



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

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## ABSTRACT

This paper analyzes the effects of temperatures on mortality and life expectancy using data on 40 million deaths 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 and income are key moderators: cold-related mortality is higher in warmer regions, heat-related mortality is higher in colder regions, and the effects of cold are stronger at lower income levels. The study also shows that the number of deaths in 2015–2024 would have been higher under the climate conditions of 1950–1979. The shift in the temperature distribution increased mortality during the warmest months but reduced mortality during the colder months, yielding a net decrease of more than 900,000 deaths over the 2015–2024 period. This reduction corresponds to an average increase in life expectancy at birth of 0.195 years.

## 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, studies that examine the full temperature distribution typically find that both extreme heat and extreme cold increase 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, understanding the mortality consequences of climate change is essential. Projections of future impacts typically combine estimates of the historical relationship between temperature and mortality with temperature projections from climate models. A growing body of work documents substantial geographic heterogeneity in projected excess mortality. Many regions (especially in

the Global South) are expected to experience large increases in mortality by the end of the century, whereas some regions in the Global North may benefit from warming, primarily due to reductions in cold-related mortality (Carleton et al., 2022; Gasparrini et al., 2017; Martínez-Solanas et al., 2021).

A separate strand of the literature has examined the recent mortality impacts of temperature exposure. These studies typically quantify effects as the number of excess deaths attributable to deviations from a minimum-mortality (optimal) temperature (Ballester et al., 2023; Gasparrini et al., 2015; Masselot et al., 2023). While these studies provide important insights, such estimates do not directly reflect the effects of climate change itself. Evidence on how recent shifts in the temperature distribution, that is, the climate change already experienced, have affected mortality remains limited, especially at the continental or global scale.

Moreover, the literature provides little evidence on how recent temperature changes have influenced life expectancy, a key summary measure of population health.<sup>1</sup> A comprehensive assessment of these impacts requires detailed estimates of age-specific temperature effects, as mortality changes at different ages contribute very differently to overall life expectancy.

This study contributes to the literature by synthesizing and extending

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<sup>1</sup> One exception is the paper by Walkowiak et al. (2025), which links non-optimal temperatures to life expectancy. However, their analysis relies on observed changes in life expectancy rather than underlying mortality effects, and it uses a less flexible model specification with relatively simplified temperature measures.

previous findings based on data from different countries, time periods, and temporal frequencies using a unified and up-to-date mortality database covering much of Europe between 2015 and 2024. The present analysis examines temporal dynamics of temperature effects, individual and spatial heterogeneity, and the role of sequences of hot and cold days. Importantly, it also quantifies how the changing climate of recent decades has shaped life expectancy at birth across European regions.

Specifically, I examine the relationship between temperature and mortality and estimate the impact of recent temperature changes on life expectancy in Europe. The analysis uses a large weekly dataset covering 40 million deaths between 2015 and 2024 across 73 geographic regions in 28 European countries. I apply a well-established and flexible empirical approach based on temperature bins to capture the nonlinearity of the temperature–mortality relationship, while controlling for location and time fixed effects that absorb spatial characteristics, seasonality, and common trends (Dell et al., 2014; Hsiang, 2016). This fixed-effect approach identifies the effects of ambient temperature from plausibly random temperature variation. The high-frequency data allow for the analysis of temporal dynamics, while the broad spatial coverage enables an investigation of how climatic conditions and income levels shape the effects of heat and cold. The estimation of lagged temperature effects ensures that short-term temporal displacement of some mortality events and delayed mortality effects (e.g. deaths due to prolonged respiratory infections) are captured by the estimated temperature coefficients.

I find that an additional day with a daily mean temperature of  $> 25^{\circ}\text{C}$  increases the number of deaths by 0.58 per 100,000 population over a five-week-long period, reflecting an increase of 2.8% relative to the average weekly mortality rate in the sample (20.62). At the other end of the temperature distribution, an additional day with a mean temperature of  $\leq 0^{\circ}\text{C}$  leads to 1.29 additional deaths, relative to a reference temperature of  $15\text{--}20^{\circ}\text{C}$ . This corresponds to a 6.3% relative effect. Within the  $10\text{--}25^{\circ}\text{C}$  range, mortality shows little variation. However, below  $10^{\circ}\text{C}$ , 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 find that the mortality effect of high temperatures is strongest during the week of exposure and declines rapidly, whereas the effect of cold temperatures emerges with a one-week delay and gradually weakens over the following weeks. In addition, accumulated temperature stress has a stronger impact on mortality than an isolated one-day exposure: the effect of heat is substantially larger when the previous day's temperature is higher, while for cold exposure, lower temperatures on the previous day increase the mortality effect of a cold day.

The analysis also corroborates previous findings that climate (long-run average temperature) 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  $25^{\circ}\text{C}$  is substantially larger in cold regions (0.95 deaths per 100,000 population) than in warm regions (0.42 deaths per 100,000 population). Conversely, the effect of a day with a mean temperature at or below  $0^{\circ}\text{C}$  is larger in warm regions (2.07 deaths per 100,000 population) than in cold regions (1.04 deaths per 100,000 population). In addition, income not only moderates the effects of temperature at the global scale (Carleton et al., 2022), but also emerges as an important moderator within Europe: the effects of cold temperatures are stronger in regions with lower income levels.

Most importantly, this paper estimates how the climate change experienced over the past few decades has influenced deaths and life expectancy in 2015–2024. Specifically, I calculate in the number of deaths in 2015–2024 that can be attributed to the shift in the temperature distribution between 1950–1979 and 2015–2024, and how these deaths influenced life expectancy at birth in 2015–2024. As previous studies have primarily focused on the future impacts of climate change,

these results provide novel and important evidence on the mortality impacts of the climate change already experienced. Across the 73 European regions included in this study, more deaths occurred during the warmest months, while fewer deaths occurred during the colder months of 2015–2024 than would have been expected under the climate conditions 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 corresponds to more than 900,000 fewer deaths. More precisely, these deaths were postponed – by at least a few months – due to climate change. 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 0.195 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 changes in deaths and life expectancy due to a warming climate. 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 are drawn from Eurostat databases. The first database contains the number of weekly deaths by sex, five-year age group (ages 0–4 to 90 years and older), and NUTS 2 region (Eurostat, 2025a).<sup>2</sup> The second database contains the population size data by age, sex, and NUTS 2 region on January 1 each year (Eurostat, 2025b). This analysis uses years between 2015 and 2024, and the sample is restricted to the countries and regions with complete age-specific death and population counts.<sup>3</sup> Smaller countries (those with a total area of less than 100,000 square kilometers) are not broken down into smaller geographical units; mortality rates are analyzed for the whole country. For larger countries, however, mortality rates are analyzed for NUTS 1 regions.<sup>4</sup>

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 are 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 are first distributed across the days of the given week (assuming that each day had the same number of deaths). Then, a new weekly dataset is 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 52nd calendar week is eight days long (except in leap years, when it is nine days).

From the death and population data, I calculate weekly mortality rates (number of deaths per week per 100,000 population) for each region-by-sex-by-age group, where region refers to the NUTS level for

<sup>2</sup> This database contains deaths occurring among the resident population living in a given area, while the date of death is determined by the date on which the death occurred.

<sup>3</sup> Five French overseas regions are 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).

<sup>4</sup> Finland and Norway are exceptions because one NUTS 1 region basically represents the whole country, so NUTS 2 regions are used.

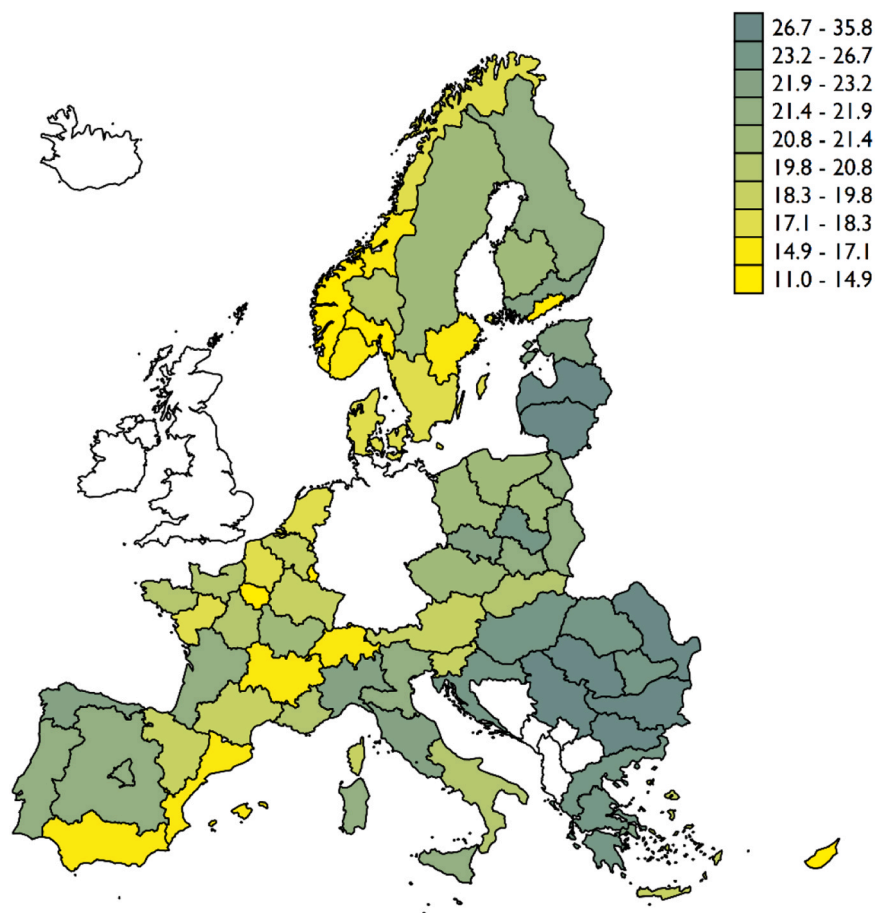


Fig. 1. Average weekly total mortality rates, 2015–2024. Notes: Mortality rate = number of deaths per week per 100,000 population.

larger countries and the country level for small countries. These weekly mortality rates serve as the dependent variable of the empirical analysis. The sample average of the total mortality rate is 20.62 (Table A2, [Supplementary Materials](#)).

The final dataset is a balanced panel covering 73 geographic units from 28 countries (Table A1, [Supplementary Materials](#)) and containing data on 40 million deaths (40,012,449).<sup>5</sup> Fig. 1 illustrates the geographic coverage of the study and shows the average weekly mortality rates. A clear East–West divide emerges. Weekly mortality rates are usually highest in the post-communist countries of Central and Eastern Europe, especially in Bulgaria, Romania, Hungary, and the Baltic states.

## 2.2. Weather

Information on weather is obtained from the E–OBS 31.0e dataset provided by the Copernicus Climate Data Store ([Copernicus Climate Change Service, Climate Data Store, 2025](#)). The E–OBS 31.0e data provides gridded data with a spatial resolution of  $0.25^\circ \times 0.25^\circ$  in regular latitude–longitude coordinates and covers the period 1950–2024 ([Cornes et al., 2018](#)). The analysis primarily uses data on daily mean temperature and precipitation. However, the main results are also presented using minimum and maximum temperatures, while

<sup>5</sup> Two major countries cannot be included in this study. The United Kingdom is excluded because it was removed from the Eurostat datasets starting in 2020 following its departure from the European Union. Germany is also excluded, as mortality data by age group are not available at the NUTS1 level, and for age groups below 40 they are not available even at the national level.

additional analyses control for wind speed and global radiation.

The daily temperature conditions at each grid point are described by seven binary variables indicating the temperature range into which the daily mean temperature at that grid point fell:  $\leq 0^\circ\text{C}$ ,  $(0,5]^\circ\text{C}$ ,  $(5,10]^\circ\text{C}$ ,  $(10,15]^\circ\text{C}$ ,  $(15,20]^\circ\text{C}$ ,  $(20,25]^\circ\text{C}$ ,  $>25^\circ\text{C}$ . Additionally, four precipitation variables show the amount of precipitation: 0 mm,  $(0,5]$  mm,  $(5,10]$  mm, and  $>10$  mm. Next, the grid-point-level weather variables are 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.<sup>6</sup> Importantly, during this aggregation, population-weighted averages are calculated using the GEOSTAT 2011 dataset ([Eurostat, 2016](#)). This dataset provides population data at a  $1\text{ km}^2$  resolution. Each population grid point is assigned to the nearest weather grid point, after which the population counts are summed to obtain the total population for the weather cells. These population figures are then used as weights when averaging the grid-cell-by-day weather data. Finally, the weekly number of days with different mean temperatures and precipitation levels is calculated by summing the daily data. Specifically, the weekly number of days in temperature category  $j$  ( $T_{\text{ryw}}^j$ ) is constructed as follows:

<sup>6</sup> For example, if on a given day the daily mean temperature in half of a region is  $24^\circ\text{C}$ , while in the other half of the region the daily mean temperature is  $26^\circ\text{C}$ , 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.

$$T_{ryw}^j = \sum_{d \in yw} \sum_{p \in r} W_p T_{rpywd}^j \quad (1)$$

where  $r$  denotes one of the 73 geographic units,  $p$  denotes grid cells,  $y$  denotes year,  $w$  denotes week, and  $d$  denotes day.  $T_{rpywd}^j$  is an indicator variable for the temperature observation in grid cell  $p$  on day  $d$ , taking the value 1 if the temperature falls in category  $j$ .  $W$  denotes the weight factor based on the population count for grid cell  $p$ . Other weather indicators are constructed similarly.

The descriptive statistics are summarized in Table A2 (Supplementary Materials). Approximately 5.7% and 5.1% of days fall into the lowest ( $\leq 0^\circ\text{C}$ ) and highest ( $> 25^\circ\text{C}$ ) temperature categories, respectively, while roughly 20–20% of days fall into the middle three temperature categories.

To explore the moderating effect of the previous day's temperature a further distinction is made. The hottest ( $> 25^\circ\text{C}$ ) and coldest ( $\leq 0^\circ\text{C}$ ) days are split into three groups based on the temperature of the preceding day. Specifically, I distinguished cold days based on whether the temperature on the previous day was below  $-3^\circ\text{C}$ , between  $-3^\circ\text{C}$  and  $0^\circ\text{C}$ , or above  $0^\circ\text{C}$ , an hot days based on whether the temperature on the previous day was below  $25^\circ\text{C}$ , between  $25^\circ\text{C}$  and  $28^\circ\text{C}$ , or above  $28^\circ\text{C}$ .

The E-OBS 31.0e dataset is also used to assess recent climate change. The temperature distribution during 2015–2024 is compared with that of 1950–1979, which serves as a baseline reflecting the climatic conditions approximately half a century prior to the period under study. First, the annual average number of days falling into the seven temperature categories ( $\leq 0^\circ\text{C}$ , ...,  $> 25^\circ\text{C}$ ) is calculated for 2015–2024, and these distributions are compared with the corresponding averages for 1950–1979:

$$\Delta T_r^j = \bar{T}_{r,2015-2024}^j - \bar{T}_{r,1950-1979}^j \quad (2)$$

where  $\bar{T}$  denotes the average number of days per year in region  $r$  when the daily mean temperature falls into temperature category  $j$ , and  $\Delta T$  represents the change between 1950–1979 and 2015–2024.<sup>7</sup> These temperature changes are subsequently used to calculate the effects of recent climate change on deaths.

Fig. A1 in the Supplementary Materials depicts these changes in the annual temperature distribution for regions with cold, mild, and warm climates. It is important to note that this classification is based solely on temperature, as this paper aims to study how the temperature–mortality relationship differs across regions with different typical temperature levels. Specifically, climate regions are defined based on the average annual mean temperature between 2000 and 2024. The first group, the cold-climate group, includes regions with an average annual mean temperature  $< 9^\circ\text{C}$ . The second group, the mild-climate group, includes regions with an average annual mean temperature between  $9^\circ\text{C}$  and  $12^\circ\text{C}$ . The third group, the warm-climate group, includes regions with an average annual mean temperature  $> 12^\circ\text{C}$ .

### 2.3. Income

To examine heterogeneity by income, data are drawn from Eurostat (Eurostat, 2025c). The dataset contains information on different income measures. This paper uses the net disposable income per inhabitant that is averaged over 2015–2022.<sup>8</sup> For heterogeneity analysis, geographic regions are divided into three groups (low, middle, high) based on

<sup>7</sup> To deal with the effects of leap years, each temperature distribution has been converted to 365-day years.

<sup>8</sup> For many regions, income figures for 2023 and 2024 are not available.

terciles.<sup>9</sup>

## 3. Methods

### 3.1. The effects of temperature on mortality

To describe the effect of temperature on mortality in Europe, the total mortality rate is first regressed on temperature and precipitation using the following distributed lag model:

$$M_{rt} = \sum_j \sum_{b=0}^4 \beta_b^j T_{r(t-b)}^j + \sum_k \sum_{b=0}^4 \gamma_b^k P_{r(t-b)}^k + \rho_{rys} + \theta_{rw} + \mu_t + \varepsilon_{rt} \quad (3)$$

where  $M$  is the total mortality rate in geographic region  $r$  at time  $t$  (year  $y$ , season  $s$ , week  $w$ ).  $T$  denotes the number of days in the  $j$ -th temperature category to which individuals were exposed, and  $P$  denotes the daily precipitation category.<sup>10</sup> Region-by-year-by-season<sup>11</sup> fixed effects ( $\rho$ ) account for unobserved location-by-time-specific factors that influence the mortality rate. Region-specific, time-invariant seasonality is captured by region-by-week fixed effects ( $\theta$ ). Finally, year-by-week fixed effects ( $\mu$ ) control time-varying factors that are common to all geographic regions in Europe. This fixed effects approach combined with a distributed lag model constitutes a well-established and flexible empirical framework (Dell et al., 2014; Hsiang, 2016). It has been widely applied in studies that examine the dynamic causal effects of temperature (e.g., Barreca et al., 2018; Barreca and Schaller, 2020; Dell et al., 2012; Deschênes and Moretti, 2009; Fritz, 2022; Hajdu, 2024a, 2025).

The coefficient  $\beta_b^j$  represents the effect of an additional day with the daily mean temperature in category  $j$  (relative to  $15\text{--}20^\circ\text{C}$ ) on the mortality rate at lag  $b$ . Since exposure to heat and cold is likely to affect mortality rates not only immediately but also with some delay, four lags are included. Thus, mortality at time  $t$  may be affected by contemporaneous weather ( $b=0$ ), as well as weather in the previous four weeks ( $b = 1, \dots, 4$ ). Importantly,  $\beta_b^j$  is equivalent to the effect of temperature at time  $t$  on mortality at time  $t + b$  (Stock and Watson, 2015). Therefore, the sum of these coefficients ( $\beta^j = \sum_{b=0}^4 \beta_b^j$ ) can be interpreted as the cumulative (or total) effect of temperature in category  $j$  at time  $t$  over a five-week period.

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

In addition, this paper also examines heterogeneity by climate, income, age, and sex. Eq. (3) is estimated separately for regions with cold, mild, and warm climates, low, medium and high income levels, for women and men, and for six broader age groups (ages 0–29, 30–49, 50–69, 70–79, 80–89, and 90+ years). When age- and sex-specific effects are estimated, the corresponding age- or sex-specific mortality rate is used as the dependent variable instead of the total mortality rate.

### 3.2. Climate change and life expectancy

Total mortality rates are used to illustrate and explore key aspects of the relationship between temperature and deaths. However, life expectancy at birth is a crucial summary measure of overall mortality

<sup>9</sup> The low-income group includes regions with a disposable income per capita lower than 12,013 EUR, the medium-income group includes regions with a disposable income between 12,013 and 20,650 EUR, while the high-income group includes regions with a disposable income level at least 20,651 EUR.

<sup>10</sup> A robustness test shows that including other weather indicators besides precipitation does not change the results.

<sup>11</sup> 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).

conditions that can more precisely capture the effects of recent climate change on deaths. Estimating life expectancy requires calculating age-specific temperature effects for age groups that are as narrow as possible. The present study relies on five-year age groups (from 0 to 4–90 years and older). To ensure that the estimated effects reflect regional differences, these age-specific temperature effects are estimated separately for groups defined by climate and income. Specifically, regressions similar to Eq. (3) are estimated separately for each age-by-climate-by-income “cell”.<sup>12</sup> From these estimations, cumulative temperature effects that are specific to age, climate, and income groups are obtained:

$$\beta_{acg}^j = \sum_{b=0}^4 \beta_{acgb}^j \quad (4)$$

where  $a$  denotes the age groups (0–4, 5–9, ..., 90–),  $c$  denotes the climate group based on the regions’ average annual mean temperature between 2000 and 2024, and  $g$  denotes the income group.

In this paper, excess deaths refer to the deaths in 2015–2024 that can be attributed to the fact that the climate of 1950–1979 was not experienced during the years 2015–2024. In other words, this is the number of deaths in 2015–2024 that is the results of the shift in the temperature distribution between 1950–1979 and 2015–2024. The annual number of deaths due to this recent change in the temperature distribution are calculated using the age-, climate- and income-specific cumulative temperature coefficients from Eq. (4), the temperature changes from Eq. (2), and age-specific population figures:

$$\bar{D}_{ra}^E = \sum_j \beta_{acg}^j \Delta T_r^j \frac{\bar{N}P_{ra}}{100,000} \quad (5)$$

where  $\bar{D}_{ra}^E$  is the average number of deaths per year in 2015–2024 in age category  $a$  in region  $r$ <sup>13</sup> that can be attributed to shifts in the temperature distribution between 1950–1979 and 2015–2024,  $\beta_{acg}^j$  is the cumulative effect for temperature category  $j$  from Eq. (4),  $\Delta T_r^j$  is the change in the annual number of days in temperature category  $j$  between 1950–1979 and 2015–2024 from Eq. (2), while  $\bar{N}P$  is the average age-specific population in 2015–2024.

Before turning to life expectancy, the total number of excess deaths per year in the 28 countries covered by the study can be obtained by summing the age- and region-specific death counts from Eq. (5). This represents the annual number of deaths, in an average year between 2015 and 2024, attributable to the change in temperature distribution between 1950–1979 and 2015–2024. Multiplying this number by ten yields the total number of deaths in 2015–2024 that occurred because the climate of 1950–1979 was not experienced:

$$D^E = 10 \times \sum_r \sum_a \bar{D}_{ra}^E \quad (6)$$

Next, the death counts from Eq. (5) are 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 2015–2024 had been identical to that of 1950–1979:

<sup>12</sup> Since only two and three regions fall into the cold-climate/middle-income and warm-climate/high-income groups, respectively, these regions are reassigned to other “cells”. Two Italian regions are moved to the warm-climate/medium-income group, as their income levels are close to the lower bound of the high-income category. One French region, whose average temperature is close to the lower bound of the warm-climate group, is moved to the mild-climate/high-income group. Finally, two Finnish regions with income levels near the upper bound of the middle-income category are moved to the cold-climate/high-income group.

<sup>13</sup> It should be noted that climate and income groups are not included in the notation, as they are determined by the regions.

$$\bar{D}_{ra}^A = \bar{D}_{ra}^O - \bar{D}_{ra}^E \quad (7)$$

where  $\bar{D}^A$  is the average number of adjusted deaths per year in 2015–2024.  $\bar{D}^O$  is the average number of observed deaths per year in 2015–2024, and  $\bar{D}^E$  is the average number of excess deaths per year in 2015–2024 from Eq. (5).

Life expectancy at birth for each region is then calculated using either the observed ( $D^O$ ) or the adjusted ( $D^A$ ) age-specific deaths following a standard approach (Preston et al., 2001). The difference between these figures shows the change in life expectancy at birth attributable to the recent shift in the temperature distribution.

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

Note that this calculation assumes that, in 2015–2024, the mortality effects of exposure to the temperatures observed in 1950–1979 would be the same as the mortality effects estimated under the temperatures observed in 2015–2024. One may argue that the currently observed temperature effects partly reflect adaptation to a changing climate. For example, populations have adapted to warmer conditions through improved access to air conditioning and other protective measures. Without the shift in the temperature distribution over the last decades, and the associated behavioral and other changes, mortality responses to a colder temperature distribution could therefore differ today.

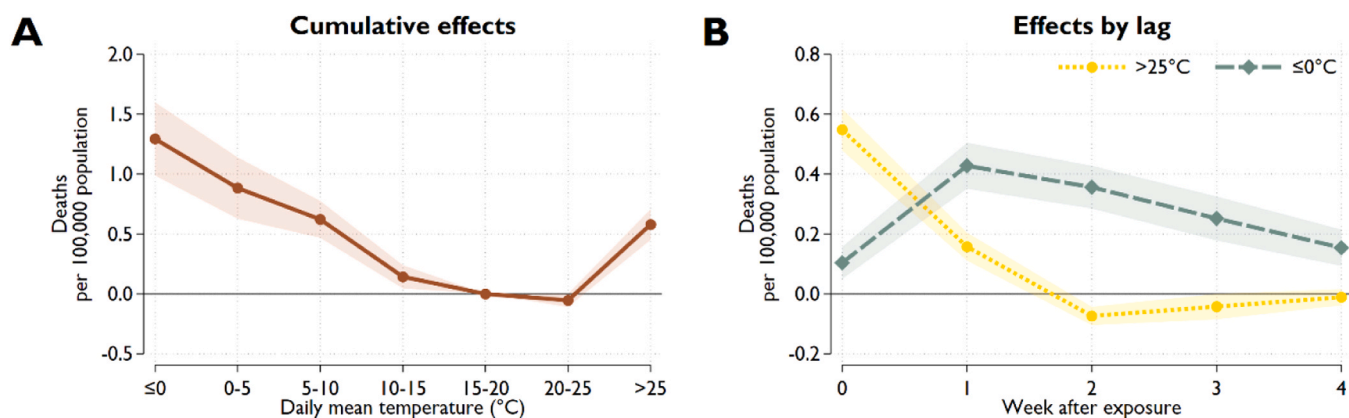
While this is a valid concern, and the observed heterogeneity in temperature effects by climate provides evidence for long-term adaptation (Carleton et al., 2022; Conte Keivabu, 2022; Heutel et al., 2021; Otrachshenko et al., 2018), evidence for short-run adaptation (i.e., changes in temperature–mortality relationships over recent decades) is more limited (Barreca et al., 2016; Burke et al., 2024; Deschenes, 2022). Therefore, using the temperature effects estimated for 2015–2024 to construct a counterfactual scenario in which the European population in 2015–2024 is exposed to the temperature distribution observed in 1950–1979 is not an unreasonable assumption. Finally, it is worth noting that this calculation can also be interpreted as the outcome of a hypothetical experiment in which today’s climate is suddenly shifted to historical conditions.

## 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 daily mean temperature of > 25°C results in 0.58 additional deaths per 100,000 population over a five-week-long period. This reflects an increase of 2.8% relative to the average weekly mortality rate in the sample (20.62). An additional day with a daily mean temperature of ≤ 0°C results in 1.29 additional deaths per 100,000 population, corresponding an increase of 6.3%. 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 ≤0°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) Coefficients by lag. The dependent variable is the weekly number of deaths per 100,000 population, with a mean of 20.6 in the sample. The reference temperature category is 15–20°C. The estimated model includes region-by-year-by-season, region-by-week, and year-by-week fixed effects, and controls for precipitation. The model includes five temperature and precipitation lags (including lag 0). Estimates are weighted by the average population of the geographic regions between 2015 and 2024. Standard errors are clustered at the geographic region level. Shaded areas represent 95% confidence intervals.

The sensitivity of the results is explored in several ways. First, it is demonstrated that including additional lags did not alter the results. Specifically, Fig. A3 in [Supplementary Materials](#) shows that exposure to temperatures of  $\leq 0^\circ\text{C}$  or  $> 25^\circ\text{C}$  does not affect mortality rates five to seven weeks later. The estimated coefficients are very close to zero. Second, a falsification test is performed where the weather variables are replaced by observations exactly one year later. Since the weather in the distant future should have no backward effects, zero temperature coefficients are expected, and exactly this is found (Fig. A4, [Supplementary Materials](#)). Third, Table A3 in the [Supplementary Materials](#) summarizes the results of alternative model specifications: an unweighted estimation (Column 2), the exclusion of precipitations (Column 3), the inclusion of wind and global radiation (Column 4), and the estimation of a Poisson model (Column 5). Fourth, the temperature–mortality relationship is estimated using alternative fixed effects (Table A4, [Supplementary Materials](#)). Fifth, narrower ( $3^\circ\text{C}$ -wide) temperature bins are used, with lower ( $\leq -3^\circ\text{C}$ ) and higher ( $> 27^\circ\text{C}$ ) thresholds for the extreme categories, but the observed temperature pattern remains similar (Fig. A5, [Supplementary Materials](#)). Sixth, it is shown that the baseline patterns are also qualitatively similar when maximum or minimum temperatures are used instead of mean temperature (Fig. A6, [Supplementary Materials](#)). Finally, I show that applying alternative clustering methods does not change the conclusions (Fig. A7, [Supplementary Materials](#)). The statistical significances are unaffected even when more conservative clustering methods are used.<sup>14</sup>

#### 4.2. Heterogeneity by climate and income

As explained in [Section 3](#), heterogeneity is examined by running separate regressions for regions with cold, mild, and warm climates, as well as for regions with low, medium, and high income levels. The results on climate-specific and income-specific heterogeneity are summarized in [Fig. 3](#).

Climate seems to influence the temperature–mortality relationship (Panel A, [Fig. 3](#)). Cold-related mortality is higher in warmer regions, whereas heat-related mortality is higher in colder regions. For example, the effect of an additional  $\leq 0^\circ\text{C}$  day is 2.07 deaths per 100,000 population in warm-climate regions, 1.43 in mild-climate regions, and 1.04 in

cold-climate regions. Conversely, the effect of an additional  $> 25^\circ\text{C}$  day is 0.42, 0.85, and 0.95 deaths per 100,000 population in warm-, mild-, and cold-climate regions, respectively. Given that exposure to heat and cold differs markedly across climate regions (Fig. A9, [Supplementary Materials](#)), these findings suggest that long-term adaptation and behavioral responses may mitigate some of the effects of frequently occurring extreme temperatures.

Income also appears to play an important role, at least at colder temperatures (Panel B, [Fig. 3](#)). Cold temperatures have stronger effects in regions with lower income levels, but the income differences diminish at higher temperatures. Below a daily mean temperature of  $10^\circ\text{C}$ , the mortality effects of cold are at least twice as high in the low-income group than in the high-income group.

When combining these two dimensions and examining the temperature effects jointly by income and climate, I find that the climate-specific differences are mostly replicated within the income groups, and the income-specific differences are also generally present within climate groups (Table A5, [Supplementary Materials](#)).<sup>15</sup> Note, however, that some of these estimates have larger uncertainty.

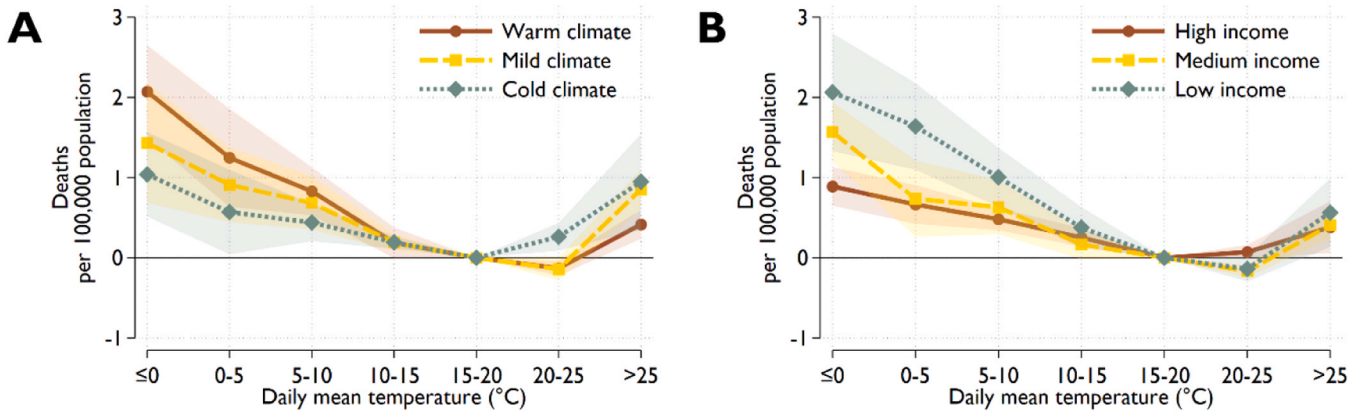
#### 4.3. Age- and sex-specific temperature effects

The next question this analysis address is how the effect of temperature varies by age and sex. First, the age-specific effects are examined across six broad age groups: 0–29, 30–49, 50–69, 70–79, 80–89, and 90+ years. 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  $\leq 0^\circ\text{C}$  and  $> 25^\circ\text{C}$  day are 0.009 and 0.006 deaths per 100,000 population, respectively. However, the number of excess deaths increases considerably with age. In the oldest age groups, the effects of  $\leq 0^\circ\text{C}$  and  $> 25^\circ\text{C}$  days are 34.2 and 15.0 deaths.

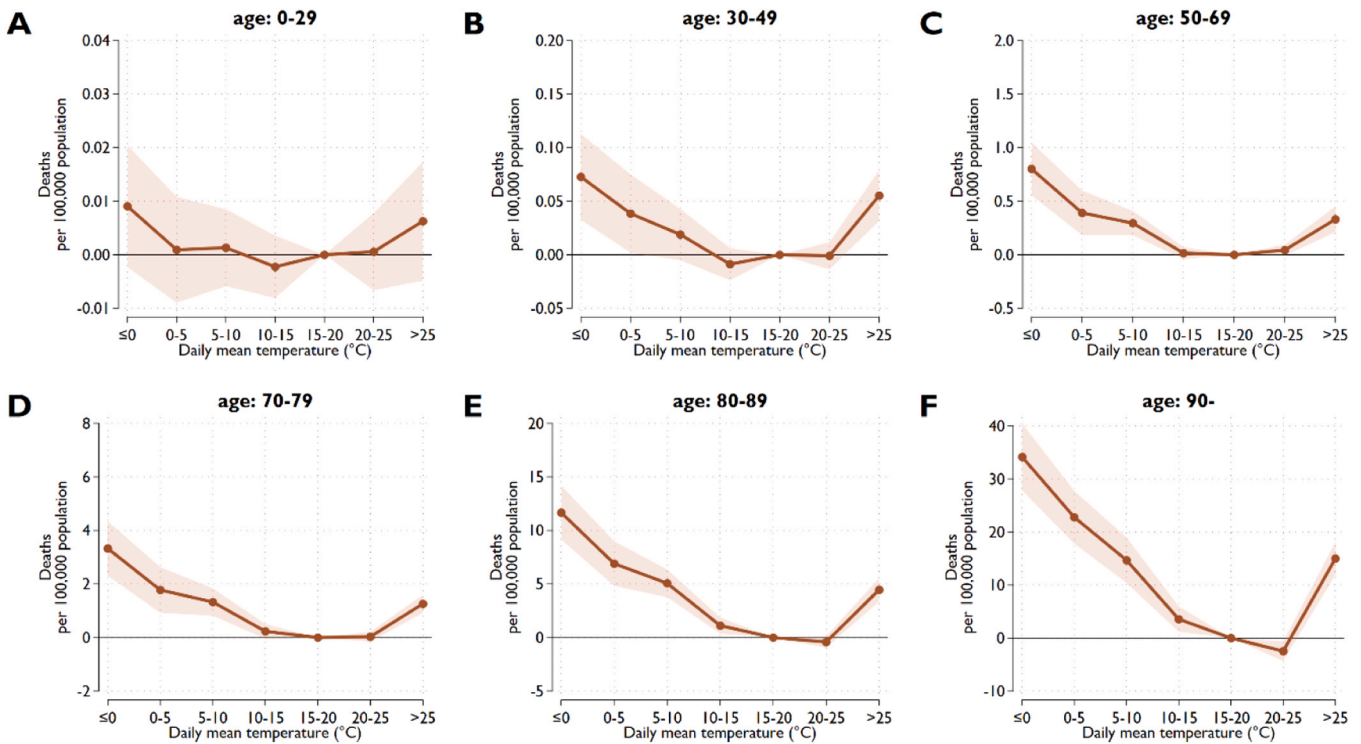
The pattern of intensification of the effects with age also holds when the temperature effects are assessed not in absolute terms but as a percentage of the average weekly mortality rate of the age groups (Fig. A10, [Supplementary Materials](#)).

<sup>14</sup> Since a significant share of the death data for the most recent years was labeled as “provisional” in the Eurostat dataset, I also demonstrate that the main pattern remains unchanged when the analysis is restricted to the years 2015–2021 (Fig. A8, [Supplementary Materials](#)).

<sup>15</sup> As explained in [Section 3.2](#), the temperature–mortality relationship cannot be analyzed for cold-climate/middle-income and warm-climate/high-income groups due to insufficient number of observations.



**Fig. 3.** The effects of temperature on mortality by climate and income. Notes: The dependent variable is the weekly number of deaths per 100,000 population. The reference temperature category is 15–20°C. The estimated model includes region-by-year-by-season, region-by-week, and year-by-week fixed effects, and controls for precipitation. The model includes five temperature and precipitation lags (including lag 0). Estimates are weighted by the average population of the geographic regions between 2015 and 2024. Standard errors are clustered at the geographic region level. Shaded areas represent 95% confidence intervals. The reported effects are the sum of the five temperature coefficients for each temperature category.



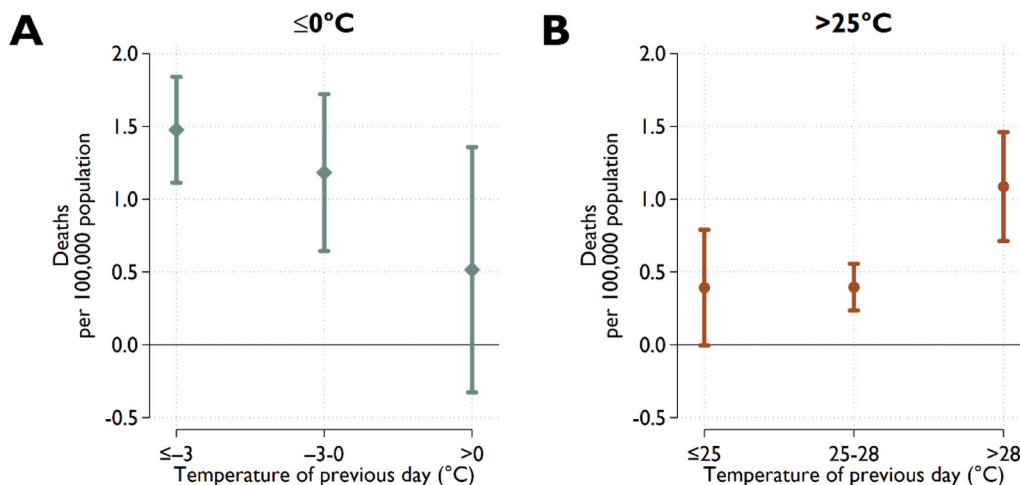
**Fig. 4.** Age-specific effects of temperature on mortality. Notes: The dependent variables are the age-specific mortality rates. The reference temperature category is 15–20°C. The estimated model includes region-by-year-by-season, region-by-week, and year-by-week fixed effects, and controls for precipitation. The model includes five temperature and precipitation lags (including lag 0). Estimates are weighted by the average population of the geographic regions between 2015 and 2024. Standard errors are clustered at the geographic region level. Shaded areas represent 95% confidence intervals. The reported effects are the sum of the five temperature coefficients for each temperature category.

The effect of temperature on total mortality appears broadly similar for both women and men (Fig. A11, [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 estimate 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. A12, [Supplementary Materials](#)).

4.4. Heterogeneity by the previous day's temperature

Fig. 5 shows the mortality effects of hot (>25°C) and cold (≤0°C) days depend on the temperature of the previous day. The effect of a day with a daily mean temperature of ≤ 0°C is about three times larger when the previous day's temperature is below –3°C than when it is above 0°C. A similar pattern is observed for heat: the higher the temperature on the previous day, the stronger the mortality effect of a day with a daily mean temperature above 25°C. These results suggest that accumulated



**Fig. 5.** Heterogeneity of the effects of heat and cold by the previous day's temperature. Notes: The dependent variables are the age-specific mortality rates. The reference temperature category is 15–20°C. The estimated model includes region-by-year-by-season, region-by-week, and year-by-week fixed effects, and controls for precipitation. The model includes five temperature and precipitation lags (including lag 0). Estimates are weighted by the average population of the geographic regions between 2015 and 2024. Standard errors are clustered at the geographic region level. Whiskers represent 95% confidence intervals. The reported effects are the sum of the five temperature coefficients for each temperature category.

temperature stress has a stronger impact on mortality than a single-day exposure.

4.5. Changes in deaths and life expectancy due to temperature changes between 1950–1979 and 2015–2024

To evaluate the impact of temperature changes between 1950–1979 and 2015–2024 on life expectancy at birth in 2015–2024, I estimate age-specific temperature effects across five-year age groups (ranging from ages 0–4 to 90+ years). Given prior evidence that climate and income substantially influence the temperature–mortality relationship (see Fig. 3), these effects are estimated separately for regions with different climate and income levels.

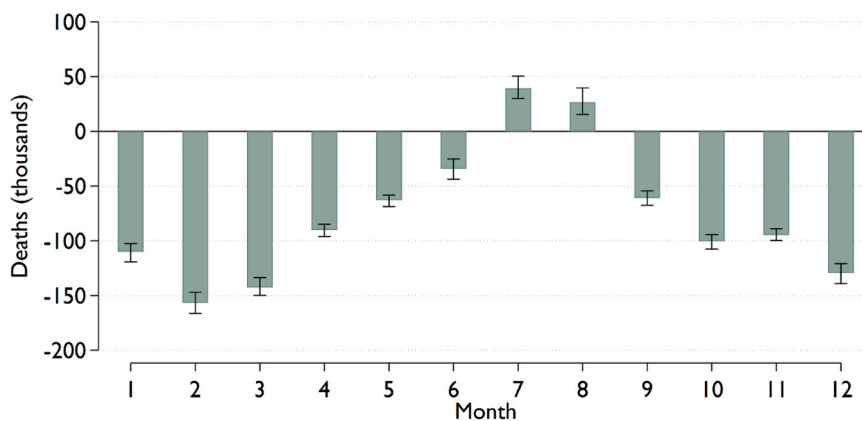
Applying the methodology outlined in Eq. (5) and Eq. (6), I estimate the total number of deaths occurring during the 2015–2024 period attributable to recent shifts in temperature distributions. The findings suggest that, across the 28 European countries included in this study, 916,518 (95% CI, 845,731–978,493) fewer deaths occurred during 2015–2024 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

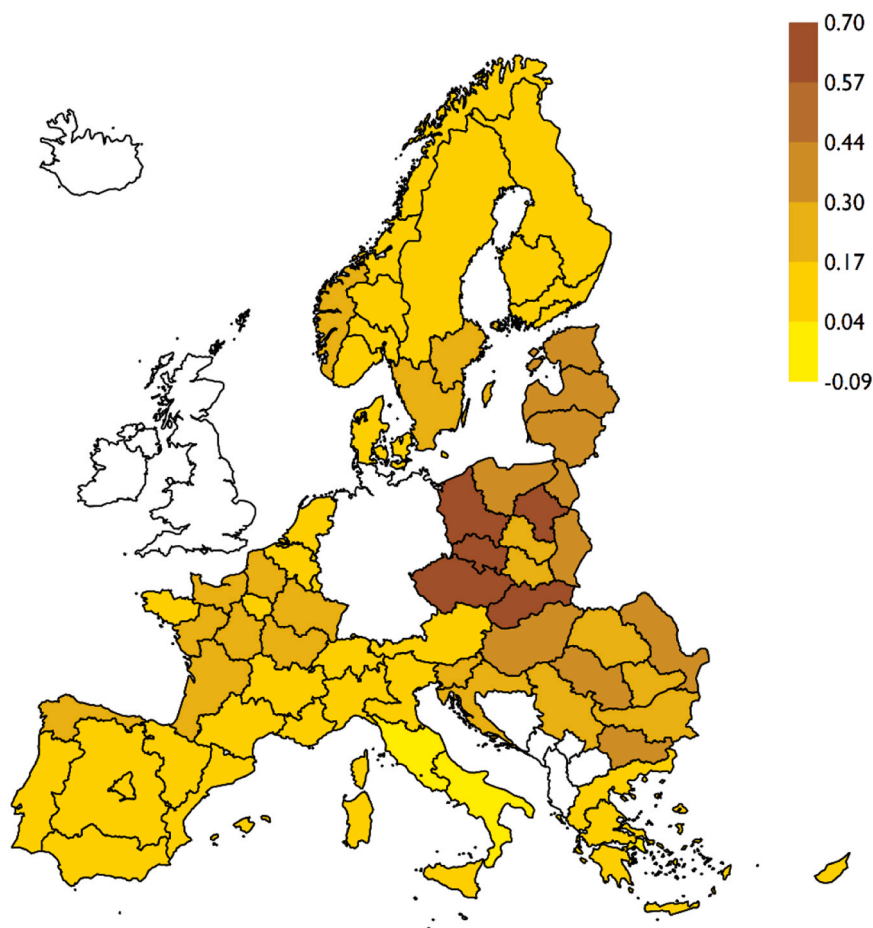
hand, an increase in the number of hot days contributed to elevated mortality. On the other hand, a marked reduction in cold days resulted in a more substantial decline in deaths. This asymmetry arises from the U-shaped relationship between temperature and mortality shown in Fig. 3, where the lowest 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 deaths in 2015–2024 that can be attributed to the warming climate. As shown in Fig. 6, more deaths occurred during the most summer months (in July and August) due to the increase in hot days than would have been expected under the climate of 1950–1979. However, the warming climate significantly reduced the number of deaths in the colder months, resulting in a substantial net decrease in mortality.

Next, I calculate life expectancies based on both observed and adjusted death counts. The adjusted death counts are derived using the age-, climate-, and income-specific temperature effects discussed earlier in this subsection, following the methodology outlined in Eqs. (5) and (7). 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



**Fig. 6.** Seasonal distribution of number of deaths in 2015–2024 attributable to temperature changes between 1950–1979 and 2015–2024. Notes: Total number of deaths for 2015–2024 that can be attributed to shifts in the temperature distribution between 1950–1979 and 2015–2024. Whiskers represent 95% confidence intervals calculated using 200 bootstrap samples.



**Fig. 7.** Changes in life expectancy at birth attributable to temperature changes between 1950–1979 and 2015–2024. Notes: Measured in years. Calculated using age-, climate-, and income-specific temperature effects, observed temperature changes between 1950–1979 and 2015–2024, and observed death counts and population in 2015–2024. The methodology is outlined in Eqs. (5) and (7).

represents the effect of changing climate 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 in 2015–2024 due to the shift in the temperature distribution between 1950–1979 and 2015–2024. The population-weighted average increase in life expectancy at birth is 0.195 years (95% CI, 0.182–0.212). In 20 regions, the gain ranges between 0.15 and 0.25 years, whereas in another 20 regions the increase exceeds 0.25 years.

The smallest gains, and in a few cases, small declines, are observed primarily in parts of the Mediterranean and Northern Europe, while the largest increases occur in Eastern regions with lower income levels. These differences reflect the complex interplay between temperature effects and shifts in climate. In the northern, cooler, high-income regions, although the temperature effects follow a U-shape, the slopes are relatively shallow; that is, there is limited difference between the effects of the coldest, moderately cold, and warmest temperature categories (see Fig. 3 and Table A5 in the Supplementary Materials). As a result, the gains from the large reduction in exposure to the coldest temperatures (see Fig. A1, Supplementary Materials) are largely offset by the increased exposure to milder and warmer temperatures.

In contrast, in Eastern countries, which tend to have milder climates and lower income levels, exposure to cold has much stronger adverse effects on mortality than exposure to mild or warm temperatures. Consequently, these regions benefitted substantially from the sharp decline in extreme cold temperatures that were far more common a few decades ago. Although similarly strong cold effects are also present in the Mediterranean countries, their frequency is much lower, so the benefits from reduced exposure are modest. At the same time, the

substantial increase in exposure to hot temperatures has led to non-negligible increases in mortality.

## 5. Discussion and conclusions

Using data on 40 million deaths in Europe during the period 2015–2024, this paper shows that both cold and hot temperatures result in increased mortality rates. While little variation is observed within the 10–25°C daily mean temperature range, mortality rates are found to rise progressively as temperatures dropped below 10°C. Similarly, daily mean temperatures above 25°C are found to lead to elevated mortality. The effects of heat and cold are substantial. A day with a mean temperature of  $\leq 0^\circ\text{C}$  increases the average weekly mortality rate by 6.3%, while the effect of a day with a mean temperature of  $> 25^\circ\text{C}$  is 2.8%. Studying the dynamics of the effects of heat and cold, I show that heat-related mortality tends to be immediate, whereas the effects of cold are more prolonged. The results also show 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. Finally, it is shown that the temperature of the previous day substantially influences the effect of heat and cold: accumulated temperature stress has a stronger impact on mortality than an isolated one-day exposure.

Climate and income are key moderators of the temperature–mortality relationship. Cold-related mortality is significantly higher in warmer regions (where extreme cold is rare and populations are less prepared for it), while heat-related mortality is greater in colder

regions (where extreme heat is rare). In addition, cold temperatures have stronger effects in regions with lower income levels. However, these differences may be prone to omitted variable bias. Importantly, climate and income are not randomly distributed: colder and warmer, or poorer and richer, regions may differ in institutional characteristics or in the age structure of the population, which can also affect the temperature–mortality relationship.

The estimated effects and the patterns documented by this paper are qualitatively similar to the findings of the previous studies. Direct comparison is difficult because existing studies are based on data from countries with different climates, income levels, population age structures, and time periods; all factors that substantially influence the mortality effects of temperature. Methodological choices (e.g., the number of lags included) also affect the estimated impacts. These differences may help explain why some studies report that heat and cold increase mortality by roughly similar magnitudes (Barreca et al., 2016; Cohen and Dechezleprêtre, 2022; Conte Keivabu, 2022; Deschênes and Greenstone, 2011; Gould et al., 2025; Helo Sarmiento, 2023), while others find that hot temperatures are more deadly (García-Witulski et al., 2023; Heutel et al., 2021; Masiero et al., 2022) or that cold has the stronger effect, particularly over the most recent decades (Chen et al., 2018; Deschenes, 2022; Deschênes and Moretti, 2009; Martínez-Solanas et al., 2021).

The estimated temperature effects of this paper, 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 warmest months, but a reduction in deaths during the colder months of 2015–2024. Since the decline in mortality during the colder seasons outweighed the increase in summer mortality, approximately 917,000 fewer deaths occurred across the 28 countries in the sample during 2015–2024 than would have been expected under the climate conditions of 1950–1979. This reduction implies that life expectancy at birth would have been lower in nearly all geographic regions had the climate 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 0.195 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, 2021a, 2023), 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, 2024b). 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 therefore likely to diminish, while the mortality burdens of summer heat may increase, as the rise in number of hot days is less constrained.<sup>16</sup> At the same time, future adaptation may mitigate some of the adverse effects of increased exposure to heat, as suggested by the observed heterogeneity in the effects of temperature on mortality across climate zones and income levels.

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  $> 25^{\circ}\text{C}$  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<sub>2</sub> 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.<sup>17</sup> 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 accelerate climate action. This imbalance could exacerbate global inequalities and compromise the fairness and effectiveness of international climate policy.

#### CRediT authorship contribution statement

**Tamás Hajdu:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

#### Declaration of Competing Interest

No competing interests are declared.

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<sup>16</sup> For an empirical example, see Martínez-Solanas et al. (2021).

<sup>17</sup> 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).

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ehb.2026.101607](https://doi.org/10.1016/j.ehb.2026.101607).

## Data availability

All data sources are publicly available from the sources indicated in the Data section. A replication package is available at "<https://doi.org/10.5281/zenodo.20034365>".

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