# What are the costs of heat spell mortality in Europe's urban areas up to 2050?

Mikael Skou Andersen,[a,b] Kristin Aunan,[c] Jesper H. Christensen,[d] Ulas Im,[d] Massimo Stafoggia,[e] Marc Suhrcke,[f] Zhuyun Ye [d], Sofia Zafeiratou,[g] Siqi Zhang,[h,i]

[a] *Department of Environmental Science, Aarhus University, Aarhus, Denmark*

[b] *iCLIMATE Aarhus University Interdisciplinary Centre for Climate Change, Aarhus, Denmark*

[c] *CICERO Center for International Climate Research, Oslo, Norway*

[d] *Department of Environmental Science, Aarhus University, Roskilde, Denmark*

[e] *Department of Epidemiology of the Lazio Region Health Service (ASL ROMA 1), Rome, Italy*

[f] *Luxembourg Institute of Socio-Economic Research, Esch-sur-Alzette, Luxembourg*

[g] *Department of Hygiene, Epidemiology and Medical Statistics, Medical School, National and Kapodistrian University of Athens, Athens, Greece*

[h] *Institute of Epidemiology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany*

[i] *Department of Environmental Health Sciences, Yale School of Public Health, New Haven, Connecticut, USA*

*Corresponding author*:

prof. Mikael Skou Andersen, msa@envs.au.dk; tel: +45-21257810

Keywords:

Climate change; Forecasting; Air quality; Health impacts; Regional effects

File generated with AMS Word template 2.0

# ABSTRACT

The objective of this study is to estimate welfare economic costs of premature cardiopulmonary disease (CPD) mortality in Europe and Asia Minor under a middle-of-the-road scenario (SSP245) for global warming. It projects future heat-related CPD fatalities in urban areas over the next 25 years for 317 regions of 39 countries, by applying regionalized exposure-response functions for heat- and air pollution-related premature mortality. These functions are derived from datasets of daily counts of CPD deaths 1994-2018 for over 30 million people, capturing the different sensitivities to heat across climate gradients. As using simple average summer temperatures can mask important variations, methodologically we operationalize heat spell intensity based on the Eurostat metric of cooling-degree-days. We find that heat-related CPD mortality could triple by mid-century from its pre-1990 level. Based on OECD methodology for the economic valuation of premature mortality, this amounts to an estimated €90 billion in annual welfare economic costs. For ten countries in southeastern Europe, costs may well exceed 1% of their annual GDP, reaching up to 4% in a heatwave year. A further important outcome of the study stems from its exploration of the interactive effects of air pollution and heat spells for premature mortality. We find that deep reductions in air pollution, beyond requirements in EU's recently revised Ambient Air Quality Directive, could prevent up to 190,000 heat-related deaths over the next 25 years, positioning air quality improvements as a critical adaptation strategy. Our findings underscore the urgency of better integrated climate and public health policies.

# SIGNIFICANCE STATEMENT

Our findings about significant health impacts of heat on premature cardiopulmonary mortality in Europe challenge assumptions inherent in previous economic studies on the social costs of carbon from global warming. We find mortality impacts in Europe to increase exponentially with temperature, a relationship thought to be linear or even non-existent in recent efforts to account for the social costs of carbon. This bears implications for future economic evaluation studies, as the value of climate change mitigation to reduce the costs of mid-century, deadly heat spells are likely higher than previously assumed, even in a relatively mild scenario of global warming.

File generated with AMS Word template 2.0

# 1. Introduction

While previous studies have established that heatwaves and global warming can be expected to increase premature mortality (Baccini et al. 2008; Honda et al. 2008; Gasparrini et al. 2015; Masselot et al. 2023; Zhang et al. 2023), the associated socio-economic costs have so far been challenging to quantify (Newman and Noy 2022). The objective here is to extend an assessment of premature mortality from heat spells into estimates of the induced welfare economic costs.

In a recent empirical study on health-related damage costs from global warming, Carleton et al. (2022) observe, that costs are borne mostly by the Global South, while developed countries should be able to adapt thanks to economic growth and use of air conditioning. The study predicts optimistically that despite global warming, there will be no premature mortality increase in Europe, as economic growth will allow for adequate adaptation.

The European Environment Agency (EEA 2023) indicates economic losses of about €16 billion annually since 2015 attributable to all weather-related extreme events, including heatwaves, while cautioning that greater economic losses can be expected in the future. A recent projection of climate change impacts published by the European Commission's Joint Research Centre (JRC) indicates that premature mortality from heatwaves dominates the overall costs for all scenarios, even if the modelling is relatively coarse (Feyen et al. 2020). Detailed projections of costs likely to arise in Europe in the next decades are needed, to allow decision-makers to assess the most cost-effective options for mitigation and adaptation.

This study seeks to fill an important part of the knowledge gap by presenting projections of health-related costs from global warming. We focus on cardiopulmonary diseases (CPD), for which the biological mechanisms that may cause heat stress and premature mortality are well understood (Kenney et al. 2014), in contrast to the above studies which report summer-time all-cause mortality, even though our dataset includes both counts. We focus on impacts towards mid-century, where despite the long-term trajectory of global warming there is less uncertainty at play. The analysis relies on a climate projection based on a 'middle-of-the-road' SSP245 scenario (Hausfather 2018).

The study contributes to the literature by showing that the welfare economic costs of heat-related premature mortality can be projected with higher precision when improving spatial resolution, resulting in higher cost estimates. Moreover, the findings confirm speculations in

3

early studies on heat-related mortality (e.g. Katsouyanni et al. 1993) of significant interactions with air pollution concentrations. The study responds to the call by Karwat and Franzke (2021) in this journal for larger and more comprehensive datasets from which to derive heat-related mortality rates, as well as their suggestion to monetize deaths. Shortcomings of our study relate to remaining inter- and intra-regional heterogeneity, for which more data and research is required.

The structure of the paper follows the four classical steps of an impact-pathway methodology for integrated environmental assessment (Rabl and Peuportier 1995), where environmental modelling (#1) and health impact assessment (#2) is linked, to project health outcomes of predefined scenarios (#3) that in a final step are monetized (#4) (Figure 1).
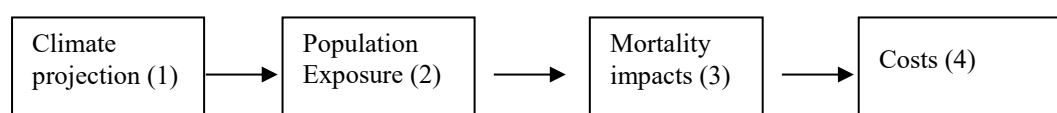


Figure 1: Impact pathway sequence with main steps of analysis

Our study applies novel regionalized exposure-response functions (ERF) for mortality incidence attributable to temperature, derived empirically from important new datasets compiled in the EXHAUSTION project, covering the warmest parts of Europe, and from existing datasets (Schneider et al. 2023). As Yin et al. (2024) show for China, we find that ERFs vary across Europe's temperature zones, reflecting not only different sensitivities in local populations along a longitudinal gradient, but also regional differences in how buildings and cities are constructed to provide comfort and to shield against heat in past climates. The study on this basis identifies eight heat stress zones across Europe (see Figure 2) to which reference ERFs (identified for each zone) are applied to estimate and project heat-related premature CPD mortality rates.

4

File generated with AMS Word template 2.0

# Annual summer Cooling Degree Days (CDD) 2006-15

**Cooling Degree Days:**
If $T_m \geq 24°C$ then
$CDD = \sum_i T^i_m - 21°C$
else $CDD = 0$
where $T^i_m$ is the mean
air temperature of day i

Legend: ■ < 12.5  ■ 12.5−40  ■ 40−100  ■ 100−175  ■ 175−250  ■ 250−325  ■ 325−450  ■ ≥ 450

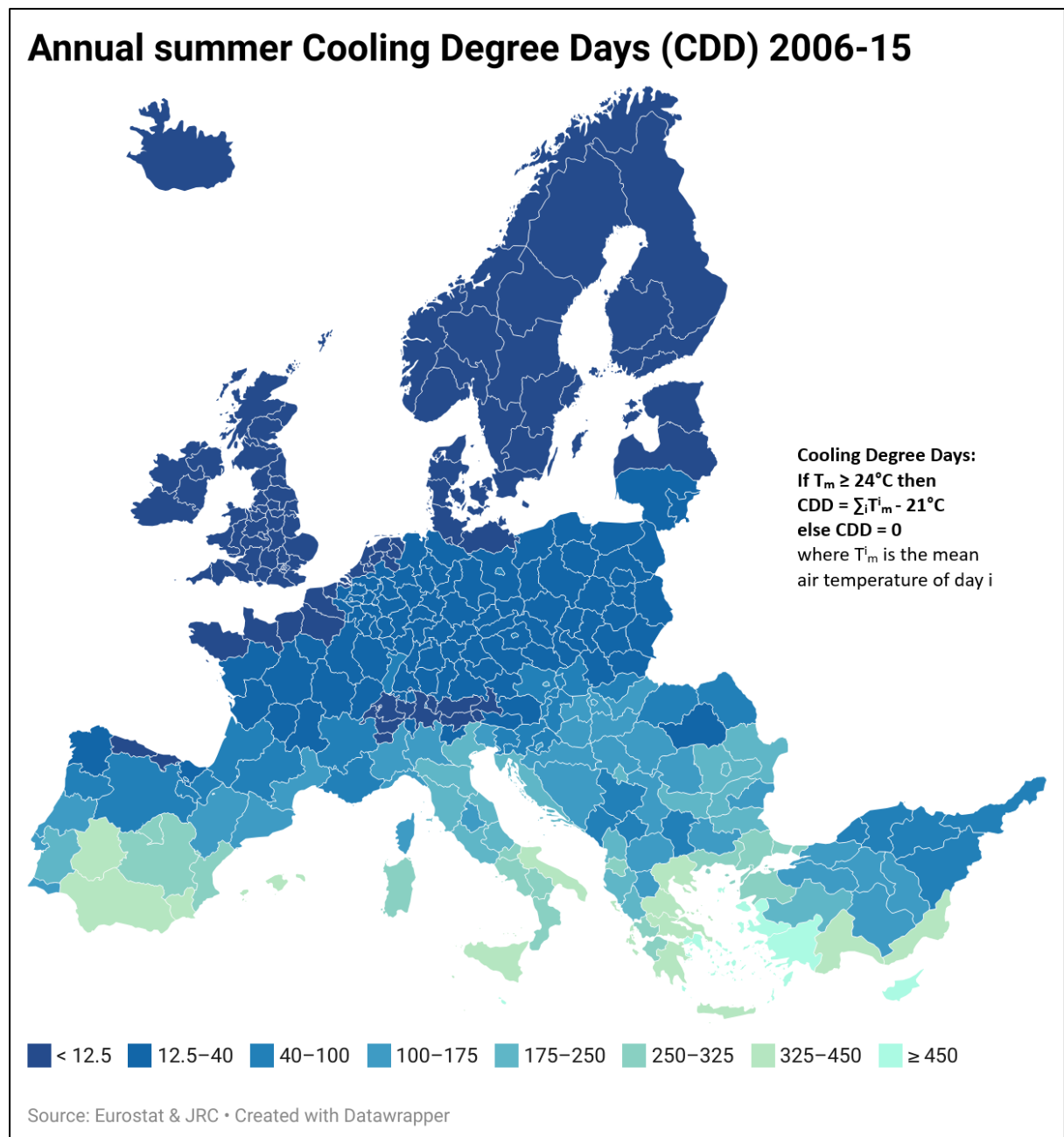Source: Eurostat & JRC · Created with Datawrapper

Fig. 2. NUTS2-regions stratified into eight heat stress zones based on average annual summer cooling degree days (CDD) 2006-15 (Source: Eurostat and JRC). Appendix Table A1 provides a listing.

The average number of summer cooling degree days at NUTS2 level has been used to stratify NUTS2 regions according to heat stress. Data on cooling degree days (CDD) for 2006-2015, corresponding to the years of exposure data, provides the basis for stratification. Building on climate projections and the identified exposure-response functions, future impacts are projected for urban areas (cities and towns excluding rural areas) across all

5

File generated with AMS Word template 2.0

NUTS2-regions of EU27, EEA[1], western Balkans[2], UK and Northern Ireland, as well as Asia Minor (western Türkiye). CDD data from an earlier period (1979-90), with impacts of exposure-response functions back-casted, offers a baseline for gauging the economic impacts from increased CPD mortality of future warming.

Based on results from regional climate modelling (Im et al. 2022), the study explores scenarios for average heat spell[3] induced CPD mortality for the summer seasons (May-September) during 2030-34 and 2045-49, respectively. As warm spells are known to fluctuate, peaking at irregular intervals, two further scenarios explore impacts of the two individual years in each decade (2030s; 2040s), where the climate modelling results indicate peaks in temperatures. We consider these to be heatwave years. Since the specific peak years vary geographically, with some clustering, the individual years chosen for the two scenarios differ by NUTS2 region, though reported under the same heading.

As a final step, heat-induced premature CPD mortalities above the baseline occurrence are costed, using the metric of the value of a statistical life (VSL). VSL reflects the willingness-to-pay for marginal mortality risk reductions, which has been shown to vary with income, and is hence differentiated here across countries according to per capita real income. This accounting procedure is sometimes considered unequitable, which is why for our pooled EU27 results, the study applies a common VSL across all EU Member States, as conventionally used in EU-level impact assessments. The methodology on VSL adheres to OECD guidelines on mortality valuation (OECD 2012). Costs are expressed as a share of national GDP.

---

[1] EEA (European Economic Area) includes Iceland, Liechtenstein, Norway and Switzerland.

[2] The six countries of western Balkans are Albania, Bosnia-Herzegovina, Kosovo, Montenegro, Northern Macedonia and Serbia, of which the latter five until April 1992 belonged to the Federal Republic of Yugoslavia.

[3] According to the World Meteorological Organization (WMO, 2023) a heatwave can be defined as a period of marked and unusually hot weather persisting for at least two consecutive days. WMO further defines a 'warm spell' as a persistent period of abnormally warm weather for the time of year, that can occur at any time of the year. However, in this study the term 'heat spell' refers to summer days (May-Sept.), where the average 24 hour daily temperature exceeds the reference city minimum mortality temperature (cf. Table 1).

File generated with AMS Word template 2.0

## 2. Materials and methods

ERFs for CPD mortality in relation to temperatures stem from the EXHAUSTION project's city-level analysis of primary data (Schneider et al. 2023). This dataset includes daily counts of mortality for all causes as well as for non-accidental causes (ICD-9 and ICD-10 codes) in overlapping periods centering around 2000-2015 for a range of cities in countries spanning different geographical and climatic conditions (see Table 1). The project compiled novel datasets from Greece and Italy, complemented by data from the Multi-Country Multi-city (MCC) Collaborative Research Network database (https://mccstudy.lshtm.ac.uk/). ERFs between temperature and mortality accounting for non-linearity and lagged effects were specified with a distributed lag non-linear model, using a parameterization previously used in multi-country studies (Gasparrini et al. 2010, 2015; Masselot et al. 2023).

While all previous studies have used average temperatures during the summer months to predict impacts on premature mortality, we use here the CDD metric according to Eurostat's definition (see formula in figure 2). In Europe, the CDD metric accounts for days with mean temperatures that exceed 24 degrees Celsius, assigning a minimum score of 3 for such days (24 minus 21 = 3). CDD metrics better capture variabilities in daily mean temperatures than simple averages. The UK and Germany, for instance, have the same average temperatures, but Germany has more days at the extreme end of the scale than the UK, thus scoring higher on the CDD metric. These differences become relevant in the context of heat wave mortality, as the derived ERFs show exponential impacts of temperatures.

We derived ERFs from the following eight reference cities for the purpose of our projections; Athens, Palermo, Madrid, Rome, Lisbon, Lyon, Paris and Helsinki (see figures 3A-3C). Here the basis in terms of population size is sufficiently large to obtain ERFs that are in almost all cases statistically significant along the full temperature curve and for a large range of air pollution concentrations (Table 1). We consider this spatially disaggregated approach of identifying ERFs an improvement over previous studies that relied on a single uniform ERF for all countries and regions (Gasparrini et al. 2017).

For each reference city, ERFs are specified for each temperature percentile of the pooled summer days, split again on each percentile according to the air pollution concentrations of $PM_{2.5}$ (primary particles with a diameter of 2.5 microns or less).

File generated with AMS Word template 2.0

The percentile-ERFs obtained have been aggregated into a single annual ERF figure across the percentiles and applied to the population in question to estimate annual heat wave triggered mortality. In most instances, the minimum mortality temperature is approximately 21 degrees, but in two of the cooler cities and regions, impacts are recorded from a few degrees below, whereby we include impacts at the lower end of the scale too (see the minimum mortality temperature (MMT) column in Table 1).

The percentile-ERFs have been derived for temperature variations over several years (cf. Table 1), whereby the highest ten percentiles of temperatures refer to select heat spell days from across the time span. For each reference city, we thus calibrate the temperature distributions, and the associated CDD scores, with their average summer temperatures during the data reference years. We sum the percentile-ERFs into an aggregate score for each city and reference time.

| | ERF-data years | Population | MMT (degrees Celsius) | Annual average CDD 2006-15 |
|---|---|---|---|---|
| Athens | 2007-2016 | 3,190,000 | 23.1 | 585 |
| Palermo | 2006-2015 | 670,000 | 21.3 | 374 |
| Madrid | 2009-2013 | 6,380,000 | 21.8 | 294 |
| Rome | 2006-2015 | 2,860,000 | 22.0 | 233 |
| Lisboa | 2004-2018 | 2,810,000 | 18.7 | 156 |
| Lyon | 2007-2015 | 1,810,000 | 23.1 | 51 |
| Paris | 2007-2015 | 2,210,000 | 21.1 | 25 |
| Helsinki | 1994-2014 | 1,590,000 | 19.0 | 4 |
| ERF: Exposure-response function; MMT: Minimum mortality temperature; CDD: Cooling Degree Days | | | | |

Table 1. Reference cities for projections; years of data, minimum mortality temperature (MMT) identified and annual average cooling degree days (Source: Schneider et al., 2023 and Eurostat, 2024).

The resulting ERFs are applied in eight respective heat stress zones across Eurostat's NUTS2 regions (cf. Figure 2). The spatial allocation of regions into these heat stress zones is based on their summer period CDD scores (see Figure 2 for the ranges). Detailed climate projections up to mid-century deliver the projected annual CDDs for the urban areas in each of the 317 regions. We consider two scenarios based on average CDD scores for 2030-34 and

File generated with AMS Word template 2.0
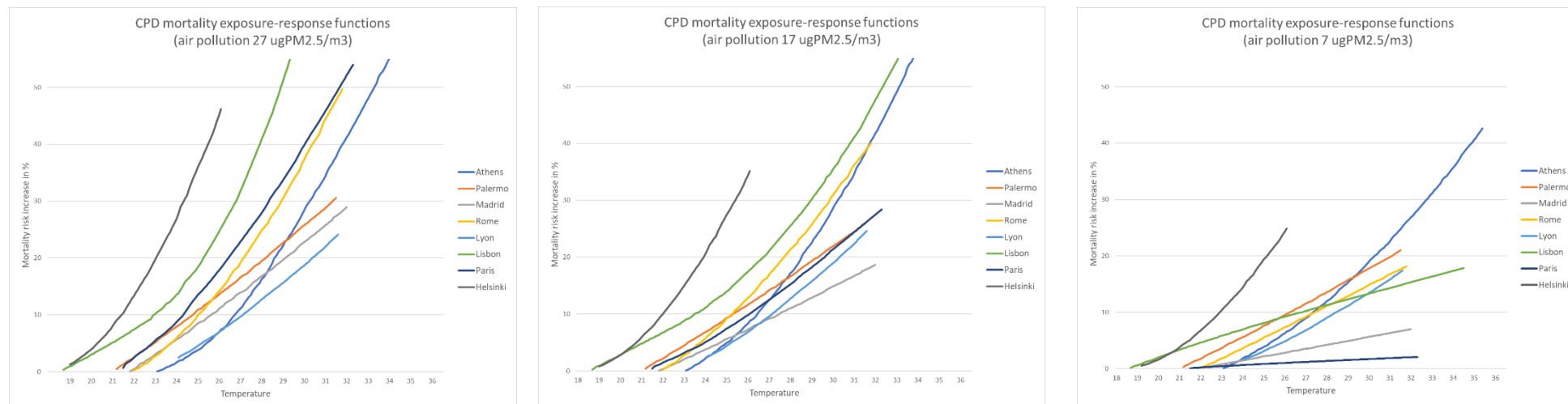
195

Fig. 3. (panel A, B and C) Exposure-response functions for CPD mortality risk relative to temperature (degrees Celsius). A. 27 ugPM$_{2.5}$/m$^3$. B. 17 ugPM$_{2.5}$/m$^3$. C. 7 ugPM$_{2.5}$/m$^3$.

File generated with AMS Word template 2.0

2045-49 respectively, and two further scenarios selecting the highest annual CDD in each of the two decades 2030s and 2040s. To obtain a site-specific ERF for each region according to its CDD, we apply coefficients obtained from ordinary least squares (OLS) regression analysis of the reference city's CDD-ERF pairs for the baseline year and projection year scenarios.

As our heat stress zone ERFs have been derived for urban populations only, we exclude rural populations from the analysis. While the Eurostat database provides the rural share of populations at national level only, we used the classifications of urbanization classes at NUTS2 level to estimate their approximate share for each region (Eurostat 2020). As rural areas are defined as entities where less than 20 per cent live in cities, while intermediate areas are defined as entities where at least 50 per cent but no more than 80 percent live in cities, we used these benchmarks to calibrate consistently across the NUTS2 regions of each country the nonrelevant rural population. We also used readily available Eurostat data and projections for the age distribution at NUTS2 level to deduct inhabitants below 25 years of age, for which CPD mortality is not expected. We used background CPD mortality frequencies from higher administrative levels, also based on Eurostat.

For projections of population numbers over the next 25 years in four non-EU western Balkan countries, we rely on data from the United Nations Population Division, whereas we refer to national statistical agencies for Serbia and Albania. For Türkiye, projections are from Turkstat and for the UK, they are from its Office for National Statistics. The analysis factors in population growth and ageing, based on regional projections from Eurostat and the above mentioned statistical agencies. It also factors in urbanization dynamics, based on national level UN Population projections, while applying procedures to avoid any double counting with population growth when disaggregating to the regional level.

Climate projections stem from the Weather Research and Forecasting (WRF) model version 4.1 (Skamarock et al. 2019), which can be used for a wide range of scales, from local to regional and global, and has several options concerning the model core and most physical parameterizations. In this study, we follow Im et al. (2022) in setting up the model domain on a 20 km horizontal resolution in Polar stereographic projection centered on 60N, and up to 10 hPa with 54 vertical layers. The study domain covers continental Europe at 25-72N, 25W-45E. Meteorological initial and boundary conditions to WRF are driven by the NCAR CESM2 model. To convert from the CESM2 output in NetCDF format to the GRIB format

10

File generated with AMS Word template 2.0

needed by the WRF pre-processor, we have modified and used the cam_to_wps utility available at https://github.com/shortwavetrough/cam_to_wps. Boundary conditions of 3-D temperature, humidity, horizontal winds and geopotential height are updated every six hours in WRF, while sea surface temperatures and sea ice are updated daily. We have used future projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6), also used for the recent IPCC sixth Assessment Report. The results have been shown to conform reasonably well with more comprehensive EURO-CORDEX ensemble projections (see Appendix B).

The outputs from WRF have been converted into CDDs for each NUTS2 region according to the 2021 nomenclature of Eurostat, covering the countries of EU27, EEA and western Balkans along with UK & Northern Ireland, and Asia Minor – omitting overseas NUTS2 regions of Spain, Portugal, and France. This procedure allows for – and facilitates calibration of WRF-results with Eurostat's CDD data for the core historical period of data collection (2006-15), whereby bias correction of specific projections at NUTS2 level has been possible. Especially for some islands and regions of limited geographical size, the chosen WRF-resolution seems to have introduced biases. Historical records for temperatures and the corresponding average CDDs for the period 1979-90 (May-September) in each of our 314 NUTS2 regions (Eurostat 2020) plus Bosnia-Herzegovina and Kosovo were calculated from the gridded (25x25 km) Agri4Cast database of the Joint Research Centre (2023), since Eurostat CDD data does not cover this period.

Out of the Shared Socio-economic Pathways (SSP) scenarios, SSP2 describes medium socio-economic challenges to climate change adaptation and mitigation and is intended to represent a future in which development trends are not extreme in any of the dimensions. SSP2-4.5 describes a "middle-of-the-road" socio-economic family with a 4.5 W m−2 radiative forcing level by 2100. As there are limited differences over the next 25 years among the various SSP scenarios, the projections of CPD fatalities are based on the regional temperature projections of this SSP2-4.5 pathway, for which we might be considered pre-assigned. We are interested in identifying the pressures in the coming decades that are relevant to present generations. Uncertainties about economic and social developments in the second half of the 21st century cause OECD and World Bank to refrain from economic forecasts extending beyond 2060.

File generated with AMS Word template 2.0

Air pollution data for recent (2021) city level background concentrations of $PM_{2.5}$ stem from a database hosted by the European Environment Agency (2023), covering EU27, EEA and western Balkans. With several cities of each NUTS2 region included, we calculated averages weighted by population numbers. For the UK, we rely on most recently published data from the UK Air site of DEFRA (2023), while for Türkiye, we use 2020 data retrieved from official sources by the Temiz Hava Hakkı Platform (Evci 2021).

Using VSL metrics, we translate heat-related CPD-fatalities into estimates of the welfare economic costs attributable to the temperature increases post-1990 – increases that we consider as resulting from global warming. VSL represents the welfare economic value of preventing a statistical fatality, i.e. the willingness to pay for marginally reducing the risk of premature death (Jones-Lee 1989, Andersen 2017). Based on a meta-review of international literature, the OECD (2012) identified and recommended an average VSL of USD3.6 million for the EU27. When correcting for Brexit and the entry of Croatia, as well as for increases in real GDP per capita (Eurostat 2023, World Bank 2023), subject to an income elasticity of 0.8, we find an updated average EU27 VSL of €4.043 million. Applying OECD's procedure for transfer of this estimate to individual countries based on their real GDP and purchasing-power parities, we can derive country-specific VSLs, denominated in 2022-euro. An adjustment in elasticity between VSL and income is made for lower-income non-EU countries (western Balkans and Türkiye), as recommended by OECD. The exchange rate in 2005 was 1.22 USD/€ (PPP-adjusted). Real GDP per capita figures from Eurostat for country-level adjustment of VSL generally refer to 2022, though to 2019 for UK, 2020 for Switzerland and North Macedonia, and 2021 for Albania. We developed own calculations for Bosnia-Herzegovina and Kosovo.

We factor in available projections of population changes and forecasts of economic growth, based on data from Eurostat (2023), World Bank (2023), UN (2022), OECD (2021) and from national statistical institutes of non-EU/EEA countries (Republic of Albania 2014; Statistical Office of Serbia 2023; Turkish Statistical Institute 2023). Economic data for historical GDP are from Eurostat, while projections are from OECD's long-term baseline projections, covering 24 EU countries, EEA, UK and Türkiye. Economic projections for western Balkans, Croatia, Malta and Cyprus are from the World Bank (2023).

# 3. Results

File generated with AMS Word template 2.0

In this section we first present the projected CPD mortality per 100,000 urban adults, before proceeding to absolute counts of heat-related fatalities per country and their ratio changes. Next, and based on these findings, follow estimations of the heat-related CPD mortality cost increases over a pre-1990 baseline. In a final sub-section, we return to the role of interactions with air pollution in reductions of premature mortality.

*a. Within the next decade higher heat-related CPD mortality in urban areas*

The minimum mortality temperature tends to be higher with CDDs (the warmer the summer climate of each zone), reflecting how people and buildings have been accustomed to shield against strong heat over longer historical periods, providing a justification for dividing Europe into heat stress zones with different ERFs. Higher ERFs relative to temperatures can be discerned from Figures 3A-3C for respectively the five southern and the three northern cities (Lyon, Paris and Helsinki). The contrasts between southern and northern Europe as a whole may also reflect differences in the significance of manual outdoor economic activities in high versus medium GDP-per-capita countries.

Providing a basis for the economic estimates, Figures 4A-4F show how CPD mortality can be expected to increase from the baseline period (1979-90) and more recently (2015-22) into the future.

Figures 4A and 4B are based on historical data for average temperatures at NUTS2 level and show how heat-related CPD mortality has been increasing over the past 25-30 years. Even before global warming gained momentum, south-east European countries were the most sensitive to global warming in terms of CPD mortality.

In 2015-22, five regions in Bulgaria, North Macedonia, Romania and Serbia have recorded heat-related CPD fatality rates of 40-50 per 100,000. Despite comparable temperatures in mediterranean regions, heat-related CPD fatality rates in Italy, Spain, Portugal and Greece are generally less than one third of that level, in part due to lower baseline CPD mortality rates.

Still, based on temperature and population growth projections for the near future (2030-34) and mid-century (2045-49) (see figures 4C and 4D) we may expect the average annual incidence within the next 25 years to exceed 25 per 100,000 in the urban areas of about 30 NUTS2 regions. Besides south-eastern Europe and the Mediterranean, these regions are also

File generated with AMS Word template 2.0
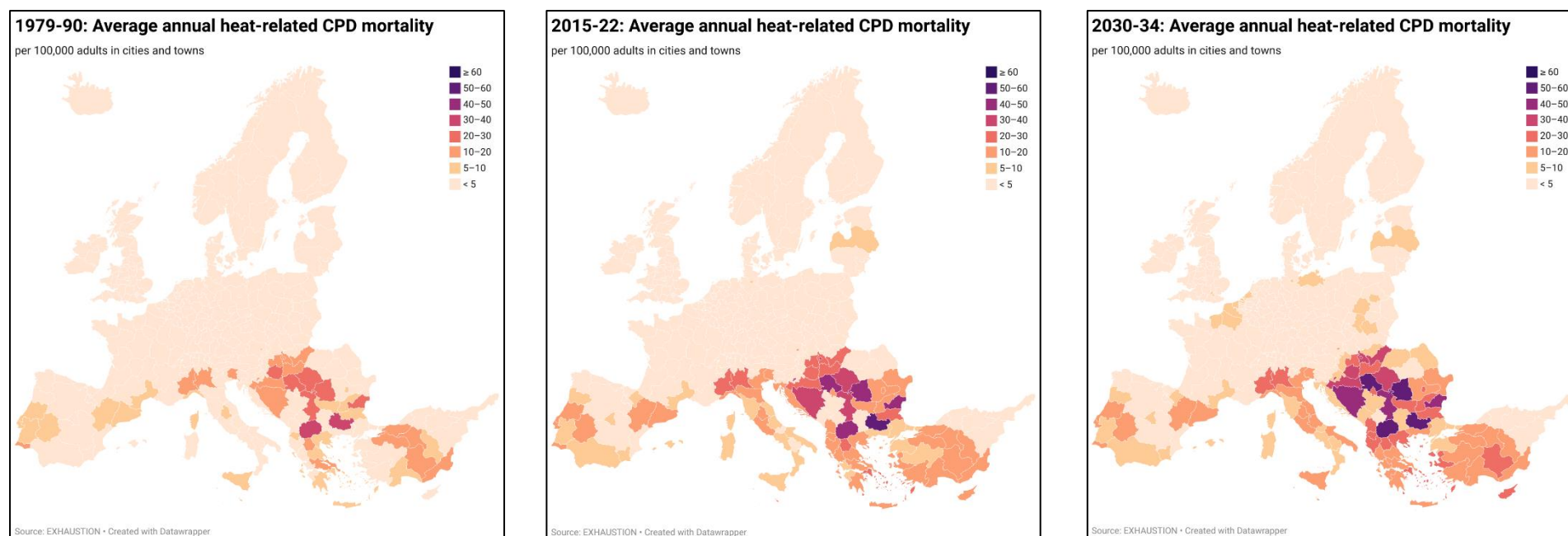
329

Fig. 4. (panels A/B/C) Heat-related CPD mortality per 100,000 adults in cities and towns (SSP245). A. Baseline (1979-90). B. Recent past (2015-22). C. Short-term scenario (2030-34).

14

File generated with AMS Word template 2.0
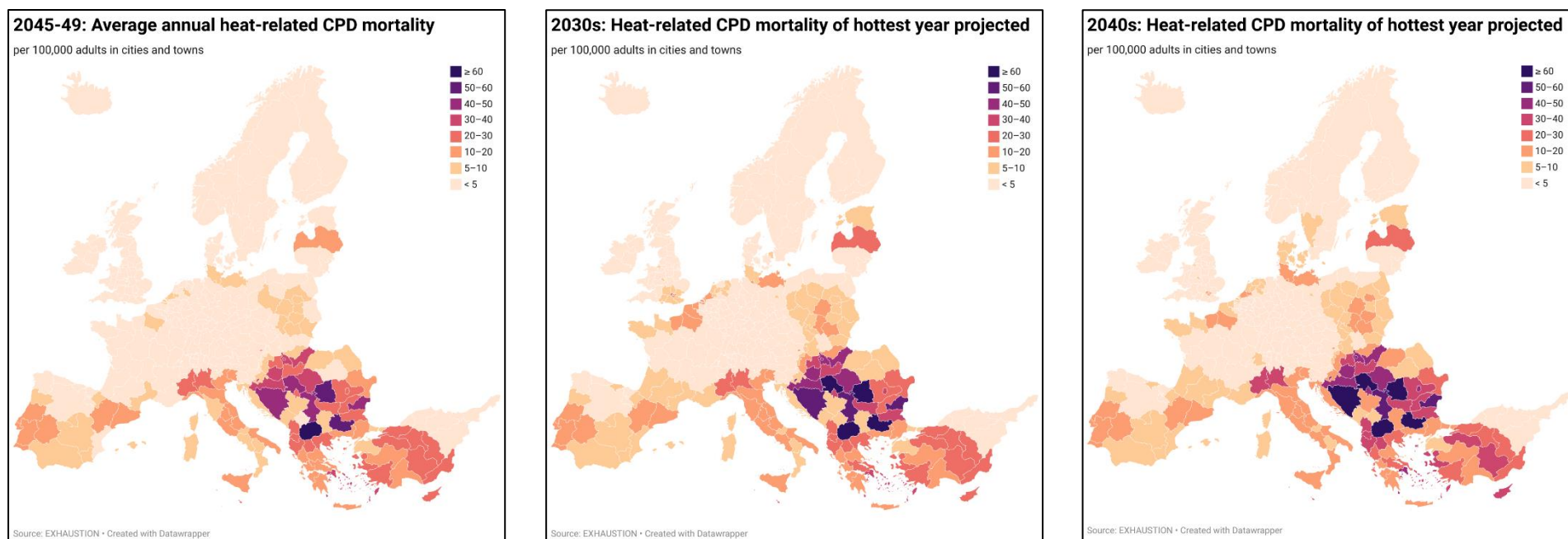
338

Fig. 4. (panels D/E/F) Heat-related CPD mortality per 100,000 adults in cities and towns (SSP245). D. Mid-century scenario (2045-49). E. *Heatwave scenario 2030s. F. *Heatwave scenario 2040s. (*specific year varies by region)

15

File generated with AMS Word template 2.0

found in Hungary. By mid-century, the NUTS2 regions featuring Plovdiv, Skopje, and Craiova could expect the highest annual heat wave triggered CPD fatality rates (>55 per 100,000) in Europe, while Varna, Nis, Novi Sad and Sarajevo are predicted to experience increasing (>40) rates too. Impacts will be felt further north as well, besides the urban areas of Hungary (>35), also in Italy, where high CPD fatality rates (>25) can be expected in two northern regions.

Average figures for heat-related fatalities tend to mask important interannual variation, as heat wave occurrence is typically pronounced in individual years. To explore heatwave-related CPD mortality, we selected from each decade and in each NUTS2 region the single year with the highest predicted summer temperature in terms of cooling degree days.

The modelling indicates how even in near future, some regions could experience strong heatwaves in specific years, and that summer warming will intensify further as we approach mid-century. Figures 4E and 4F show how four of the above NUTS2 regions (e.g. Craiova, Plovdiv, Skopje, Novi Sad) within the next ten years, i.e. by the early 2030s, should expect to see heatwave-related CPD fatalities above 60 per 100k, while by the late 2040s Sarajevo and Nis could reach this level too. In fact, numerous NUTS2 regions across large tracts of Europe are recorded for increases in heatwave year related CPD fatalities.

It also becomes clear that some regions in Türkiye, such as Izmir, Ankara and Konya, that used to be only modestly warm, could become more seriously affected by heatwaves. As for the UK, our modelling indicates the likelihood of increasing fatality numbers in Greater London during near-future heat waves.

Based on these results, adaptation and mitigation needs can be assessed in a more nuanced way, compared to considering only a simple annual average of summer temperatures over a longer time span.

*b. Changes in heat-related CPD mortality towards mid-century*

Table 2 provides absolute numbers per country for the same time periods and scenarios as reviewed above. Results for 2015-22 reveal how the highest absolute numbers of heat-related CPD fatalities are estimated to have occurred in Italy, followed by Türkiye, Spain, Romania and Hungary (in descending order), accounting in total for about 12,750 annual fatalities. While this figure is up from about 5,000 annual fatalities 35 years ago, it is projected to increase to about 14,900 within the next decade and with 1,600 more towards mid-century –

16

File generated with AMS Word template 2.0

| Fatalities<br><br>Country | 1979-90*<br>(historical) | 2015-22*<br>(recent) | 2030-34*<br>(next decade) | 2045-49*<br>(mid-century) | Max 2030s** | Max 2040s** |
|---|---|---|---|---|---|---|
| Cyprus (EU) | 10 | 103 | 134 | 158 | 154 | 209 |
| Italy (EU) | 2,193 | 4,895 | 6,121 | 6,260 | 6,907 | 7,675 |
| Malta (EU) | 16 | 68 | 90 | 107 | 108 | 131 |
| Portugal (EU) | 245 | 531 | 548 | 563 | 750 | 763 |
| Spain (EU) | 732 | 1,698 | 1,899 | 2,024 | 2,291 | 2,315 |
| w-Türkiye | 785 | 3,679 | 3,879 | 5,066 | 4,871 | 6,434 |
| Albania | 67 | 234 | 306 | 314 | 348 | 400 |
| Bosnia-H.# | 237 | 432 | 546 | 539 | 700 | 824 |
| Bulgaria (EU) | 413 | 787 | 824 | 882 | 1,038 | 1,143 |
| Croatia (EU) | 188 | 389 | 536 | 536 | 631 | 754 |
| Greece (EU) | 412 | 1,120 | 1,279 | 1,420 | 1,609 | 1,679 |
| Kosovo# | 3 | 19 | 33 | 36 | 49 | 61 |
| Montenegro | 3 | 13 | 18 | 18 | 22 | 25 |
| N Macedonia | 331 | 468 | 551 | 603 | 647 | 647 |
| Romania (EU) | 614 | 1,275 | 1,542 | 1,657 | 2,015 | 2,335 |
| Serbia | 390 | 808 | 1,015 | 1,020 | 1,310 | 1,534 |
| Austria (EU) | 113 | 219 | 274 | 287 | 324 | 370 |
| Czechia (EU) | 20 | 81 | 119 | 131 | 196 | 211 |
| Hungary (EU) | 712 | 1,185 | 1,433 | 1,509 | 1,858 | 2,024 |
| Lithuania (EU) | 5 | 12 | 14 | 22 | 28 | 33 |
| Poland (EU) | 136 | 463 | 770 | 1,033 | 1,465 | 1,675 |
| Slovakia (EU) | 12 | 57 | 86 | 99 | 144 | 151 |
| Slovenia (EU) | 2 | 15 | 23 | 24 | 36 | 43 |
| Belgium (EU) | 16 | 65 | 100 | 93 | 178 | 149 |
| France (EU) | 200 | 592 | 848 | 779 | 1,428 | 1,335 |
| Germany (EU) | 129 | 499 | 754 | 901 | 1,241 | 1,535 |
| Liechtenstein | 0 | <1 | <1 | <1 | <1 | <1 |
| Luxembourg (EU) | <1 | <1 | <1 | <1 | 1 | 1 |
| Netherlands (EU) | 15 | 216 | 388 | 485 | 714 | 855 |
| Switzerland | 10 | 74 | 94 | 96 | 144 | 166 |
| Denmark (EU) | <1 | 12 | 30 | 79 | 124 | 210 |
| Estonia (EU) | <1 | 16 | 17 | 29 | 48 | 62 |
| Finland (EU) | 1 | 18 | 12 | 38 | 35 | 83 |
| Iceland | 0 | 0 | 0 | 0 | 0 | 0 |
| Ireland (EU) | <1 | <1 | 3 | <1 | 23 | 1 |
| Latvia (EU) | 3 | 55 | 61 | 100 | 192 | 195 |
| Norway | 1 | 1 | 1 | 7 | 6 | 19 |
| Sweden (EU) | 2 | 22 | 38 | 90 | 144 | 216 |
| UK | 12 | 365 | 670 | 434 | 2,715 | 1,700 |
| EU27 sum | 6,191 | 14,391 | 17,933 | 19,285 | (23,662) | (26,113) |
| All countries, sum | 8,025 | 20,483 | 25,045 | 27,417 | (34,475) | (37,923) |

# imputed climate projections; *annual, during summer period (May-September) among adults in cities
**sum of one-year maximum decadal heat spell fatalities of all individual NUTS2 regions, notwithstanding specific year

Table 2. Estimated annual heat-related CPD fatalities in urban areas.

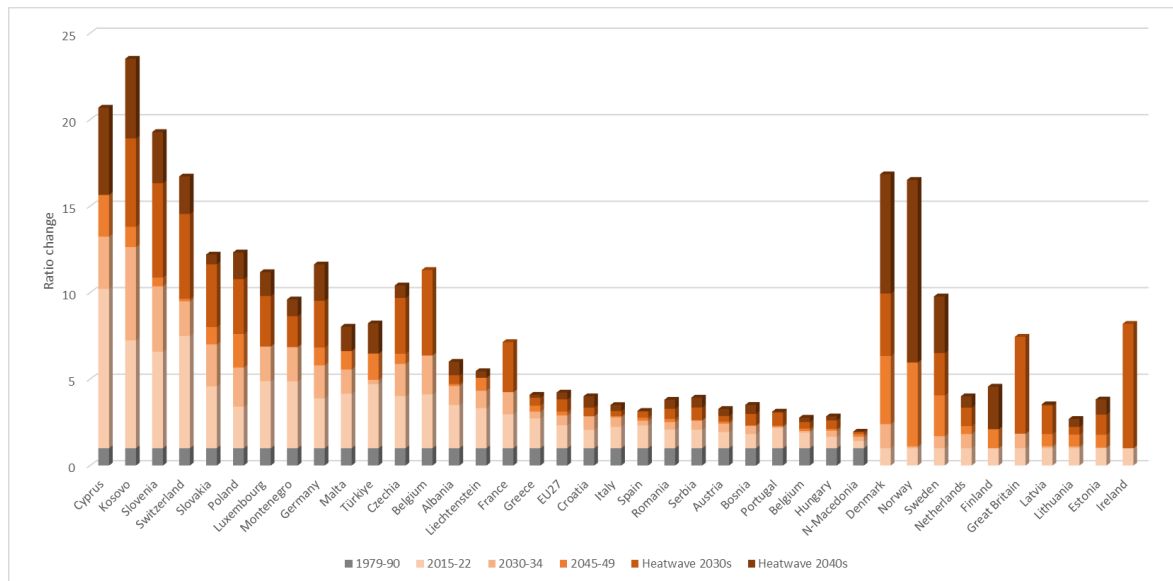File generated with AMS Word template 2.0

Fig. 5. Ratio change with respect to heat-related CPD fatalities in cities and towns among adults (> 25 years) attributable to post-1990 global warming (SSP245) in countries of EU27, EEA and western Balkans and Türkiye. For Nordic and Baltic countries plus Netherlands, Ireland and UK ratio change is for post-2022 global warming, due to insignificant 1990 fatality levels.

peaking up to about 20,700 in these five countries alone, when considering individual heatwave years across regions.

Average annual fatalities in the EU27 countries, accounting for 14,400 presently (2015-22) are projected to increase somewhat more strongly in relative terms, i.e. by 3,500 within the next decade – and a further 1,400 by mid-century. The total EU27 annual average will more than double from 6,200 in 1990 to 17,900 by mid-century – peaking at up to 26,000 when considering individual heatwave years across regions.

The six countries of the western Balkans have seen a doubling from about 1,000 to 2,000 fatalities from 1990 to present and are projected to experience a further increase to 2,500 by mid-century – peaking at 3,500 in heatwave years.

EEA countries Norway and Switzerland that previously hardly experienced heat-related CPD fatalities will by mid-century be likely to experience large relative increases (compared to the present), as shown in Figure 5. Within the EU27, large ratio changes (>10) can be expected for Cyprus and Slovenia. The ratio change will also be considerable in individual heatwave years for Denmark and Norway. In contrast, Balkan and Mediterranean countries - despite their higher absolute numbers - should experience less change in terms of ratios, save

File generated with AMS Word template 2.0

mountainous Kosovo that tops the list of ratio changes. Poland, Germany and France see a higher ratio change than the EU27 average, while Türkiye ranks well above Italy and Spain.

*c. Annual costs of heat-related CPD mortality*

The highest average annual cost by mid-century, exceeding 2.5 per cent of annual GDP, are predicted to arise in North Macedonia, Cyprus and Malta. They are followed by seven countries (Serbia, Bosnia-Herzegovina, Greece, Croatia, Hungary, Bulgaria, and Italy) where the average annual cost is estimated to exceed 1 per cent of annual GDP. In fact, they are all expected to exceed that level within the next decade. However, for heatwave years by mid-century, costs are estimated to peak at above 3.5 percent of annual GDP in Serbia, Northern Macedonia, Cyprus and Malta, with costs in Bosnia-Herzegovina going above 2.5 per cent (as shown in Figure 6). In Croatia along with Hungary and Greece, they will exceed 1.8 percent. Figure 6 provides the accumulated changes, with the sum of the GDP share indicated always with reference to the respective period (i.e. mid-decade estimates of GDP for the 2030s and 2040s).
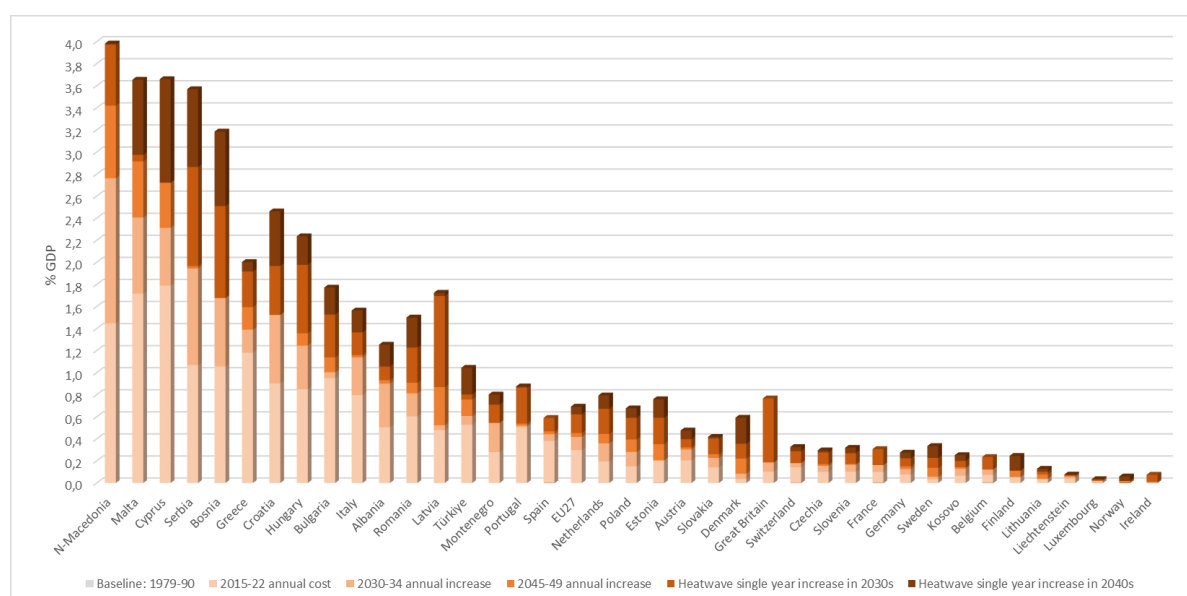


Fig. 6. Annual costs of CPD fatalities in cities and towns among adults (> 25 years) attributable to post-1990 increasing summer heat (SSP245) relative to national GDP in countries of EU27, EEA and western Balkans plus Türkiye and UK (incl. NI) – adjusted for population changes and projected economic growth.

File generated with AMS Word template 2.0

| Costs<br><br>Country | 2015-22<br>(M€) | 2030-34<br>(M€) | 2045-49<br>(M€) | Max 2030s*<br>(M€) | Max 2040s*<br>(M€) |
|---|---|---|---|---|---|
| Cyprus (EU) | 380 | 569 | 738 | 663 | 992 |
| Italy (EU) | 11,449 | 17,938 | 19,909 | 21,527 | 26,835 |
| Malta (EU) | 177 | 288 | 384 | 355 | 481 |
| Portugal (EU) | 1,020 | 1,232 | 1,374 | 2,054 | 2,233 |
| Spain (EU) | 3,518 | 5,139 | 6,006 | 6,866 | 7,356 |
| w-Türkiye | 7,899 | 14,329 | 22,669 | 18,929 | 29,914 |
| Albania | 270 | 556 | 635 | 652 | 853 |
| Bosnia-H.[#] | 315 | 599 | 646 | 898 | 1,258 |
| Bulgaria (EU) | 971 | 1,277 | 1,502 | 1,943 | 2,338 |
| Croatia (EU) | 636 | 1,249 | 1,349 | 1,586 | 2,194 |
| Greece (EU) | 2,295 | 3,350 | 4,177 | 4,624 | 5,250 |
| Kosovo[#] | 20 | 46 | 56 | 71 | 99 |
| Montenegro | 26 | 59 | 65 | 77 | 96 |
| N Macedonia | 242 | 535 | 731 | 770 | 851 |
| Romania (EU) | 2,200 | 3,735 | 4,324 | 5,640 | 7,139 |
| Serbia | 891 | 1,879 | 2,094 | 2,768 | 3,802 |
| Austria (EU) | 525 | 895 | 1,056 | 1,172 | 1,557 |
| Czechia (EU) | 199 | 401 | 490 | 715 | 845 |
| Hungary (EU) | 1,316 | 2,400 | 2,828 | 3,812 | 4,658 |
| Lithuania (EU) | 27 | 35 | 72 | 94 | 120 |
| Poland (EU) | 1,082 | 2,494 | 3,732 | 5,230 | 6,402 |
| Slovakia (EU) | 133 | 266 | 338 | 471 | 541 |
| Slovenia (EU) | 45 | 88 | 99 | 144 | 184 |
| Belgium (EU) | 241 | 467 | 471 | 898 | 809 |
| France (EU) | 1,687 | 3,169 | 3,129 | 6,004 | 6,131 |
| Germany (EU) | 1,731 | 3,213 | 4,239 | 5,711 | 7,716 |
| Liechtenstein | 0 | <1 | 1 | <1 | 1 |
| Luxembourg (EU) | 3 | 6 | 7 | 9 | 12 |
| Netherlands (EU) | 953 | 2,017 | 2,779 | 3,777 | 4,959 |
| Switzerland | 366 | 564 | 650 | 900 | 1,181 |
| Denmark (EU) | 60 | 166 | 486 | 695 | 1,296 |
| Estonia (EU) | 52 | 66 | 123 | 190 | 267 |
| Finland (EU) | 77 | 53 | 204 | 170 | 451 |
| Iceland | 0 | 0 | 0 | 0 | 0 |
| Ireland (EU) | 0 | 15 | 0 | 123 | 7 |
| Latvia (EU) | 27 | 35 | 72 | 94 | 120 |
| Norway | 4 | 5 | 49 | 35 | 142 |
| Sweden (EU) | 93 | 195 | 544 | 776 | 1,325 |
| UK | 1,726 | 3,751 | 2,649 | 15,408 | 10,589 |
| EU27 sum | 31,038 | 50,881 | 60,582 | 75,840 | 92,574 |
| EU27 same VSL | 33,140 | 54,122 | 65,277 | 80,532 | 99,303 |
| All countries, sum | 42,803 | 73,218 | 90,838 | 116,359 | 141,733 |

[#]Imputed CDD; *Sum of the maximum decadal heat spell costs of all individual NUTS2 regions, notwithstanding specific year

Table 3. Annual welfare economic costs above pre-1990 baseline of heat-related CPD fatalities.

File generated with AMS Word template 2.0

In contrast, costs relative to GDP are less severe in those countries that have been estimated to experience the largest ratio change in heat-related CPD-mortality for individual years (see Figure 5), even if fatalities are valued relatively more due to citizens higher levels of income. Costs do generally not exceed the EU27 average of 0.7 per cent of GDP, except for the UK and the Netherlands.

Table 3 provides absolute figures for the welfare economic costs of the heat-related CPD-fatalities projected to arise and attributable to global warming over a 1979-90 baseline. Türkiye features the highest average annual costs in the coming decades at more than €22 billion, followed by Italy at about €19 billion by the 2040s. The highest figures relating to specific heatwave years are found in Türkiye, at €29 billion, and Italy at €26 billion, followed by a projected heatwave year of the 2030s in UK at €15 billion.

The EU27 is facing average annual welfare economic costs attributable to heat-related CPD premature mortality in the range of €54-65 billion (at uniform VSL) in the two coming decades, with estimations that fatalities may peak in individual heat wave years, triggering costs of up to €80-99 billion when considering and summing maximum impact years per decade across NUTS2 regions.
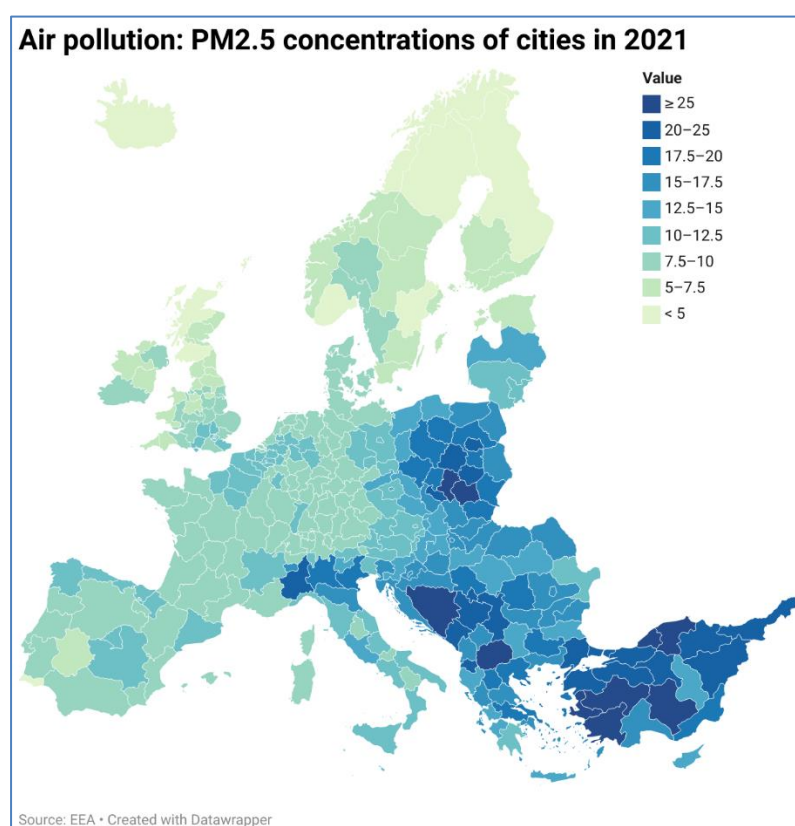


Fig. 7. Background concentrations with particles (ug/m$^3$ of PM$_{2.5}$) in cities and towns.

File generated with AMS Word template 2.0

*d. Adaptation with air pollution abatement*

It is evident from the exposure-response functions identified with our data set (see Figure 3), how heat-related CPD incidence is reinforced by higher levels of air pollution with particles (PM$_{2.5}$).

Hence, one way to adapt to a warmer climate and reduce the number of CPD fatalities, compatible with transitioning away from fossil fuels and into renewable energy, is to reduce levels of air pollution. The World Health Organization (WHO) recommends aiming for an exposure level not higher than 5 ugPM$_{2.5}$/m$^3$ to reduce health impacts and premature mortality (WHO 2021). Only ten of the 317 regions comply with this threshold.

We focus on implications for the Balkan and Mediterranean countries, as they have some of the highest CPD fatality frequencies per 100,000 identified by the analysis, as well as relatively high levels of air pollution in many regions. In 2021 more than 20 of their NUTS2 regions had air pollution concentrations at 20-30 ugPM$_{2.5}$/m$^3$ in urban background (see Figure 7), 4-6 times the threshold recommended by WHO.

The comprehensive datasets from the city level analysis allowed us to derive exposure-response functions for heat-related mortality controlled for daily particle concentrations (Schneider et al. 2023), whereby we can contrast fatality rates at WHO-recommended levels to levels consistent with recent air pollution levels.

Findings suggest that average annual heat-related CPD mortality in Balkan and Mediterranean countries can be reduced significantly if embarking on an energy and transport transformation to meet WHO's recommendation (Table 4). Within the next 25 years, the number of fatalities can be reduced about 190,000 – or annually about 7,500, down from the projection of annually about 19-21,000 to about 12-13,000 in these countries (cf. Table 2 and Table 4). In other words, with 2021 levels of air pollution maintained in this region, the number of CPD fatalities would be about 50 per cent higher than with a targeted pollution abatement adaptation strategy. The strategy would be especially impactful in western Balkans, where fatalities will otherwise be about 90% higher. It would be directly reflected in assessments of costs, which would shrink correspondingly.

File generated with AMS Word template 2.0

| Fatalities with $PM_{2.5} < 5ug/m^3$<br><br>Country | 2030-34*<br>(annual) | 2045-49*<br>(annual) | Max<br>2030s*<br>(one year) | Max<br>2040s*<br>(one year) | Mid-<br>century<br>annual<br>fatality<br>reduction<br>(per cent) |
|---|---|---|---|---|---|
| Cyprus (EU) | 107 | 126 | 123 | 166 | 20% |
| Italy (EU) | 3,493 | 4,175 | 4,564 | 5,072 | 33% |
| Malta (EU) | 83 | 98 | 99 | 120 | 8% |
| Portugal (EU) | 530 | 543 | 725 | 744 | 4% |
| Spain (EU) | 1,480 | 1,522 | 1,729 | 1,777 | 25% |
| w-Türkiye | 2.165 | 2,748 | 2,676 | 3,503 | 46% |
| Albania | 169 | 174 | 192 | 221 | 45% |
| Bosnia-H. | 254 | 252 | 305 | 347 | 53% |
| Bulgaria (EU) | 528 | 557 | 648 | 699 | 37% |
| Croatia (EU) | 267 | 265 | 317 | 361 | 51% |
| Greece | 782 | 868 | 995 | 1,024 | 39% |
| Kosovo | 20 | 22 | 30 | 38 | 38% |
| Montenegro | 11 | 11 | 13 | 15 | 40% |
| N Macedonia | 277 | 298 | 311 | 334 | 50% |
| Romania (EU) | 1,082 | 1,160 | 1,378 | 1,572 | 30% |
| Serbia | 636 | 643 | 805 | 935 | 37% |
| sum | 11,882 | 13,462 | 14,910 | 16,927 | 37% |

Table 4. Heat-related CPD-fatalities projected when countries comply with WHO's recommendation to aim for air quality with $PM_{2.5}$ not higher than 5 micrograms per $m^3$.

The European Union, unfortunately, in its Directive on Ambient Air Quality and Cleaner Air for Europe (2024/2881) has opted for a higher air quality threshold of 10 $ugPM_{2.5}/m^3$. When also considering countries' lax implementation of EU air pollution laws (Yamineva and Romppanen 2017) member states and candidate countries are at risk to forfeit the win-win opportunity of reducing heat-related mortality concurrently with cleaning the air (e.g. from fossil fuels).

# 4. Discussion and conclusions

Previous attempts to project the future numbers and costs of heat-related fatalities mostly relied on uniform ERFs and did not factor in the essential interplay with air pollution (Hunt et al. 2017, Diaz et al. 2019). In contrast, the present analysis benefits from the availability of more complex ERFs derived from a huge dataset of heat-related excess mortality sorted against daily levels of air pollution with $PM_{2.5}$. Moreover, previous projections were typically focused on a smaller set of cities or countries, abstaining from projecting overall patterns at pan-European scale (Huang et al. 2023, Karwat and Franzke 2021, Gasparrini et al. 2017).

File generated with AMS Word template 2.0

The study by Luthi et al. (2023) despite its global focus does not factor in population growth and ageing of populations, nor the role of air pollution.

The regional division featuring different ERFs for different climatic zones in fact corresponds to a method applied in a pioneering study of 15 cities by Baccini et al. (2008) and coauthors (Kendrovski et al. 2017), though with much greater differentiation here. This procedure is of significance to capture contrasts within the larger countries included in the analysis, and even for some of the middle-sized countries. We consider this an improvement relative to previous studies.

### a. ERF heterogeneities

Still, the ERF´s may not always be a perfect fit due to various heterogeneities. Heat island effects are more pronounced in the largest cities (Chitu et al. 2023, Huang et al. 2023), and so our reference city ERF's may overestimate impacts to smaller cities, even if this is mitigated by our CDDs having been calculated at regional level, likely to underestimate the heat spell intensities of larger cities. Also, the penetration rates of air conditioning (AC) can be expected to differ both intra- and inter-regionally, but our estimates are predominantly conservative in that six of our eight ERF reference cities appear to have higher AC penetration rates than the corresponding regions of their heat stress zone, judged from national level data (Italy: regional). In only some regions of two heat stress zones there are slightly lower AC rates than the references. However, to factor in the role of AC is challenging, as we can observe the persistence of heat-related deaths even in Greece with an AC penetration rate above 80% (ADEME 2023). The practices of residential AC use in southern Europe are no doubt more erratic than in USA and Japan.

Differences in pre-existing adaptation policies introduced in some of the reference cities is a further source of heterogeneity. Even if we rely on data from a relatively early period, the 2003 heatwave over western Europe had triggered heat alert systems with precautionary measures in Paris, Rome and Madrid for instance, so that ERFs derived here and applied across the respective climatic zones may underestimate possible impacts in other regional settings without such measures in place. According to WHO's mapping of heat action plans (WHO 2021), several countries did not yet have such in place by 2019, e.g. Cyprus, Serbia, Poland, Czechia, Montenegro and all Nordic countries but Sweden.

Conversely, other ERFs may overestimate impacts in countries that have meanwhile developed heat action plans, e.g. Malta and the Netherlands. Hence, the results presented here

24

File generated with AMS Word template 2.0

remain a somewhat coarse estimation, despite the greatly improved data basis and finer spatial resolution for our analysis.

*b. Air conditioning a panacea?*

Italy is a country that has seen a gradual increase of AC in private homes over the past twenty years, yet very little is known about the extent to which AC is able to mitigate the mortality impacts of heat spells (IEA 2018). From 2006-15, the period that our mortality data refers to, AC ownership in Italy already averaged 30 per cent (ISTAT 2021), yet our data demonstrates the persistence of heat-related CPD mortality impacts also in this country.

The costs of powering AC in countries with inefficient energy systems and relatively modest average household incomes, as in southern Italy and the Balkans, may help explain the vulnerability to heat-related CPD mortality detected in our analysis. With incomes being unequally distributed, there are substantial population groups for whom it remains a challenge to keep their homes cool during heat spells. The same groups may well be dependent on manual outdoor jobs in a labor market with limited social security arrangements to allow for absence during heat spells. Findings from Vancouver, Canada, show that materially deprived households feature risk ratios three times higher than the average (Henderson et al., 2023).

Davis et al. (2021) show how annual household incomes of about USD10,000, corresponding to €9,000, constituted an affordability threshold for installation of AC in Italy, and with penetration increasing only gradually above that level. For the poorest quintile of households in Italy's southern regions, this level of income will not be reached until shortly before 2050, even if optimistically applying the economic growth rate forecasts of OECD equally to all income groups (Table 5). Also in Bulgaria, Croatia and Romania the lowest quintiles will remain well below an AC affordability threshold by mid-century, except in their capital regions. Finally, the five countries of western Balkans (no data for Bosnia-Herzegovina) have median income levels 8-40% below the poorest EU member state (Eurostat 2025). Thus, for low-income households in south-eastern Europe, acquiring and operating AC will remain a challenge.

|  | Bulgaria | Croatia | Italy (south) | Romania |
|---|---|---|---|---|
| 2030-2035 | €2,361-2,923 | €4,425-4,736 | €7,392-8,882 | €1,323-3,609 |
| 2045-2049 | €4,310-7,388 | €6,901-7,096 | €8,598-10,252 | €2,137-5,830 |

Table 5. Annual disposable household income in Euro of the lowest quantiles. Interval of lowest and highest NUTS2 region outside the capitals (authors' projection from base year 2020 based on Eurostat 2023 and OECD 2021)

File generated with AMS Word template 2.0

The exposure-response functions from heat spells derived from our data (Figure 3) lead us to suggest that the inequitable access to AC may have a role to play in the premature CPD-mortality triggered. Thus, we tend not to share the optimism of Carleton et al. (2022) that uptake of AC will altogether prevent heat-related mortality from occurring in Europe. More research is needed to understand adoption and behavioral aspects related to AC penetration and use, to allow for its due consideration in projections.

*c. Comparison with results from other studies*

To compare the outcomes of our ERFs with previous studies, we considered the 2003 heatwave, for which 70,000 deaths across Europe has been estimated by a consortium of national statistical agencies. They provide a break-down of this figure at Member State level, estimating that 20,000 deaths occurred in Italy (Robine et al. 2008). In comparison, when applying our ERFs for all-cause mortality with the CDDs and air pollution levels of the time for Italy's NUTS2-regions, we arrive at an estimate of about 22,000 heat-related deaths in Italy 2003. Hence, our dataset and findings should be considered in conformity with this important study, despite differences in methodology and the narrower focus here on CPD mortality.

As heat-related CPD-mortality accounts for about half of heat-related all-cause mortality, our results are also well in conformity with Ignjacevic et al. (2024), who in their SSP245 scenario estimate for 2030 arrive at 48,000 all-cause deaths, while we project about 25,000 cases of CPD-mortality.

However, the use of a one-size-fits-all minimum mortality temperature as low as 18 degrees Celsius in Ballester et al. (2023) contributes presumably to their 60,300 heat-related all-cause deaths in 35 European countries for the hot summer of 2022. In contrast, for the same countries we estimate 15,800 cases of CPD-mortality annually for 2015-2022, as the minimum mortality temperature identified with statistical significance in this study is well above 18 degrees in most of southern Europe (cf. Table 1). Hence our estimate of all-cause deaths is about 5,000 lower than the 2015-21 average identified by Ballester et al.

Hence, when our study suggests that the number of heat-stress-attributable CPD fatalities and the associated socio-economic costs in Europe will increase significantly over the next two decades, the findings do not appear to be an outlier result. Nevertheless, our findings challenge conventional wisdom in the economics literature on the social costs of global

File generated with AMS Word template 2.0

warming, as reflected in the study by Carleton et al. (2022) cited above. Even Rennert et al. (2022), who present a significantly increased estimate of the social cost of carbon, are relying on a simple linear ERF for European heat wave mortality (Cromar et al., 2021), suggesting mortality impacts of a magnitude only half the level of our findings.

*d. Main findings*

For the hottest heat wave years analyzed, EU27 welfare economic costs of premature mortality are here found to triple relative to present annual averages (2015-22), while they quadruple for western Balkans and Türkiye. Measured against GDP, there will be large variations, with the EU27 average at 0.4 per cent of total GDP, while ten European countries will suffer casualties corresponding to costs well above 1 per cent of their GDP. Whether these figures are considered large or small will depend on the observer, however they add up with other costs of climate change (notably productivity losses) and will have relevance in determining the social costs of carbon as well as the optimal costs for adaptation.

Still, the most important contribution of the present study to the heat spell literature is arguably. to have captured the intricate interplay of air pollution and heat spells. While the complexity of this relationship warrants further research, it has significant policy implications. The costs of premature mortality could be reduced in most of the countries investigated by aiming for adaptation strategies that accelerate measures to reduce air pollution with $PM_{2.5}$. Simulations suggest that rapid and targeted measures to reduce air pollution to the level recommended by WHO could reduce the number of heat-related CPD fatalities in the Mediterranean and Balkan countries by up to 190,000 over the next 25 years.

*Data Availability Statement.*

File generated with AMS Word template 2.0

Data analyzed in this study was largely a re-analysis of existing data, some of which are openly available at locations cited in the reference section. Further documentation about data, data processing and data acquisition is available in the full Data Management Plan of the EXHAUSTION project, available at https://cordis.europa.eu/project/id/820655/results

## APPENDIX A

### Europe's heat stress zones

| CDD range 2006-15 | NUTS2 regions (codes according to Eurostat, 2020) |
|---|---|
| >450 | CY00; EL30; EL41; EL42; MT00; TR31; TR32 |
| 325-450 | EL43; EL52; EL61; EL62; EL64; EL65; ES43; ES53; ES61; ES62; ITF4; ITG1; TR61; TR62 |
| 250-325 | AL02; EL51; EL63; ES30; ES42; ES52; ITF2; ITF3; ITF5; ITF6; ITG2; TR10; TR21; TR22 |
| 175-250 | AL01; AL03; BG31; BG32; BG34; EL54; HR03; ITF1; ITH3; ITH5; ITI1; ITI3; ITI4; PT18; RO22; RO31; RO32; RS11; TR33 |
| 100-175 | AT13; BA00; BG33; BG42; EL53; ES24; ES51; ES70; FRJ1; FRM0; HU11; HU12; HU21; HU23; HU32; HU33; HR02; HR05; ITC1; ITC3; ITC4; ITI2; ITH4; MK00; PT15; PT16; PT17; RO41; RO42; RS12; RS22; TR41; TR42; TR51; TR52; TR71 |
| 40-100 | AT11; AT12; BG41; CZ01; DE30; ES22; ES23; ES41; FRF1; FRI1; FRJ2; FRK2; FRL0; HU22; HU31; HR06; ME00; PT11; RO11; RO21; RS21; SI03; SI04; SK01; SK02; TR72; TR81; TR82; TR83; TR90; XK00 |
| 12.5-40 | AT21; AT22; AT31; BE10; BE21; BE22; BE23; BE24; BE31; BE32; BE33; BE34; BE35; CH03; CH04; CH07; CZ02; CZ03; CZ04; CZ05; CZ06; CZ07; CZ08; DE11; DE12; DE13; DE14; DE21; DE22; DE23; DE24; DE25; DE26; DE27; DE40; DE50; DE71; DE72; DE73; DE91; DE92; DE93; DE94; DEA1; DEA2; DEA3; DEA4; DEA5; DEB1; DEB2; DEB3; DEC0; DED2; DED4; DED5; DEE0; DEG0; ES11; ES21; FR10; FRB0; FRC1; FRC2; FRF2; FRF3; FRG0; FRI2; FRI3; FRK1; ITH2; LI00; LT-all; LU00; NL22; NL41; NL42; PL-all; RO12; SK03; SK04; |
| <12,5 | AT32; AT33; AT34; BE25; CH05; CH06; DE60; DE80; DEF0; DK-all; EE00; ES12; ES13; FI-all; FRD1; FRD2; FRE1; FRE2; FRH0; IE-all; IS00; ITC2; ITH1; LV00; NL11; NL12; NL13; NL21; NL23; NL31; NL32; NL33; NL34; NO-all; SE-all; UK-all |
| AL: Albania; AT: Austria; BA: Bosnia-Herzegovina; BE: Belgium; BG: Bulgaria; CH: Switzerland; CY: Cyprus; CZ: Czechia; DE: Germany; DK: Denmark; EL: Greece; EE: Estonia; ES: Spain; FI: Finland; FR: France; HR: Croatia; HU: Hungary; IE: Ireland; IS: Iceland; IT: Italy; LI: Liechtenstein; LT: Lithuania; LV: Latvia; LU: Luxembourg; ME: Montenegro; MK: North Macedonia; MT: Malta; NL: Netherlands; NO: Norway; PL: Poland; PT: Portugal; RO: Romania; RS: Serbia; SE: Sweden; SI: Slovenia; SK: Slovakia; TR: Türkiye; UK: United Kingdom; XK: Kosovo. | |

Table A1. Inventory of NUTS2 regions classified into heat stress zones, based on reference city ERFs. Implemented in figure 2 of main text.

## APPENDIX B

### Comparison of WRF simulations with EURO-CORDEX

To better understand how the WRF simulations perform in the context of other models across both historical and future periods, we compared the WRF outputs with the EURO-CORDEX multi-model ensemble simulations based on CMIP5 scenarios (Jacob et al., 2014, p. 20). We focused specifically on the annual maximum temperature (TXx). For consistent

28

File generated with AMS Word template 2.0

comparison across different greenhouse gas emission pathways in future projections, we aligned the SSP1-2.6 and SSP2-4.5 scenarios from our WRF and CESM2 simulations with the RCP 2.6 and RCP 4.5 scenarios from EURO-CORDEX, respectively. The comparison spans the period 1980-2049, with historical simulations from EURO-CORDEX covering 1980-2005 and from our study covering 1980-2014. The EURO-CORDEX ensemble results are represented by their median values and 5-95% percentile ranges to capture the spread of model variations.

The WRF simulations (WRF_CESM2, WRF_ssp126 and WRF_ssp245) generally fall within the spread of the EURO-CORDEX ensemble (Fig. A1), indicating the general consistency and robustness of the WRF downscaling approach. The interannual variations and the magnitude of TXx in WRF simulations are largely dominated by the driving CESM2 model, with the differences between WRF and CESM2 being small (0-0.5 °C) and not statistically significant across most zones. The largest difference is presented in Eastern Europe, where CESM2 shows a statistically significant ($p < 0.05$) higher TXx (1.5 °C) compared to WRF (Fig. A1-e). Comparing the WRF and CESM2 results with the EURO-CORDEX ensemble median, we find that the CMIP6-based scenarios from WRF and CESM2 project overall higher TXx values than the CMIP5-based EURO-CORDEX projections (Fig. A1). The differences range from 0.9-3.2 °C across different zones, with the largest differences in the North (Fig. A1-e) and the smallest in the South (Fig. A1-b). These differences remain consistent across both the historical and future period, but can be influenced by many factors such as the choice of models, scenarios, and internal variability. The overall consistency between the WRF simulations and the EURO-CORDEX ensemble lends confidence to the robustness of our projections, although the specific magnitude and spatial pattern of the projected changes may differ due to the use of different models and scenarios.
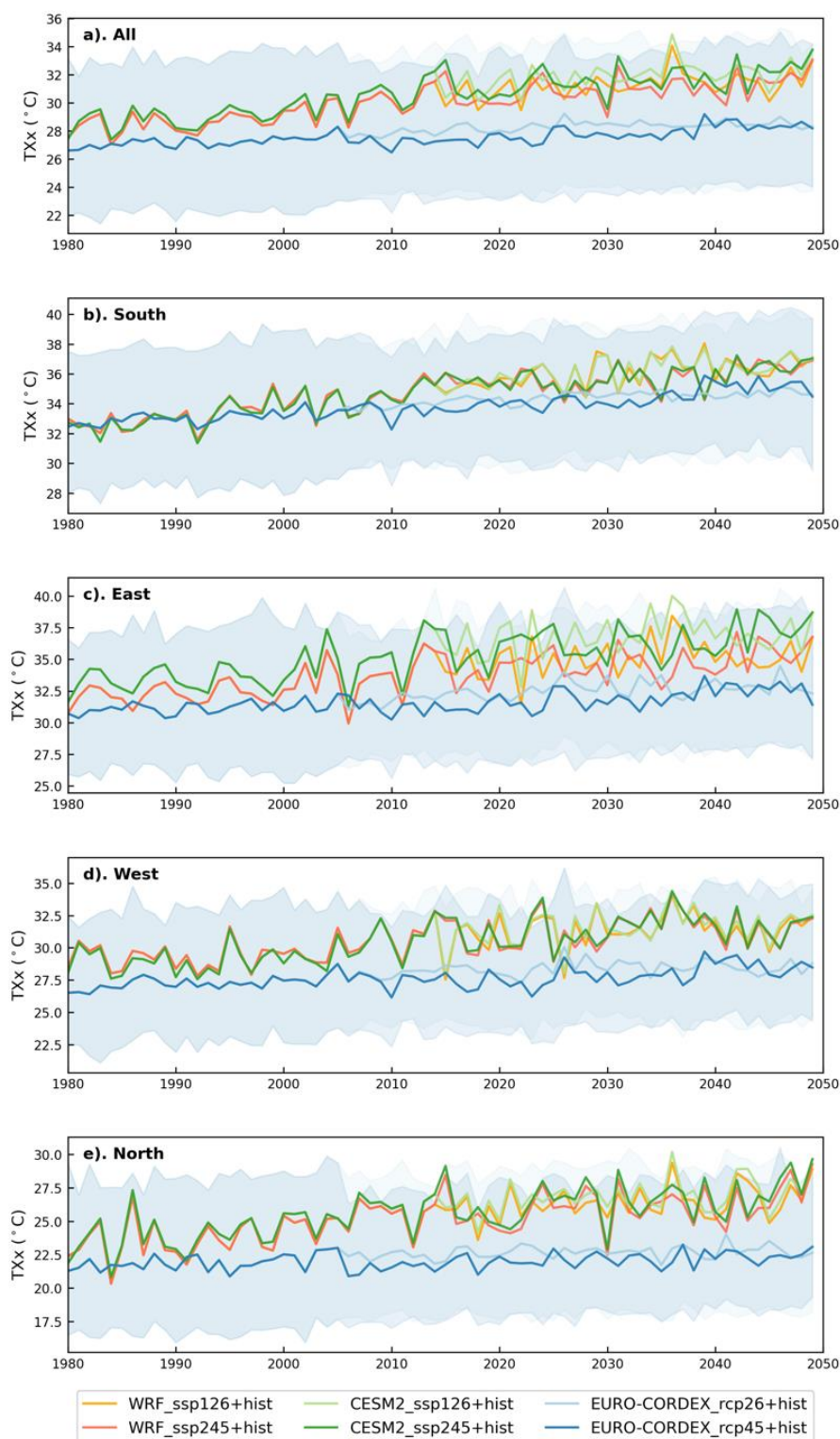
File generated with AMS Word template 2.0

Fig. A1. Interannual variability of region-mean annual maximum temperature (TXx, in °C) across the continental Europe and various European climate zones. The data is derived from historical (WRF_CESM2) and future (WRF_ssp126 and WRF_ssp245) simulations from WRF, CESM2 historical and future (CESM2_ssp126 and CESM2_ssp245) simulations, and the EURO-CORDEX ensemble median for historical and future RCP 2.6 and RCP 4.5 scenarios. The shaded regions represent the interquartile range (5th to 95th percentile) of the EURO-CORDEX ensemble, illustrating the spread.

File generated with AMS Word template 2.0

# REFERENCES

ADEME (The French Agency for Ecological Transition), 2023: Rate of equipment ownership for air conditioning. Database on energy efficiency indicators, accessed 27 April 2023, https://www.indicators.odyssee-mure.eu/

Andersen, M.S., 2017: Co-benefits of climate mitigation: Counting statistical lives or life-years? Ecological Indicators **79**, 11–18.

Baccini, M., and Coauthors, 2008: Heat effects on mortality in 15 European cities. *Epidemiology* **19**(5), 711-719.

Ballester, J., and Coauthors, 2023: Heat-related mortality In Europe during the summer of 2022. *Nature Medicine* **29**, 1857-1866.

Carleton, T., and Coauthors, 2022: Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Quarterly Journal of Economics* **137**(4), 2037-2105.

Chitu, Z., and Coauthors, 2023: Large sex differences in vulnerability to circulatory-system disease under current and future climate in Bucharest and its rural surroundings. *Environmental Research* **234**: 116531.

Cromar, K.R., 2021: Global health impacts for economic models of climate change. A systematic review and meta-analysis. *Annals of the American Thoracic Society* **19**(7), 1203-1212.

Davis, L., and Coauthors, 2021: Air conditioning and global inequality. *Global Environmental Change* **69**: 102299.

DEFRA (Department for Environment, Food and Rural Affairs), 2023: UK AIR Background Mapping data for local authorities, accessed 19 December 2023, https://uk-air.defra.gov.uk/data/laqm-background-maps?year=2022

Diaz, J., and Coauthors, 2019: Mortality attributable to high temperatures over the 2021-2050 and 2051-2100 time horizons in Spain: Adaptation and economic estimate. *Environmental Research* **172**: 475-485.

European Environment Agency, 2023a: Economic losses from weather- and climate-related extremes in Europe, accessed 10 November 2023, https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related

File generated with AMS Word template 2.0

European Environment Agency, 2023b: *Air quality health risk assessments for cities and urban centres*, accessed 22 January 2024, https://discomap.eea.europa.eu/App/AQViewer/index.html?fqn=Airquality_Dissem.hra.cities_sel#

Eurostat, 2020: *Statistical regions in the European Union and partner countries*. Publications Office of the European Union, 188 pp.

Eurostat, 2021: *Applying the degree of urbanisation*. Publications Office of the European Union, 102 pp.

Eurostat. 2023: Online database, accessed last time 31. January 2025, https://ec.europa.eu/eurostat/web/main/data/database.

Eurostat, 2025: Living conditions in enlargement countries, accessed 24. July 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Living_conditions_in_candidate_countries_and_potential_candidates&oldid=606110,

Evci, H., ed., 2021: *Hava Kirliliği ve Sağlık Etkileri [Air pollution and health effects]*, Temiz Hava Hakki Platformu Hakkinda [About the Right to Clean Air Platform], 92 pp. https://www.ttb.org.tr/userfiles/files/KaraRapor2021.pdf

Feyen, L., J.C. Ciscar, S. Gosling, D. Ibarreta, and A. Soria, eds., 2020: Climate change impacts and adaptation in Europe. *JRC PESETA IV final report*, EUR30180EN. Publications Office of the European Union, 71 pp.

Gasparrini, A., B. Armstrong, M.G. Kenward, 2010: Distributed lag non-linear models. *Statistics in Medicine* **29**, 2224–34.

Gasparrini, A., and Coauthors, 2015: Temporal variation in heat-mortality associations: a multi-country study. *Environmental Health Perspectives* **123**, 1200–07.

Gasparrini, A., and Coauthors, 2017: Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planetary Health* **1**, e360-367.

Hausfather, Z., 2018: Explainer how shared socioeconomic pathways explore future climate change, accessed 21 March 2024, https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/

File generated with AMS Word template 2.0

Henderson, S.B., and Coauthors, 2022: Analysis of community deaths during the catastrophic 2021 heat dome. *Environmental Epidemiology* **6,** e189

Honda, Y., and Coauthors, 2014: Heat-related mortality risk model for climate change impact projection. *Environmental Health and Preventive Medicine* **19**, 56–63.

Huang, W., P. Masselot, E. Bou-Zeid, S. Fatichi, A. Paschalis, T. Sun, A. Gasparrini and G. Manoli, 2023: Economic valuation of temperature-related mortality attributed to urban heat islands in European cities. *Nature Communications* 14, 7438.

Huang, Z., J. Lim and M. Skidmore, 2024: The impacts of heat and air pollution on mortality in the United States. *Weather, Climate, and Society* **16**(2), 275-301.

Hunt A., J. Ferguson, M. Baccini, P. Watkiss and V. Kendrovski, 2017: Climate and weather service provision: Economic appraisal of adaptation to health impacts. *Climate Services* **7**, 78–86.

IEA (International Energy Agency), 2018: *The future of cooling*. OECD/IEA Publishing, 92 pp.

Ignjacevic, P., and Coauthors, 2024: Climate-induced mortality projections in Europe: Estimation and valuation of heat-related deaths. *International Journal of Disaster Risk Reduction* **111**, 104692

Im, U., and Coauthors, 2022: Climate and air pollution projections over Europe. EXHAUSTION report D3.3., 41 pp., https://cordis.europa.eu/project/id/820655/results

ISTAT (Istituto Nazionale di Statistica, Italia), 2021: Stat-base, Household economic conditions and disparities -ownership of durable goods, accessed 23 April 2023, https://www.istat.it/en/analysis-and-products/databases/statbase.

Jacob, D., and Coauthors, 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change* **14**, 563–578. https://doi.org/10.1007/s10113-013-0499-2

JRC (Joint Research Centre of the European Commission), 2023: Agri4cast resources portal, last accessed 20 November 2023, https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d

Jones-Lee, M.W., 1989: *The economics of safety and physical risk*. Basil Blackwell, 320 pp.

File generated with AMS Word template 2.0

Karwat, A., and C. Franzke, 2021: Future projections of heat mortality risk for major European cities. *Weather, Climate, and Society* **13**(4), 913-931.Katsouyanni, K, and Coauthors, 1993: Evidence for interaction between air pollution and high temperature in the causation of excess mortality. *Archives of Environmental Health* **48**(4): 235–242.

Kenney, W.L., D.H. Craighead and L.M. Alexander, 2014: Heat waves, aging and human cardiovascular health. *Medicine and Science in Sports and Exercise* **46**(10) 1891-1899.

Kendrovski, V., and Coauthors, 2017; Quantifying Projected Heat Mortality Impacts under 21st-Century Warming Conditions for Selected European Countries. *International Journal of Environmental Research and Public Health* **14**, 729.

Luthi, S., and Coauthors, 2023: Rapid increase in the risk of heat-related mortality. *Nature Communications* **14**, 4894.

Masselot, P., and Coauthors, 2023: Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. *Lancet Planetary Health* **7**, e271–281.

Newman, R. and I. Noy, 2022: The global costs of extreme weather that are attributable to climate change. *Nature Communications* **14**, 6103.

OECD, 2012: *Mortality Risk Valuation in Environment, Health and Transport Policies.* OECD Publishing, 143 pp. http://dx.doi.org/10.1787/9789264130807-en

OECD (2021) *Economic Outlook #109. Long-term baseline projections*, accessed 13 October 2022, https://www.oecd.org/en/data/indicators/real-gdp-long-term-forecast.html

Rabl, A. and B. Peuportier, 1995: Impact pathway analysis: A tool for improving environmental decision processes. *Environmental Impact Assessment Review* **15**, 421–442.

Rennert, K., and Coauthors, 2022: Comprehensive evidence implies a higher social cost of CO2. *Nature* **610**, 687-692.

Republic of Albania Institute of Statistics, 2014: *Albania population projections 2011-2031.* 200 pp.

Robine, J., S. Cheung, S. Le Roy, H. van Oyen, C. Griffiths, J. Michel and F. Herrmann, 2008: Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologie* **331**, 171-178.

File generated with AMS Word template 2.0

Schneider, A., and Coauthors, 2023: Exposure-response functions for interactive effects of temperature and air pollution, EXHAUSTION report D2.4., 83 pp., https://cordis.europa.eu/project/id/820655/results

Skamarock, W.C., and Coauthors, 2019: Description of the Advanced Research WRF Version 4, NCAR Technical Note. National Center for Atmospheric Research. 142 pp. https://doi.org/10.6084/m9.figshare.7369994.v4

Statistical Office of the Republic of Serbia, 2023: Population projections, accessed December 11 2023, https://www.stat.gov.rs/en-US/

Turkish Statistical Institute, 2023: Population by scenarios 2018-2080, last accessed January 21 2025, https://data.tuik.gov.tr

United Nations Population Division, 2022: World Population prospects 2022. Demographic Indicators by region, subregion and country, annually for 1950-2100, Medium fertility variant, accessed 11 January 2024, https://population.un.org/wpp/downloads

World Bank, 2023a: Toward Sustainable Growth. *Western Balkans Regular Economic Report #24*, 116 pp.

World Bank, 2023b: Indicators, accessed 3 November 2022, https://data.worldbank.org/indicator/

World Health Organization, 2021: *Heat and health in the WHO European Region: updated evidence for effective prevention.* WHO Regional Office for Europe, 190 pp.

World Health Organization, 2021: *WHO global air quality guidelines. Particulate matter (PM2,5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*, 300 pp.

World Meteorological Organization, 2023: *Guidelines on the definition and characterization of extreme weather and climate events*, WMO-no. 1310, 36 pp. https://rcc.dwd.de/DWD-RCC/EN/overview/documents/01_wmo_guidelines.pdf?__blob=publicationFile&v=3

Yamineva, Y. and S. Romppanen, 2017: Is law failing to address air pollution? Reflections on international and EU developments. *Review of European, Comparative & International Environmental Law* 26(3), 189-200.

Yin, B., Y. Chen and X. Xu, 2024: How does temperature change affect residents' health? A multidimensional health perspective. *Weather, Climate, and Society* **16**(4), 723-738.

File generated with AMS Word template 2.0

Zhang, S. and Coauthors, 2023: Assessment of short-term heat effects on cardiovascular mortality and vulnerability factors using small area data in Europe. *Environment International* **179**, 108154.

File generated with AMS Word template 2.0