Projecting future Temperature-Related Mortality in Europe under global climate change

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1. Introduction

As global temperatures continue to rise due to anthropogenic climate change, the frequency and intensity of extreme weather events are expected to increase (IPCC, 2023). Europe, with its aging population, is particularly vulnerable to temperature-related mortality, as older individuals are more susceptible to the effects of extreme temperatures (K. Chen et al., 2024; Shibasaki et al., 2013). Understanding the future burden of temperature-related mortality is widely recognised as essential for the identification of new health risks and the development of effective adaptation strategies (Watts et al., 2015).

The broader literature is conducted primarily in urban areas, where most inhabitants reside, often neglecting rural regions (Gasparrini et al., 2017; Zhao et al., 2021). These studies predominantly focus on projecting heat-related mortality, with limited attention to cold-related mortality (Basu, 2009; Hajat et al., 2009; Heiden et al.,2020).

Our study aims to understand how temperature-related mortality in Europe will vary in the next future. First, the analysis assumes stable populations with no changes in vulnerability. Second, it accounts for changes in population structure. To control for potential confounders, we consider variables documented in the literature as potentially correlating with temperature and mortality such as urbanization, GDP per capita, and air pollution (PM2.5) (Hales et al., 2012; World Bank, 2020).

To achieve this, we firstly model the relationship between temperature and mortality in Europe based on a combination of historical mortality data, meteorological records, and socioeconomic indicators. The historical data cover the period that goes from 2014 to 2023 at NUTS3 level for 28 European countries encompassing both rural and urban areas. We included Representative Concentration Pathways (RCPs), to have information on future changes in emissions, in combination with General Circulation Models (GCMs), to encompass future climate variables. Future demographic and socio-economic changes which are relevant for vulnerability and adaptive capacity are captured through the Shared Socioeconomic Pathways (SSPs) (Lutz & Muttarak, 2017). The SSPs can be combined with the RCPs in a consistent scenario framework in order to inform alternative futures for climate and society (O'Neill et al., 2020).

Our paper contributes to a growing body of research on future impacts of extreme temperatures on human health by examining how temperatures change will shape future mortality patterns in Europe accounting for demographic changes and the future climate.

2. Scenario Framework

The historical European mortality trend has identified cold months as the most detrimental for human health (R. Chen et al., 2018; Zhao et al., 2021). Cold temperatures facilitate the spread of flu and virus, leading to increased mortality rates during the winter months (Gasparrini et al., 2015; Son et al., 2019). The adverse health outcomes associated with cold weather have long been recognized as a critical factor in seasonal mortality patterns (Achebak et al., 2019; Anderson & Bell, 2009; Carder et al., 2008). On the contrary, for hot temperatures, which have gained increased scientific research attention especially since the heatwave of summer 2003 where 70,000 excess deaths across Europe were associated to (Robine et al., 2007). With rising temperatures due to human-induced climate-change, an increase in heat-related deaths has been registered (Stott et al., 2016), the most recent of which occurred in 2022, with 61,672 excess deaths estimated (Ballester et al., 2023).

As part of a warming world, growing concerns is emerging on understanding the future mortality burdens related to extreme temperatures (Gasparrini et al., 2017; Huang et al., 2011; Vicedo-Cabrera et al., 2018). World Weather Attribution (WWA) define extreme heat events in the Mediterranean no longer as rare events (World Weather Attribution, 2024a); cold waves as less severe and frequent in the northern European latitudes, then projected to be more detrimental across the mid-latitudes (World Weather Attribution, 2021, 2024b). Overall, in Europe there is a clear upward trend in the number of days during which the maximum Universal Thermal Climate Index (UTCI)[1] falls within the categories of 'strong' or 'very strong' heat stress in the northern part, and 'very strong' or 'extreme' heat stress in the southern one (Fiala et al., 2011). In northern Europe, the number of winter days when the minimum UTCI reached 'extreme cold stress' has decreased from around 4% in the 1980s to about 2% in the last decade (Copernicus, 2021).

To understand how the future climate will unfold, key tools for predicting climate change impacts at global and regional scales are the so-called General Circulation Models (GCMs). GCMs are complex numerical models which

[1] The Universal Thermal Climate Index (UTCI) is defined as the physiological comfort of the human body under specific meteorological conditions (Bröde et al., 2012).

account for physical processes of the atmosphere, oceans, and land to simulate response of global climate to the increasing greenhouse gas emission (IPCC, 2013). The greenhouse gas concentration trajectories used in climate modelling to describe possible future climate outcomes, are described by the Representative Concentration Pathways (RCPs) (Moss et al., 2010). RCP4.5 and RCP8.5, which we use in this study, represent moderate and high-emission scenarios, respectively, and influence global warming projections in GCM simulations.

To explore future population dynamics, we consolidate the RCPs with Shared Socioeconomic Pathways scenarios (SSPs), widely used in climate and global change research (Jiang & O'Neill, 2017; van Vuuren et al., 2017, O'Neill et al., 2017, Striessnig et al., 2019). The SSPs are narratives (O'Neill et al., 2017), described by a set of five alternative scenarios of future societal development (Striessnig et al., 2019). This design allows us to test different combinations of socioeconomic development and emissions, producing a range of quantitative estimates. The first scenario "SSP1 (Sustainability)" envisions an optimistic path to sustainability, with improvements in both environmental and human well-being (Detlef et al., 2017). The second scenarios "SSP2 (Middle of the Road)" represents the baseline scenario, where historical trends continue, posing moderate challenges for adaptation and mitigation (Fricko et al., 2017). The third scenario "SSP3 (Regional Rivalry)" predicts slow economic growth, rising inequality, and weak institutions, hindering efforts to address environmental issues (Fujimori et al., 2017). The fourth scenario "SSP4 (Inequality)" highlights different trajectories across and within countries, where environmental policies are dominated by elites, resulting in uneven development and limited adaptive capacity for vulnerable populations (Calvin et al., 2017). The fifth scenario "SSP5 (Fossil-Fuelled Development)" sees economic growth driven by fossil fuels achieving human development goals but facing high mitigation challenges due to a high fossil fuel dependency (Ghio et al., 2023; Kriegler et al., 2017).

3. Data

3.1. Mortality and Population Data

We collected observed weekly mortality data by age group, sex, and NUTS 3 from the Eurostat. As population exposures, we gathered the annual population data, available from the Eurostat by age group, sex, and NUTS 3. We compiled the file at a monthly level from the historical period 2014 – 2023, including individuals all age groups. We compute the monthly mortality rates as the ratio between death counts and monthly exposures. To account for population change in future demographic and socioeconomic scenario, we rely on SSPs downscaled population projections (Riahi et al. 2017). We are going to adjust the mortality component with the Eurostat data populations projections available on 1st January by age, sex, and NUTS 3 region (Eurostat, 2021a), and the projected deaths by age, sex, and NUTS 3 region (Eurostat, 2021b). The resulting output will be future mortality trajectories and also new population projections at the NUTS3 region where temperature-related deaths are accounted for.

3.2. Meteorological Data

For the daily meteorological information, we employ the E-OBS from Copernicus Climate Data Store (CDS) with a spacing of 0.1° x 0.1° from 2014 to 2023 at 29.0e version (Copernicus Climate Change Service, 2024; Cornes et al., 2018). As control variables we utilize the solar radiation, relative humidity, and wind speed recorded in each NUTS3 region. We use the temperature dataset to build the average count of days in the temperature bins (see the complete description in "4. Research Methods"). For the projected temperatures, we use the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset, which provide a global downscaled climate scenario (NCCS, 2024a). The NEX-GDDP-CMIP6 is derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across all four "Tier 1" greenhouse gas emissions scenarios known as Shared Socioeconomic Pathways (SSPs) (NCCS, 2024b). We combine impact estimates from various GCMs for two climate change scenarios based on the RCP4.5 and RCP8.5 mid (2051-2055) and end (2086-2100) of century scenarios. We build the average count of days in the temperature bins described in paragraph 4 of the research methods.

3.3. Air pollution and socioeconomic indicators

To control for biases, we consider variables that might correlate with temperature and mortality. The air pollution data are provided daily by the Copernicus Atmosphere Monitoring Service (CAMS) (Copernicus, 2024; Inness et al., 2019). We construct the monthly average level of the air pollutant particulate matter 2.5 (PM2.5) at NUTS 3 level. As socioeconomic indicators we include the "urban-rural typology" information, which identify each region as predominantly urban, intermediate or predominantly rural (Eurostat, 2018), allowing us to clarify the role of urbanization level in temperature-related mortality. Furthermore, we added the information about the Gross Domestic Product (GDP) at current market prices by NUTS 3 (Eurostat, 2024). We classify the regional GDP per capita, which is used to measure and compare the economic activity of regions, in low, middle or high category. Data on future development of urbanization level and GDP values are made available by Eurostat at country level (Eurostat, 2022a, 2022b). Our intention is to use this information to adjust our future estimates to clarify the future temperature-related mortality pattern in Europe.

4. Research Methods

4.1. Temperature – mortality curve

To estimate the overall relationship between temperature and human mortality in Europe, we employ a Poisson regression with Fixed Effects (FE). We describe the equation as follows:

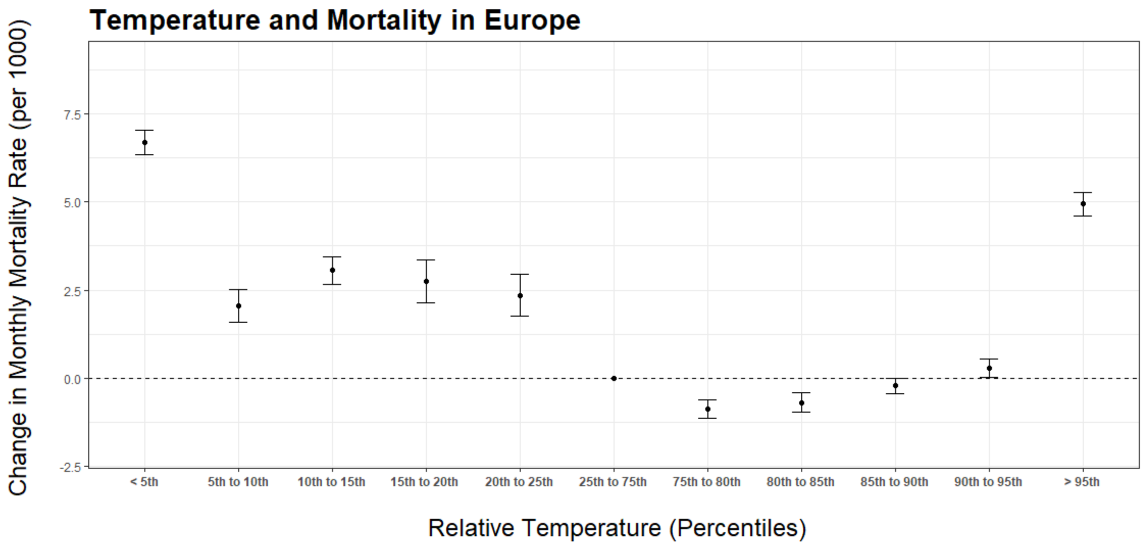
$$\log(Y_{nt}) = \log(E_{nt}) + \sum_j \Theta_j TEMP_{nt}^j + X_{nt}\beta_{nt} + \alpha_{nw} + \delta_{yw} \qquad (1)$$

where Y_{nt} is the monthly counts of deaths in month-year t and NUTS 3 region n; E_{nt} is an offset term capturing the exposure to death risk in the NUTS 3 region n and month-year t; *TEMP* captures the number of days in temperature range j, in month-year t and NUTS 3 region n; the coefficients Θ_j is the effect on mortality of exchanging one day in the comfort zone for a day in the j-th bin; the covariates X_{nt} with associated coefficients β_{nt} are the control variables; α_{nw} captures NUTS 3 region by month fixed effects; δ_{yw} account for year by month fixed effects. We cluster standard errors at the NUTS 3 level. Daily average temperature bins were created using percentiles from the temperature distribution for each NUTS3 unit over the study period. We counted the number of days per month in each NUTS3 that fell within a temperature range. Eleven bins were established: 1) ≤ 5th percentile, 2) 5th–10th, 3) 10th–15th, 4) 15th–20th, 5) 20th–25th, 6) 25th–75th (comfort zone, excluded from analysis), 7) 75th–80th, 8) 80th–85th, 9) 85th–90th, 10) 90th–95th, and 11) > 95th percentile.

The extrapolated temperature - mortality curve calculated in the historical period (2014-2023) is then replicated along the whole projection period accounting for the new temperatures. First, the analysis is conducted under the assumption of stable populations and no changes in vulnerability. Second, the examination incorporates changes in population structure by SSPs scenarios. The analysis includes uncertainty quantification estimates (Burke et al., 2015).

5. Expected findings

We observed a U-curve shape temperature–mortality relationship, with increases in monthly mortality rate (per 1000) above the 75th and below the 25th relative temperature percentiles, that correspond to extreme heat and extreme cold of the temperatures spectrum, respectively.



By replicating our series over the projection period, under the assumption of stable populations, we expect to observe the mortality burden from cold temperatures still larger than that for heat, especially across the moderate cold temperatures. However, mortality due to cold is expected to decline compared to current levels. Conversely, heat-related mortality is expected to significantly increase in the future.

Accounting for aging populations and demographic changes, we expect to continue to see older adults as the most vulnerable group. Furthermore, climate change is expected to exacerbate regional mortality disparities, particularly impacting southern Europe due to the increasing frequency and intensity of heatwaves. Urban regions, with higher levels of PM2.5 and more intense heat islands effect, are expected to show higher mortality than rural areas. Regions with lower GDP may exhibit higher mortality rates due to a lack of infrastructure and access to healthcare.

The extent of future temperature-related mortality will likely depend on adaptation measures, and improvements in the socioeconomic and environmentally friendly quality of life.

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