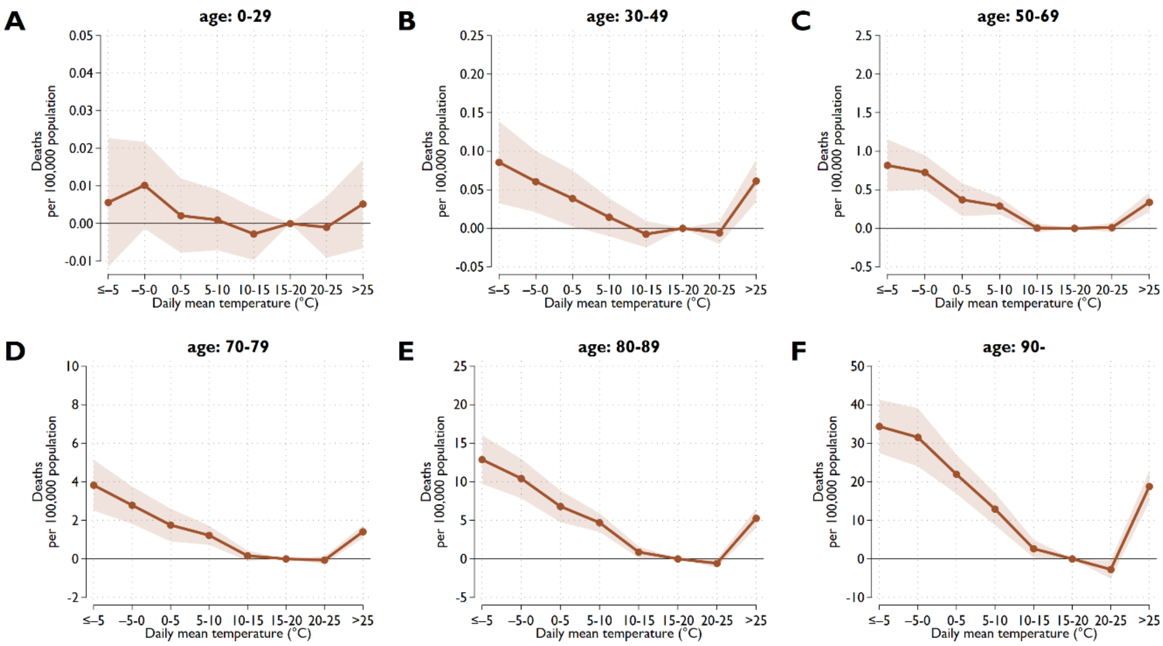
*4.3. Age- and sex-specific temperature effects*

The next question this analysis addressed was how the effect of temperature varies by age and sex. First, the age-specific effects were examined across six broad age groups: 0–29, 30–49, 50–69, 70–79, 80–89, and 90+.[10] These results show that for most age groups, the pattern seen in the baseline estimate emerges, i.e., both cold and warm temperatures increase mortality rates, but the effect of cold is stronger (Fig. 4). However, it is also clear that the mortality effects of temperature intensify with age. In the youngest age group, temperature has no substantial effect on mortality: the effects of an additional ≤−5°C and >25°C day are 0.0056 and 0.0052 deaths per 100,000 population, respectively. However, the number of excess deaths increases considerably with age. In the oldest age groups, the effects of ≤−5°C and >25°C days are 34.4 and 18.8 deaths.

The pattern of intensification of the effects with age also holds when the temperature effects are assessed not in absolute terms but as a percentage of the average weekly mortality rate of the age groups (Fig. A8, Supplementary Materials).

[10] Age-specific temperature coefficients were obtained by estimating a version of Eq. (2) with the age-specific mortality rates serving as the dependent variable instead of the total mortality rate. Similar method was used to estimate sex-specific effects.

**Fig. 4: Age-specific effects of temperature**




Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

The effect of temperature on total mortality appears broadly similar for both women and men (Fig. A9, Supplementary Materials), with little difference observed across temperature categories. However, this comparison does not account for differences in age structure between sexes: men have a younger age distribution, with a higher proportion in younger age groups and a lower proportion in the oldest cohorts – where temperature-related mortality is the highest – relative to women. To account for this, I estimated sex-specific temperature effects within each broad age group. The results indicate that colder temperatures, in particular, have a stronger effect on mortality among men than among women in all age groups, except the youngest, where no meaningful difference is observed (Fig. A10, Supplementary Materials).

### *4.4. Excess death and the effects on life expectancy*

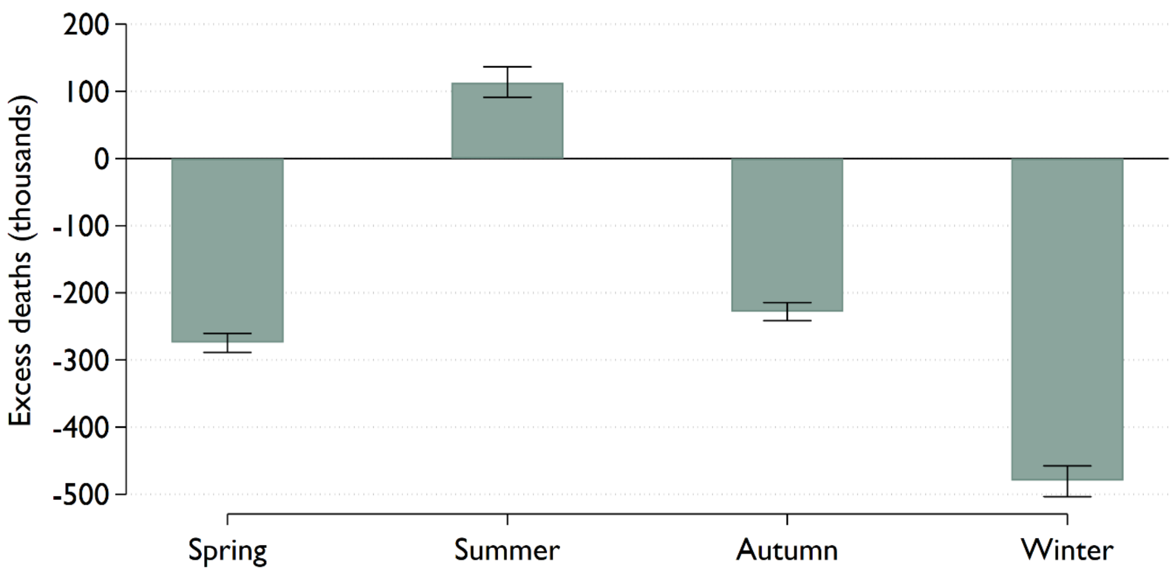
To evaluate the impact of temperature changes between 1950–1979 and 2015–2024 on life expectancy at birth, I estimated age-specific temperature effects across five-year age groups (ranging from ages 0–4 to 90+). Given prior evidence that climate significantly influences the temperature–mortality relationship (see Fig. 3), these effects were estimated separately for the three climate zones: regions with an average annual mean temperature below 8.5°C, between 8.5°C and 12.5°C, and above 12.5°C.

Applying the methodology outlined in Eq. (4) and Eq. (5), I estimated the total number of excess deaths occurring during the 2015–2024 period attributable to recent shifts in temperature distributions. The findings suggest that, across the 28 European countries included in this study, 869,333 (95% CI, 817,286–923,460) fewer deaths occurred during this period than would have been expected under the temperature distribution of 1950–1979. More precisely, these deaths were postponed to a later date due to the warming climate.

This reduction in mortality results from two opposing effects. On one hand, an increase in the number of hot days contributed to elevated mortality. On the other hand, a marked reduction in cold days resulted in a more substantial decline in deaths. This asymmetry arises from the U-shaped relationship between temperature and mortality shown in Fig. 3, where the lowest mortality risk is observed at temperatures between 10°C and 25°C. Mortality risk increases at temperatures both below and above this optimal range.

This pattern is further illustrated by the seasonal distribution of excess deaths. As shown in Fig. 5, 113,000 additional deaths occurred during the summer months of 2015–2024 due to the increase in hot days. However, the warming climate significantly reduced the number of deaths in spring, autumn, and winter (by a total of 982,000), resulting in a substantial net decrease in mortality.

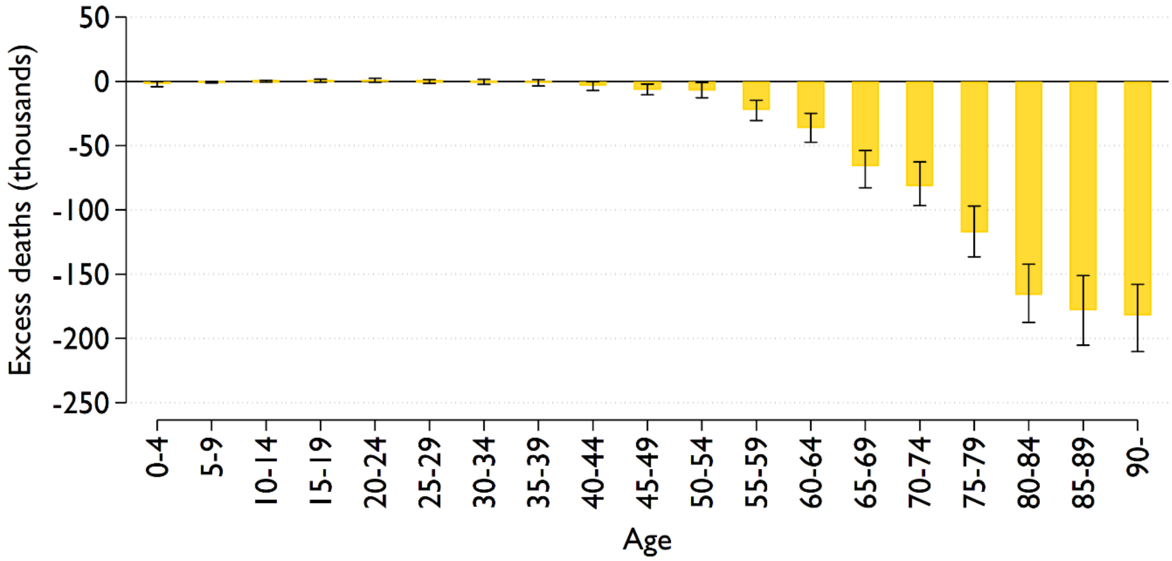
**Fig. 5: Seasonal distribution of excess deaths attributable to temperature changes between 1950–1979 and 2015–2024**




Notes: Total number of excess deaths for 2015–2024. Whiskers represent 95% confidence intervals calculated using 200 bootstrap samples.

With respect to the age-specific distribution of the estimated mortality reduction, approximately 35% is attributable to changes among individuals aged 60–79, while around 60% is accounted for by those aged 80 and above (Fig. 6).

**Fig. 6: Excess deaths by age group attributable to temperature changes between 1950–1979 and 2015–2024**

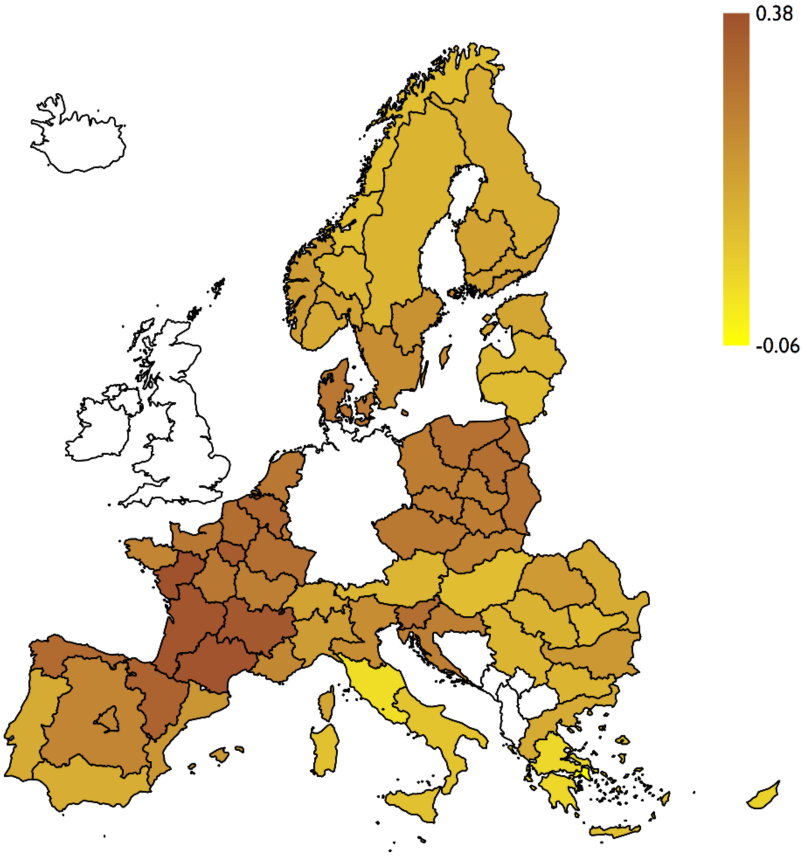



Notes: Total number of excess deaths for 2015–2024. Whiskers represent 95% confidence intervals calculated using 200 bootstrap samples.

Next, I calculated life expectancies based on both observed and adjusted death counts. The adjusted death counts were derived using the climate- and age-specific temperature effects discussed earlier in this subsection, following the methodology outlined in Eq. (4) and (6). The adjusted life expectancy reflects the value that would have been observed if the temperature distribution during the years 2015–2024 had been the same as that recorded between 1950 and 1979. Therefore, the difference between the observed and adjusted life expectancy represents the effect of temperature changes between these two periods.

The results are summarized in Fig. 7. Nearly all European regions included in this study experienced an increase in life expectancy due to the shift in temperature distribution between 1950–1979 and 2015–2024. The population-weighted average increase in life expectancy is 0.202 years (95% CI, 0.187–0.216). In 22 geographic regions, the gain ranges between 0.15 and 0.25 years, while in 24 other regions, the increase exceeds 0.25 years. The smallest gains – or, in a few cases, slight declines – are primarily observed in parts of the Mediterranean and the North.

**Fig. 7: The effect of recent temperature changes on life expectancy at birth**




Notes: The effect of temperature changes between 1950–1979 and 2015–2024.

## 5. Discussion and conclusions

This paper examined the effects of temperature on mortality in Europe during the period 2015–2024. The findings indicate that both cold and hot temperatures result in increased mortality rates. While little variation was observed within the 10–25°C daily mean temperature range, mortality rates were found to rise progressively as temperatures dropped below 10°C. Similarly, daily mean temperatures above 25°C were found to lead to elevated mortality. However, the effects of colder temperatures were found to be substantially stronger than those of heat. The results showed that the impact of both cold and heat increases markedly with age: mortality rates among children and young adults are largely unaffected by temperature extremes, whereas temperature has the strongest effects among the oldest age group. Studying the dynamics of the effects of heat and cold, I found that heat-related mortality tends to be immediate, whereas the effects of cold are more prolonged. Finally, climate emerged as a key moderator of the temperature–mortality relationship. Cold-related mortality was found to be significantly higher in warmer regions, while heat-related mortality was found to be greater in colder regions.

The estimated temperature effects, combined with the observed changes in temperature between 1950–1979 and 2015–2024, mean that recent climate change has led to a significant increase in deaths during the summer months, but a reduction in deaths during the spring, autumn, and winter months of 2015–2024. Since the decline in mortality during the colder seasons outweighed the increase in summer mortality, 869,000 fewer deaths occurred – or were postponed to a later date – across the 28 countries in the sample during 2015–2024. This reduction implies that life expectancy at birth would have been lower in nearly all geographic regions had the temperature distribution remained as it was in 1950–1979. Specifically, the decrease in the number of cold days and the increase in hot days contributed to an average gain in life expectancy of 0.20 years in Europe.

In light of these findings, the question arises: does climate change have a definitively positive impact on human health in Europe today and in the longer term? Unfortunately, the answer is no. Mortality is a very important indicator, but it is only one of many indicators of human health, and for many other outcomes, the effects of temperature do not follow the same U-shaped pattern observed for mortality. Instead, the relationship often appears linear, or health deteriorates only with rising temperatures, while cold and mild temperatures have similar effects. These patterns have been documented for emergency department visits (Gould et al., 2025; Hajdu, 2025), primary health care utilization (Fritz, 2022), fetal losses (Hajdu and Hajdu, 2023, 2021a), indicators of health at birth (Deschênes et al., 2009; Barreca and Schaller, 2020; Hajdu and Hajdu, 2021b), mental health outcomes (Burke et al., 2018; Mullins and White, 2019), and sleep (Obradovich et al., 2017; Minor et al., 2022; Hajdu, 2024). In these cases, global warming is likely to lead to worsening health outcomes, as the harmful effects of increased heat exposure are not offset by any health gains from reduced cold exposure. Simply because, unlike in the case of mortality, cold does not appear to have any strong adverse effects on these health indicators.

This study focused on the direct and short-term effects of temperature on mortality. However, extreme temperatures and a changing climate may also influence mortality through more complex and delayed pathways that are not captured in this analysis. For example, a warming climate could introduce new threats to human health in Europe, such as the spread of vector-borne diseases (Caminade et al., 2019; Thomson and Stanberry, 2022). In addition, deterioration in the aforementioned health indicators may have longer-term impacts on mortality. For example, low birth weight and preterm birth have been linked to increased adult mortality (Crump, 2020; Risnes et al., 2011), and similar long-term risks have been documented for short sleep duration (Cappuccio et al., 2010; Zhao et al., 2023).

It is also important to consider that future warming – further shifting the temperature distribution to the right – may have a direct adverse effect on mortality. As the number of very cold days continues to decline, the potential for further reductions becomes increasingly limited. The mortality benefits associated with a warming climate and milder winters are likely to diminish over time, while the mortality burdens of summer heat may increase, potentially resulting in a net negative effect on mortality.[11]

Additionally, many European regions will be exposed to extreme heat levels not previously experienced. For example, in future decades, the average temperature on days falling within the >25°C category is expected to exceed the corresponding values observed between 2015 and 2024. Climate change is also expected to increase the frequency and duration of heatwaves (Dosio et al., 2018; Perkins-Kirkpatrick and Lewis, 2020; Russo et al., 2015). Since the mortality effects of heat tend to be more severe when high temperatures persist across consecutive days (Nguyen et al., 2023; Otrachshenko et al., 2018), the adverse health effects of heat are likely to become more severe in the future than those estimated in this study. Consistent with this reasoning, a study quantifying the economic damages of climate change in the United States found that the larger the temperature increase by the end of the 21st century, the greater the share of excess mortality in total economic damages (Hsiang et al., 2017).

The results of this study also highlight a profound global inequality associated with climate change. While Europe has contributed a substantial share of historical and current global $CO_2$ emissions (Davis and Caldeira, 2010; Friedlingstein et al., 2023), the mortality burdens of climate change appear to be disproportionately concentrated in the Global South (Carleton et al., 2022; Deivanayagam et al., 2023). Although heat-related mortality is projected to increase in the future, many European countries may even experience some net positive health (mortality) effects, at least in the short term, as demonstrated by the findings of this study.[12] This stark disparity between emissions responsibility and health impacts may undermine global climate efforts. Wealthy European nations may not feel a sufficient sense of urgency or face adequate political pressure, given that their populations are less exposed to the immediate mortality consequences of global warming. In other words, despite being responsible for a disproportionate share of emissions, high-income countries may lack strong incentives to

[11] For an empirical example, see Martínez-Solanas et al. (2021).
[12] Similar results have been reported in other studies (Carleton et al., 2022; Gasparrini et al., 2017; Martínez-Solanas et al., 2021; Walkowiak et al., 2025).

accelerate climate action. This imbalance could exacerbate global inequalities and compromise the fairness and effectiveness of international climate policy.

## References


Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Pegenaute, F., Herrmann, F.R., Robine, J.M., Basagaña, X., Tonne, C., Antó, J.M., 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

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., Shapiro, J.S., 2016. Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century. Journal of Political Economy 124, 105–159. https://doi.org/10.1086/684582

Barreca, A., Clay, K., Deschênes, O., Greenstone, M., Shapiro, J.S., 2015. Convergence in Adaptation to Climate Change: Evidence from High Temperatures and Mortality, 1900-2004. American Economic Review 105, 247–251. https://doi.org/10.1257/aer.p20151028

Barreca, A., Schaller, J., 2020. The impact of high ambient temperatures on delivery timing and gestational lengths. Nature Climate Change 10, 77–82. https://doi.org/10.1038/s41558-019-0632-4

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J., Medina-Ramón, M., 2011. Heat Waves and Cause-specific Mortality at all Ages. Epidemiology 22, 765. https://doi.org/10.1097/EDE.0b013e31823031c5

Burke, M., González, F., Baylis, P., Heft-Neal, S., Baysan, C., Basu, S., Hsiang, S., 2018. Higher temperatures increase suicide rates in the United States and Mexico. Nature Climate Change 8, 723–729. https://doi.org/10.1038/s41558-018-0222-x

Caminade, C., McIntyre, K.M., Jones, A.E., 2019. Impact of recent and future climate change on vector-borne diseases. Annals of the New York Academy of Sciences 1436, 157–173. https://doi.org/10.1111/nyas.13950

Cappuccio, F.P., D'Elia, L., Strazzullo, P., Miller, M.A., 2010. Sleep Duration and All-Cause Mortality: A Systematic Review and Meta-Analysis of Prospective Studies. Sleep 33, 585–592. https://doi.org/10.1093/sleep/33.5.585

Carleton, T., Jina, A., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Kopp, R.E., McCusker, K.E., Nath, I., Rising, J., Rode, A., Seo, H.K., Viaene, A., Yuan, J., Zhang, A.T., 2022. Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits. The Quarterly Journal of Economics 137, 2037–2105. https://doi.org/10.1093/qje/qjac020

Chen, R., Yin, P., Wang, L., Liu, C., Niu, Y., Wang, W., Jiang, Y., Liu, Y., Liu, J., Qi, J., You, J., Kan, H., Zhou, M., 2018. Association between ambient temperature and mortality risk and burden: time series study in 272 main Chinese cities. BMJ 363, k4306. https://doi.org/10.1136/bmj.k4306

Cohen, F., Dechezleprêtre, A., 2022. Mortality, Temperature, and Public Health Provision: Evidence from Mexico. American Economic Journal: Economic Policy 14, 161–92. https://doi.org/10.1257/pol.20180594

Conte Keivabu, R., 2022. Extreme Temperature and Mortality by Educational Attainment in Spain, 2012–2018. Eur J Population 38, 1145–1182. https://doi.org/10.1007/s10680-022-09641-4

Copernicus Climate Change Service, Climate Data Store, 2025. E-OBS daily gridded meteorological data for Europe from 1950 to present derived from in-situ observations (31.0e). https://doi.org/10.24381/cds.151d3ec6
Cornes, R.C., van der Schrier, G., van den Besselaar, E.J.M., Jones, P.D., 2018. An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. Journal of Geophysical Research: Atmospheres 123, 9391–9409. https://doi.org/10.1029/2017JD028200
Crump, C., 2020. Preterm birth and mortality in adulthood: a systematic review. J Perinatol 40, 833–843. https://doi.org/10.1038/s41372-019-0563-y
Davis, S.J., Caldeira, K., 2010. Consumption-based accounting of CO2 emissions. Proceedings of the National Academy of Sciences 107, 5687–5692. https://doi.org/10.1073/pnas.0906974107
Deivanayagam, T.A., English, S., Hickel, J., Bonifacio, J., Guinto, R.R., Hill, K.X., Huq, M., Issa, R., Mulindwa, H., Nagginda, H.P., Sato, P. de M., Selvarajah, S., Sharma, C., Devakumar, D., 2023. Envisioning environmental equity: climate change, health, and racial justice. The Lancet 402, 64–78. https://doi.org/10.1016/S0140-6736(23)00919-4
Deschenes, O., 2022. The impact of climate change on mortality in the United States: Benefits and costs of adaptation. Canadian Journal of Economics/Revue canadienne d'économique 55, 1227–1249. https://doi.org/10.1111/caje.12609
Deschênes, O., Greenstone, M., 2011. Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US. American Economic Journal: Applied Economics 3, 152–185. https://doi.org/10.1257/app.3.4.152
Deschênes, O., Greenstone, M., Guryan, J., 2009. Climate Change and Birth Weight. American Economic Review 99, 211–17. https://doi.org/10.1257/aer.99.2.211
Deschênes, O., Moretti, E., 2009. Extreme Weather Events, Mortality, and Migration. Review of Economics and Statistics 91, 659–681. https://doi.org/10.1162/rest.91.4.659
Dosio, A., Mentaschi, L., Fischer, E.M., Wyser, K., 2018. Extreme heat waves under 1.5 °C and 2 °C global warming. Environ. Res. Lett. 13, 054006. https://doi.org/10.1088/1748-9326/aab827
Eurostat, 2025a. Deaths by week, sex, 5-year age group and NUTS 2 region. https://doi.org/10.2908/demo_r_mwk2_05
Eurostat, 2025b. Population on 1 January by age, sex and NUTS 2 region. https://doi.org/10.2908/demo_r_d2jan
Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Bakker, D.C.E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I.T., Peters, G.P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Anthoni, P., Barbero, L., Bates, N.R., Becker, M., Bellouin, N., Decharme, B., Bopp, L., Brasika, I.B.M., Cadule, P., Chamberlain, M.A., Chandra, N., Chau, T.-T.-T., Chevallier, F., Chini, L.P., Cronin, M., Dou, X., Enyo, K., Evans, W., Falk, S., Feely, R.A., Feng, L., Ford, D.J., Gasser, T., Ghattas, J., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Houghton, R.A., Hurtt, G.C., Iida, Y., Ilyina, T., Jacobson, A.R., Jain, A., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Joos, F., Kato, E., Keeling, R.F., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J.I., Körtzinger, A., Lan, X., Lefèvre, N., Li, H., Liu, J., Liu, Z., Ma, L., Marland, G., Mayot, N., McGuire, P.C., McKinley, G.A., Meyer, G., Morgan, E.J., Munro, D.R., Nakaoka, S.-I., Niwa, Y., O'Brien, K.M., Olsen, A., Omar, A.M., Ono, T., Paulsen, M., Pierrot, D., Pocock, K., Poulter, B., Powis, C.M., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T.M., Schwinger, J., Séférian, R., Smallman, T.L., Smith, S.M., Sospedra-Alfonso, R., Sun, Q., Sutton, A.J., Sweeney, C., Takao, S., Tans, P.P., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G.R., van Ooijen, E., Wanninkhof, R., Watanabe, M., Wimart-Rousseau, C., Yang, D.,

Yang, X., Yuan, W., Yue, X., Zaehle, S., Zeng, J., Zheng, B., 2023. Global Carbon Budget 2023. Earth System Science Data 15, 5301–5369. https://doi.org/10.5194/essd-15-5301-2023
Fritz, M., 2022. Temperature and non-communicable diseases: Evidence from Indonesia's primary health care system. Health Economics 31, 2445–2464. https://doi.org/10.1002/hec.4590
García-Witulski, C., Rabassa, M.J., Conte Grand, M., Rozenberg, J., 2023. Valuing mortality attributable to present and future temperature extremes in Argentina. Economics & Human Biology 51, 101305. https://doi.org/10.1016/j.ehb.2023.101305
Gasparrini, A., Armstrong, B., 2011. The Impact of Heat Waves on Mortality. Epidemiology 22, 68. https://doi.org/10.1097/EDE.0b013e3181fdcd99
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., 2015. 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.D., Heaviside, C., Vardoulakis, S., Hajat, S., Haines, A., Armstrong, B., 2017. Projections of temperature-related excess mortality under climate change scenarios. The Lancet Planetary Health 1, e360–e367. https://doi.org/10.1016/S2542-5196(17)30156-0
Gould, C.F., Heft-Neal, S., Heaney, A.K., Bendavid, E., Callahan, C.W., Kiang, M.V., Graff Zivin, J., Burke, M., 2025. Temperature extremes impact mortality and morbidity differently. Science Advances 11, eadr3070. https://doi.org/10.1126/sciadv.adr3070
Guo, Y., Gasparrini, A., Armstrong, B., Li, S., Tawatsupa, B., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Leone, M., Pan, X., Tong, S., Tian, L., Kim, H., Hashizume, M., Honda, Y., Guo, Y.-L.L., Wu, C.-F., Punnasiri, K., Yi, S.-M., Michelozzi, P., Saldiva, P.H.N., Williams, G., 2014. Global Variation in the Effects of Ambient Temperature on Mortality: A Systematic Evaluation. Epidemiology 25, 781–789.
Hajdu, T., 2025. Heterogeneous impacts of climate change on morbidity. Economics & Human Biology 58, 101517. https://doi.org/10.1016/j.ehb.2025.101517
Hajdu, T., 2024. Temperature exposure and sleep duration: Evidence from time use surveys. Economics & Human Biology 54, 101401. https://doi.org/10.1016/j.ehb.2024.101401
Hajdu, T., Hajdu, G., 2023. Climate change and the mortality of the unborn. Journal of Environmental Economics and Management 118, 102771. https://doi.org/10.1016/j.jeem.2022.102771
Hajdu, T., Hajdu, G., 2021a. Post-conception heat exposure increases clinically unobserved pregnancy losses. Scientific Reports 11, 1987. https://doi.org/10.1038/s41598-021-81496-x
Hajdu, T., Hajdu, G., 2021b. Temperature, climate change, and birth weight: evidence from Hungary. Popul Environ 43, 131–148. https://doi.org/10.1007/s11111-021-00380-y

Helo Sarmiento, J., 2023. Into the tropics: Temperature, mortality, and access to health care in Colombia. Journal of Environmental Economics and Management 119, 102796. https://doi.org/10.1016/j.jeem.2023.102796

Heutel, G., Miller, N.H., Molitor, D., 2021. Adaptation and the Mortality Effects of Temperature across U.S. Climate Regions. The Review of Economics and Statistics 103, 740–753. https://doi.org/10.1162/rest_a_00936

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., Houser, T., 2017. Estimating economic damage from climate change in the United States. Science 356, 1362–1369. https://doi.org/10.1126/science.aal4369

Khatana, S.A.M., Werner, R.M., Groeneveld, P.W., 2022. Association of Extreme Heat With All-Cause Mortality in the Contiguous US, 2008-2017. JAMA Network Open 5, e2212957. https://doi.org/10.1001/jamanetworkopen.2022.12957

Martínez-Solanas, È., Quijal-Zamorano, M., Achebak, H., Petrova, D., Robine, J.-M., Herrmann, F.R., Rodó, X., Ballester, J., 2021. Projections of temperature-attributable mortality in Europe: a time series analysis of 147 contiguous regions in 16 countries. The Lancet Planetary Health 5, e446–e454. https://doi.org/10.1016/S2542-5196(21)00150-9

Masiero, G., Mazzonna, F., Santarossa, M., 2022. The effect of absolute versus relative temperature on health and the role of social care. Health Economics 31, 1228–1248. https://doi.org/10.1002/hec.4507

Masselot, P., Mistry, M., Vanoli, J., Schneider, R., Iungman, T., Garcia-Leon, D., Ciscar, J.-C., Feyen, L., Orru, H., Urban, A., Breitner, S., Huber, V., Schneider, A., Samoli, E., Stafoggia, M., de'Donato, F., Rao, S., Armstrong, B., Nieuwenhuijsen, M., Vicedo-Cabrera, A.M., Gasparrini, A., Achilleos, S., Kyselý, J., Indermitte, E., Jaakkola, J.J.K., Ryti, N., Pascal, M., Katsouyanni, K., Analitis, A., Goodman, P., Zeka, A., Michelozzi, P., Houthuijs, D., Ameling, C., Rao, S., Silva, S. das N.P. da, Madureira, J., Holobaca, I.-H., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Ragettli, M.S., Analitis, A., Katsouyanni, K., Surname, F. name, Zafeiratou, S., Fernandez, L.V., Monteiro, A., Rai, M., Zhang, S., Aunan, K., 2023. Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. The Lancet Planetary Health 7, e271–e281. https://doi.org/10.1016/S2542-5196(23)00023-2

Minor, K., Bjerre-Nielsen, A., Jonasdottir, S.S., Lehmann, S., Obradovich, N., 2022. Rising temperatures erode human sleep globally. One Earth 5, 534–549. https://doi.org/10.1016/j.oneear.2022.04.008

Mullins, J.T., White, C., 2019. Temperature and mental health: Evidence from the spectrum of mental health outcomes. Journal of Health Economics 68, 102240. https://doi.org/10.1016/j.jhealeco.2019.102240

Nguyen, C.V., Nguyen, M.-H., Nguyen, T.T., 2023. The impact of cold waves and heat waves on mortality: Evidence from a lower middle-income country. Health Economics 32, 1220–1243. https://doi.org/10.1002/hec.4663

Obradovich, N., Migliorini, R., Mednick, S.C., Fowler, J.H., 2017. Nighttime temperature and human sleep loss in a changing climate. Science Advances 3, e1601555. https://doi.org/10.1126/sciadv.1601555

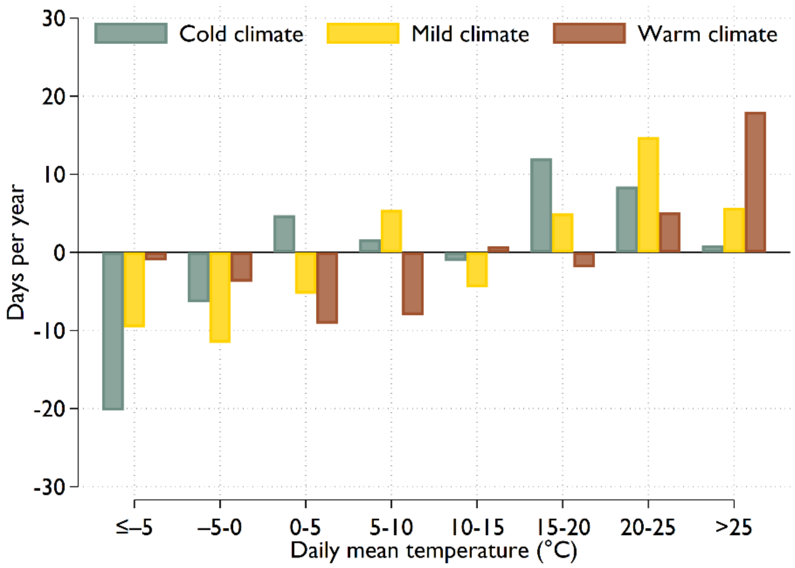
Otrachshenko, V., Popova, O., Solomin, P., 2018. Misfortunes never come singly: Consecutive weather shocks and mortality in Russia. Economics & Human Biology 31, 249–258. https://doi.org/10.1016/j.ehb.2018.08.008

Otrachshenko, V., Popova, O., Solomin, P., 2017. Health Consequences of the Russian Weather. Ecological Economics 132, 290–306. https://doi.org/10.1016/j.ecolecon.2016.10.021

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nat Commun 11, 3357. https://doi.org/10.1038/s41467-020-16970-7
Preston, S.H., Heuveline, P., Guillot, M., 2001. Demography: Measuring and Modeling Population Processes. Blackwell Publishing.
Risnes, K.R., Vatten, L.J., Baker, J.L., Jameson, K., Sovio, U., Kajantie, E., Osler, M., Morley, R., Jokela, M., Painter, R.C., Sundh, V., Jacobsen, G.W., Eriksson, J.G., Sørensen, T.I.A., Bracken, M.B., 2011. Birthweight and mortality in adulthood: a systematic review and meta-analysis. International Journal of Epidemiology 40, 647–661. https://doi.org/10.1093/ije/dyq267
Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10, 124003. https://doi.org/10.1088/1748-9326/10/12/124003
Schuster, H., Polleres, A., Anjomshoaa, A., Wachs, J., 2025. Heat, health, and habitats: analyzing the intersecting risks of climate and demographic shifts in Austrian districts. Sci Rep 15, 22812. https://doi.org/10.1038/s41598-025-05676-9
Schwarz, L., Chen, C., Castillo Quiñones, J.E., Aguilar-Dodier, L.C., Hansen, K., Sanchez, J.R., González, D.J.X., McCord, G., Benmarhnia, T., 2025. Heat-related mortality in Mexico: A multi-scale spatial analysis of extreme heat effects and municipality-level vulnerability. Environment International 195, 109231. https://doi.org/10.1016/j.envint.2024.109231
Thomson, M.C., Stanberry, L.R., 2022. Climate Change and Vectorborne Diseases. New England Journal of Medicine 387, 1969–1978. https://doi.org/10.1056/NEJMra2200092
Walkowiak, M.P., Walkowiak, D., Walkowiak, J., 2025. Evolving threats in an unforgiving climate: impact of non-optimal temperatures on life expectancy. Popul Environ 47, 10. https://doi.org/10.1007/s11111-025-00480-z
Zhao, B., Meng, Y., Jin, X., Xi, W., Ma, Q., Yang, J., Ma, X., Yan, B., 2023. Association of Objective and Self-Reported Sleep Duration With All-Cause and Cardiovascular Disease Mortality: A Community-Based Study. Journal of the American Heart Association 12, e027832. https://doi.org/10.1161/JAHA.122.027832

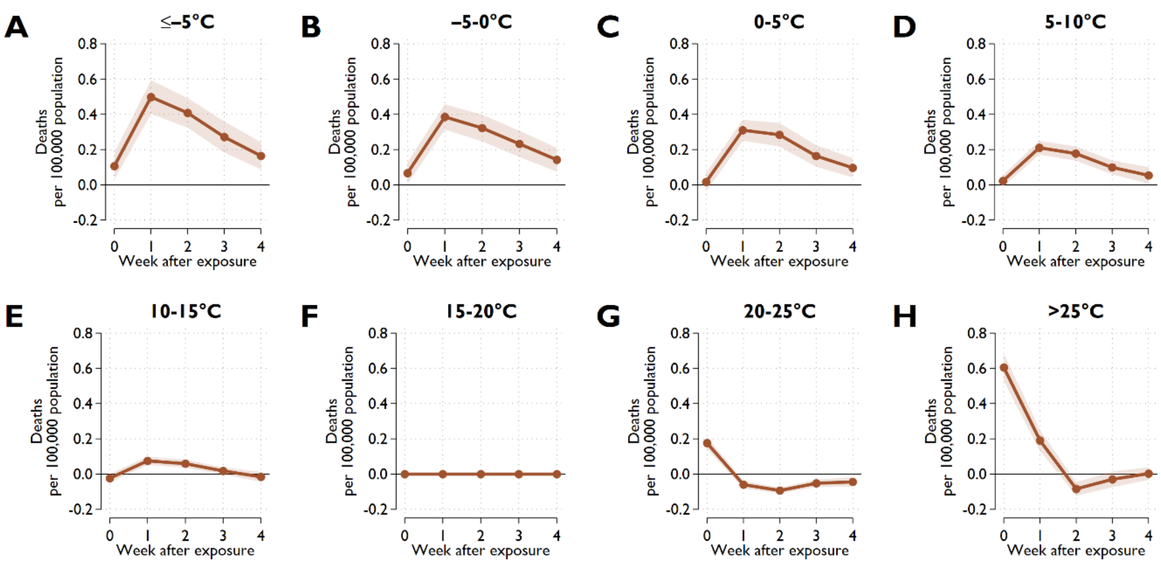
## Supplementary Materials

### Fig. A1: Temperature changes between 1950–1979 and 2015–2024



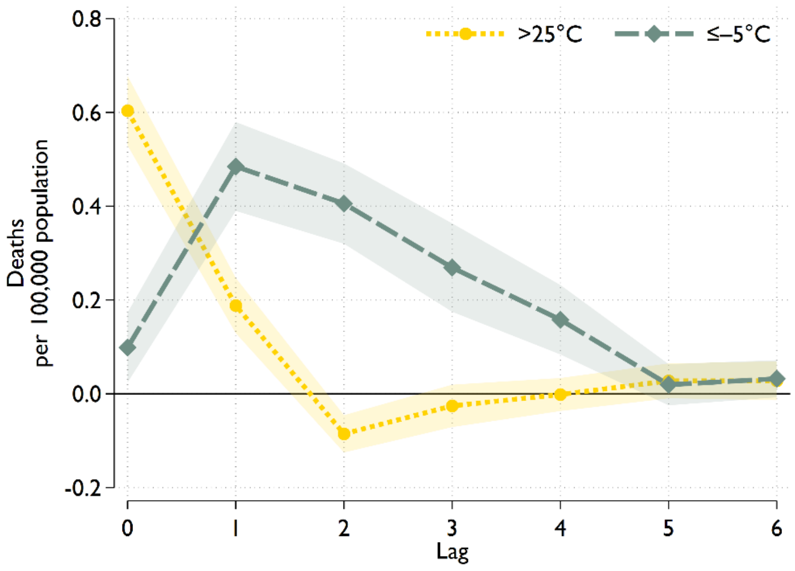

Notes: Population weighted averages of the regions in the three climate groups.

### Fig. A2: Temperature effects by lag



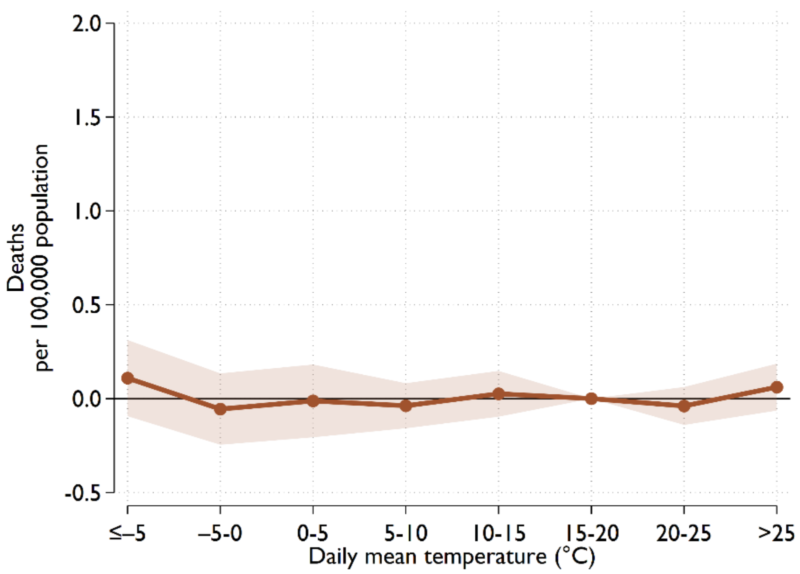

Notes: Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

**Fig. A3: Temperature effects allowing for six lags**



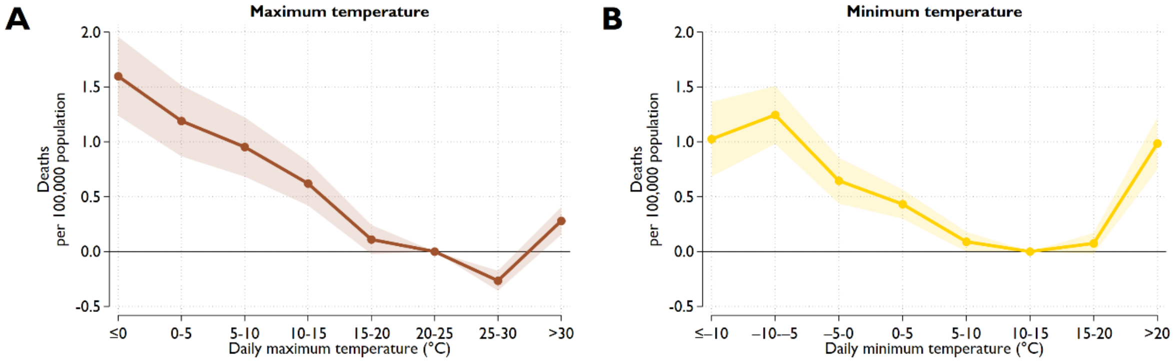

Notes: Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

**Fig. A4: Falsification test using future temperatures**



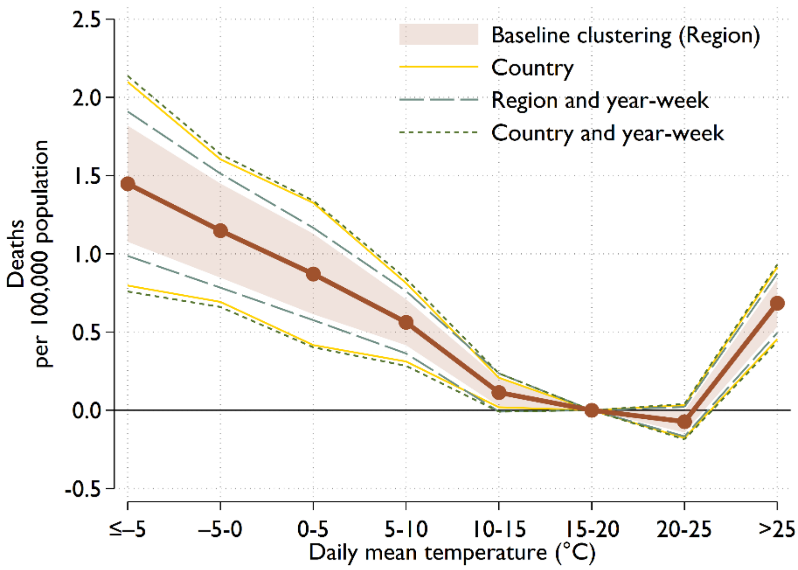

Notes: Cumulative effects for lags 0–4. This analysis used temperature and precipitation measured one year later. Only the years between 2015 and 2023 were used. Reference temperature category: 15–20°C. The shaded area represents 95% confidence intervals.

## Fig. A5: Temperature effects using maximum and minimum temperatures



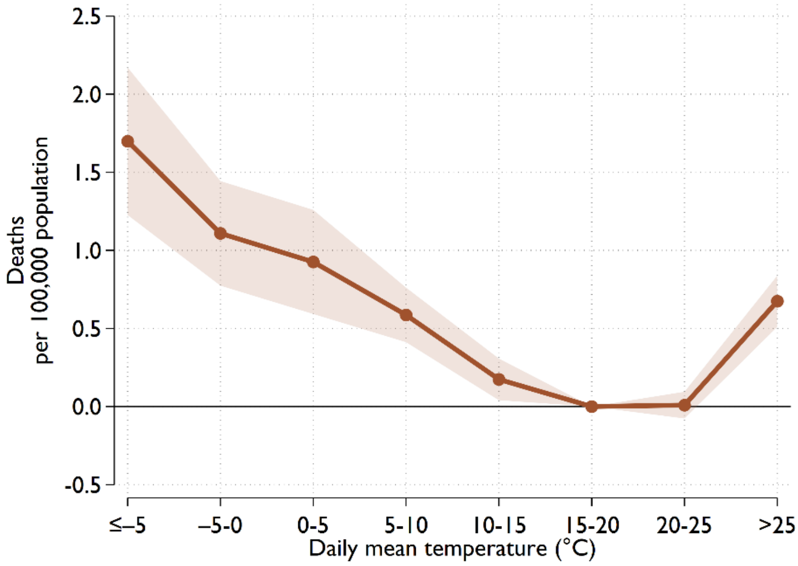

Notes: Cumulative effects for lags 0–4. Reference temperature category: (A) 20–25°C, (B) 10–15°C. The shaded areas represent 95% confidence intervals.

## Fig. A6: Alternative clustering methods



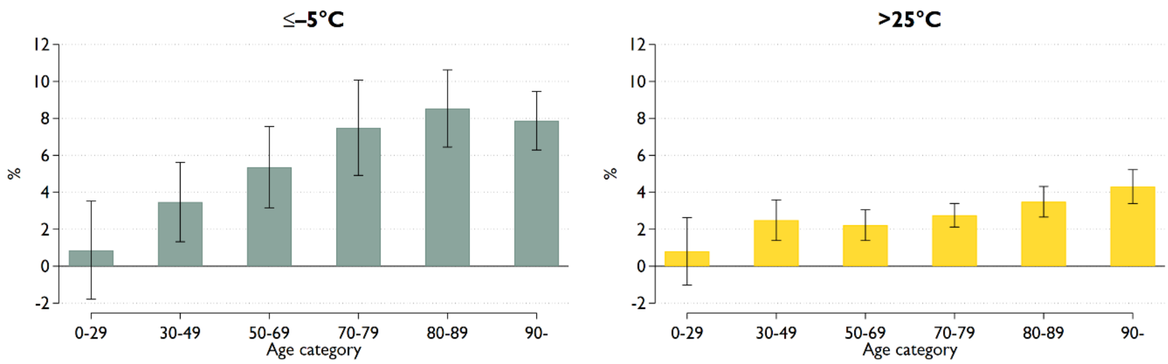

Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded area and thin lines represent 95% confidence intervals.

**Fig. A7: Temperature effects in 2015-2021**



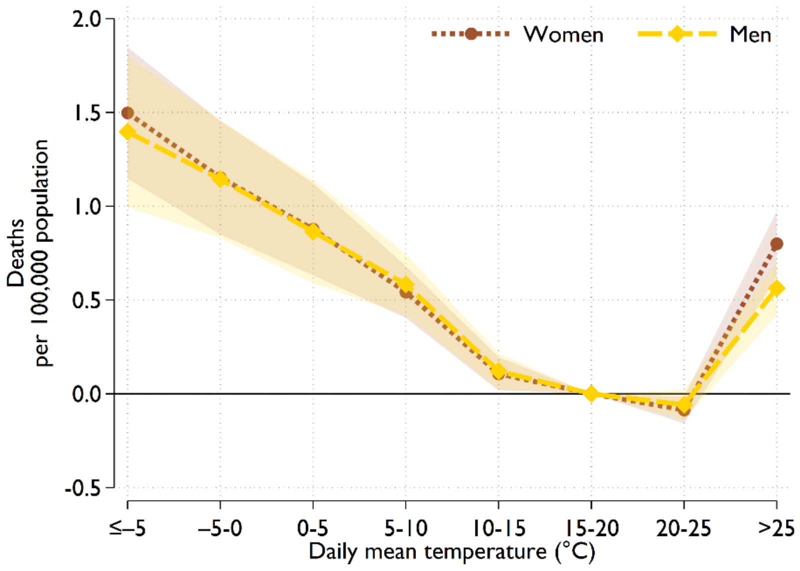

Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded area represents 95% confidence intervals. Only the years between 2015 and 2021 are included.

**Fig. A8: Percentage effects of heat and cold by age**



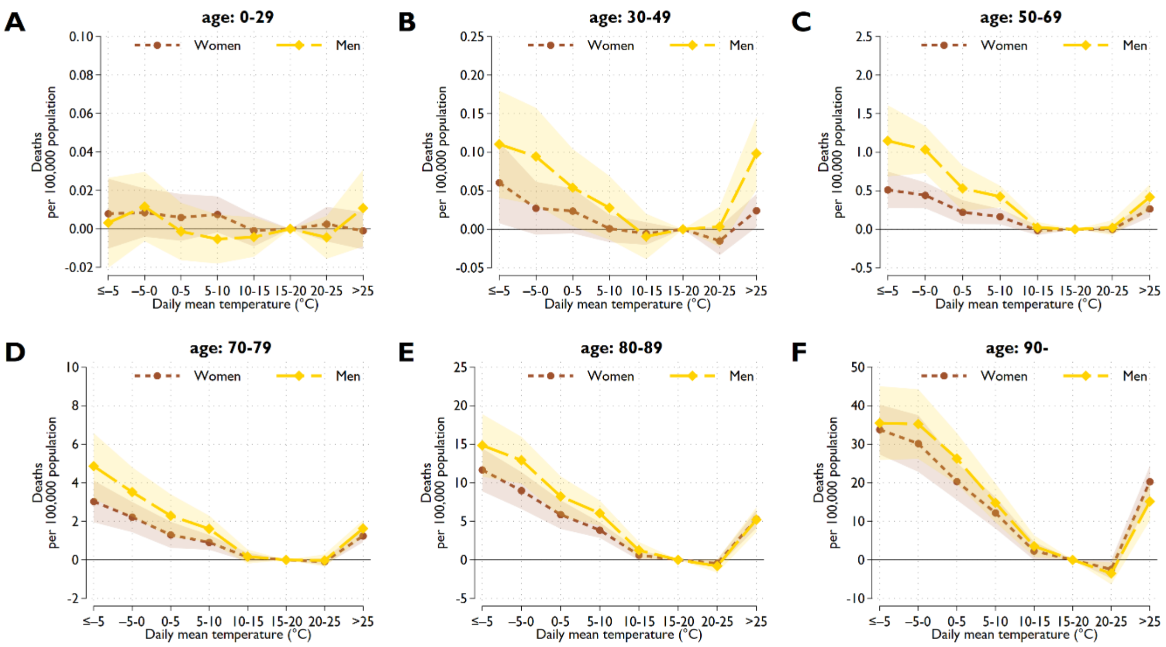

Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. Whiskers represent 95% confidence intervals. The effects are expressed as a percentage of the average weekly mortality rate of the age groups.

## Fig. A9: Sex-specific effects of temperature on total mortality rates




Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

## Fig. A10: Age-specific effects of temperature by sex




Notes: Cumulative effects for lags 0–4. Reference temperature category: 15–20°C. The shaded areas represent 95% confidence intervals.

**Table A1:Descriptive statistics**

| Variable | Mean | SD | Min | Max | N |
|---|---|---|---|---|---|
| Total mortality rate | 20.61 | 5.46 | 0.68 | 79.29 | 37,960 |
| N of ≤−5°C days | 0.12 | 0.60 | 0 | 7.41 | 37,960 |
| N of (−5,0]°C days | 0.39 | 0.98 | 0 | 9.00 | 37,960 |
| N of (0,5]°C days | 1.03 | 1.59 | 0 | 8.63 | 37,960 |
| N of (5,10]°C days | 1.49 | 1.76 | 0 | 8.20 | 37,960 |
| N of (10,15]°C days | 1.51 | 1.75 | 0 | 7.60 | 37,960 |
| N of (15,20]°C days | 1.36 | 1.80 | 0 | 7.00 | 37,960 |
| N of (20,25°C] days | 0.84 | 1.50 | 0 | 7.00 | 37,960 |
| N of >25°C days | 0.29 | 0.96 | 0 | 7.00 | 37,960 |

Notes: Population-weighted figures. Unit of observations: region-by-week.

**Table A2: Sensitivity tests**

| Daily mean temperature (°C) | (1) Baseline | (2) Unweighted | (3) Excl. precipitation | (4) fixed effects: RY, RW, YW | (5) fixed effects: RYS, RW, RW×t, YW | (6) fixed effects: RYS, RW, RW×t, RW×$t^2$, YW | (7) fixed effects: RY, RW |
|---|---|---|---|---|---|---|---|
| ≤−5°C | 1.45 (0.19) | 1.46 (0.17) | 1.45 (0.18) | 1.24 (0.18) | 1.48 (0.22) | 1.76 (0.26) | 1.69 (0.14) |
| −5-0°C | 1.15 (0.15) | 1.25 (0.13) | 1.14 (0.15) | 1.15 (0.17) | 1.13 (0.17) | 1.44 (0.20) | 1.67 (0.11) |
| 0-5°C | 0.87 (0.13) | 0.98 (0.13) | 0.86 (0.13) | 0.70 (0.15) | 0.88 (0.15) | 1.14 (0.19) | 0.98 (0.11) |
| 5-10°C | 0.56 (0.07) | 0.59 (0.07) | 0.55 (0.07) | 0.36 (0.11) | 0.58 (0.08) | 0.70 (0.10) | 0.52 (0.08) |
| 10-15°C | 0.11 (0.04) | 0.21 (0.05) | 0.10 (0.04) | −0.04 (0.04) | 0.08 (0.05) | 0.09 (0.07) | −0.00 (0.05) |
| 15-20°C | ref. cat. | ref. cat. | ref. cat. | ref. cat. | ref. cat. | ref. cat. | ref. cat. |
| 20-25°C | −0.07 (0.03) | −0.04 (0.04) | −0.06 (0.04) | −0.17 (0.06) | −0.05 (0.04) | −0.09 (0.05) | −0.05 (0.05) |
| >25°C | 0.68 (0.08) | 0.73 (0.06) | 0.71 (0.08) | 0.43 (0.11) | 0.69 (0.09) | 0.54 (0.11) | 0.71 (0.12) |

Notes: Fixed effects: R-geographic region, Y-year, W-week, S-season, t-linear time trend, $t^2$-quadratic time trend. Standard errors clustered by region are in parentheses.