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] AND 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

(Manuscript received 10 February 2025, in final form 30 September 2025, accepted 14 October 2025)

ABSTRACT: The objective of this study is to estimate the welfare economic costs of premature cardiopulmonary disease (CPD) mortality in Europe and Asia Minor under a middle-of-the-road scenario 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 from 1994 to 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 midcentury from its pre-1990 level. Based on Organisation for Economic Co-operation and Development (OECD) methodology for the economic valuation of premature mortality, this amounts to an estimated EUR 90 billion in annual welfare economic costs. For 10 countries in southeastern Europe, costs may well exceed 1% of their annual GDP, reaching up to 4% in a heat wave 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 the 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 the 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 nonexistent 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 midcentury deadly heat spells is likely higher than previously assumed, even in a relatively mild scenario of global warming.

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

1. Introduction

While previous studies have established that heat waves and global warming can be expected to increase premature mortality (Baccini et al. 2008; Honda et al. 2014; Gasparrini et al. 2015; Masselot et al. 2023; Zhang et al. 2023), the associated socioeconomic costs have so far been challenging to quantify (Newman and Noy 2023). 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 the 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 2023a) indicates economic losses of about EUR 16 billion annually since 2015 attributable to all weather-related extreme events, including heat waves, 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 heat waves dominates the overall costs for all

Denotes content that is immediately available upon publication as open access.

Corresponding author: Mikael Skou Andersen, msa@envs.au.dk

DOI: 10.1175/WCAS-D-25-0026.1

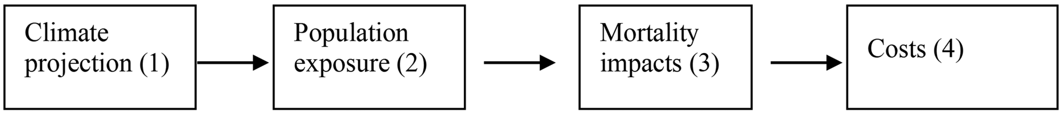

FIG. 1. Impact pathway sequence with main steps of analysis.

scenarios, even if the modeling is relatively coarse (Feyen et al. 2020). Detailed projections of the 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 (CPDs), 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 summertime all-cause mortality, even though our dataset includes both counts. We focus on impacts toward midcentury, 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" shared socioeconomic pathway (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 early studies on heat-related mortality (e.g., Katsouyanni et al. 1993) of significant interactions with air pollution concentrations. The study thus is in conformity with recent findings in the United States by Huang et al. (2024) and it responds to the call by Karwat and Franzke (2021), also 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 intraregional heterogeneity, for which more data and research are 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 modeling (1) and health impact assessment (2) are linked to project health outcomes of predefined scenarios (3) that, in a final step, are monetized (4) (Fig. 1).

Our study applies novel regionalized exposure-response functions (ERFs) 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 Fig. 2) to which reference ERFs (identified for each zone) are applied to estimate and project heat-related premature CPD mortality rates.

The average number of summer cooling degree-days at the NUTS2 level has been used to stratify NUTS2 regions (cf. appendix A, Table A1) according to heat stress. Data on cooling degree-days (CDDs) for 2006–15, corresponding to the years of exposure data, provide 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 NUTS2 regions of the EU27, EEA,[1] western Balkans,[2] United Kingdom, 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, offer a baseline for gauging the economic impacts from increased CPD mortality of future warming.

Based on results from regional climate modeling (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 the impacts of the two individual years in each decade (2030s, 2040s) where the climate modeling results indicate peaks in temperatures. We consider these to be heat wave 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 Organisation for Economic Co-operation and

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

[2] The six countries of the 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 heat wave 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–September), where the average 24-h daily temperature exceeds the reference city minimum mortality temperature (cf. Table 1).

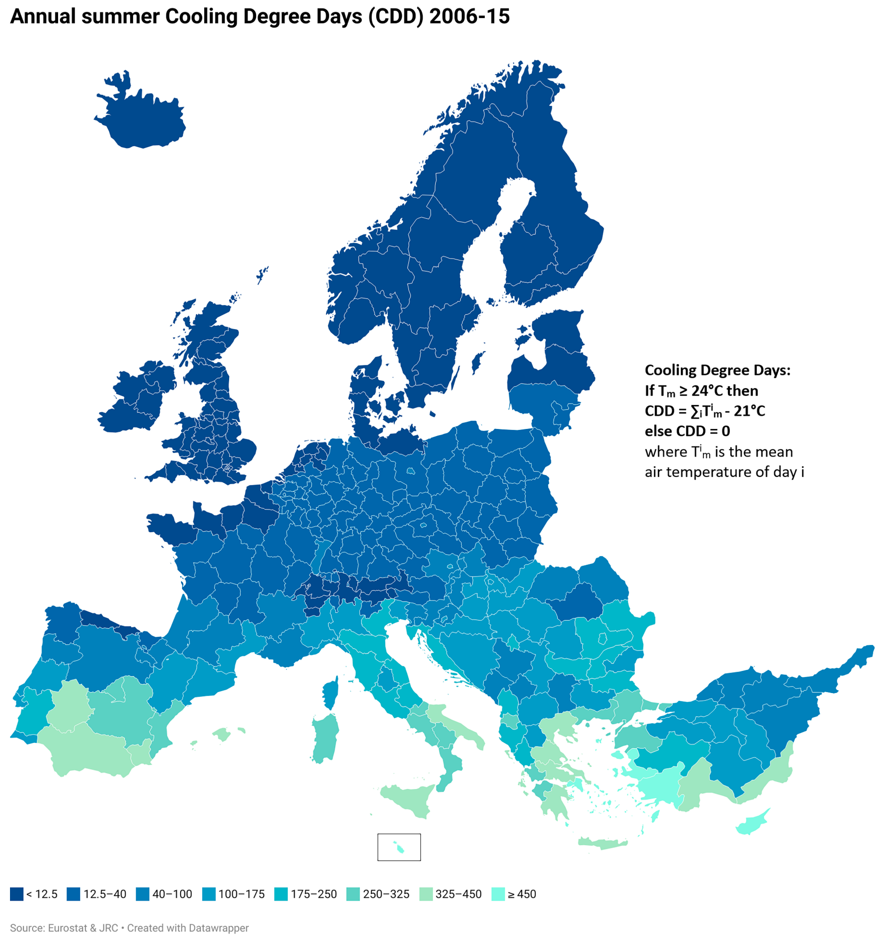

FIG. 2. NUTS2 regions stratified into eight heat stress zones based on average annual summer CDDs 2006–15 (Source: Eurostat and JRC). Table A1 provides a listing.

Development (OECD) guidelines on mortality valuation (OECD 2012). Costs are expressed as a share of national GDP.

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 nonaccidental causes (ICD-9 and ICD-10 codes) in overlapping periods centering around 2000–15 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 Multicity (MCC) Collaborative Research Network database (https://mccstudy.lshtm.ac.uk/). ERFs between temperature and mortality accounting for nonlinearity and lagged effects were specified with a distributed lag nonlinear model, using a parameterization previously used in multicountry 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 Fig. 2). In Europe, the CDD metric accounts for days with mean temperatures that exceed 24°C, assigning a minimum score of 3 for such days $(24 - 21 = 3)$. CDD metrics better capture variabilities in daily mean temperatures than simple averages. The United Kingdom and Germany, for instance, have the same average temperatures,

TABLE 1. Reference cities for projections; years of data, MMT identified, and annual average CDDs (source: Schneider et al. 2023; Eurostat 2023).

	ERF-data years	Population	MMT (°C)	Annual average CDD 2006–15
Athens	2007–16	3 190 000	23.1	585
Palermo	2006–15	670 000	21.3	374
Madrid	2009–13	6 380 000	21.8	294
Rome	2006–15	2 860 000	22.0	233
Lisboa	2004–18	2 810 000	18.7	156
Lyon	2007–15	1 810 000	23.1	51
Paris	2007–15	2 210 000	21.1	25
Helsinki	1994–2014	1 590 000	19.0	4

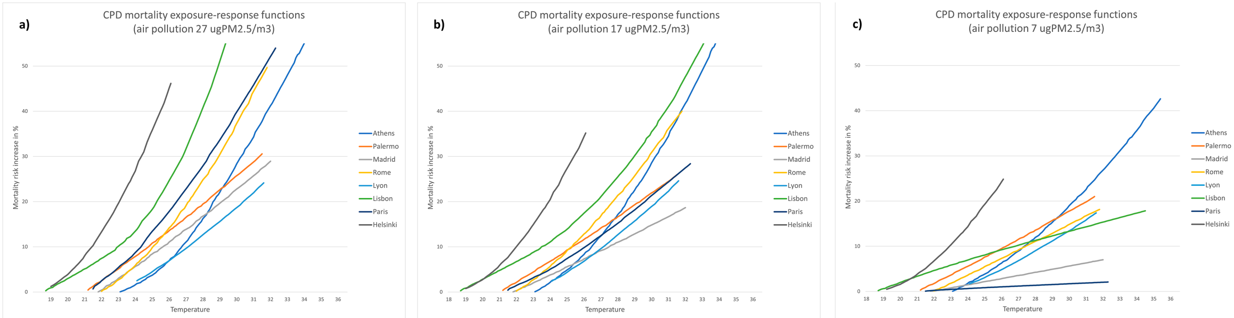

FIG. 3. (a)–(c) Exposure-response functions for CPD mortality risk relative to temperature (°C). (a) 27 μg $PM_{2.5}$ m^{-3}. (b) 17 μg $PM_{2.5}$ m^{-3}. (c) 7 μg $PM_{2.5}$ m^{-3}.

but Germany has more days at the extreme end of the scale than the United Kingdom, 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 Figs. 3a–c). 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).

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°, 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 10 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.

The resulting ERFs are applied in eight respective heat stress zones across Eurostat's NUTS2 regions (cf. Fig. 2). The spatial allocation of regions into these heat stress zones is based on their summer period CDD scores (see Fig. 2 for the ranges). Detailed climate projections up to midcentury 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 2045–49, respectively, and two further scenarios selecting the highest annual CDD in each of the two decades, the 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 the national level only, we used the classifications of urbanization classes at the NUTS2 level to estimate their approximate share for each region (Eurostat 2020). As rural areas are defined as entities where less than 20% live in cities, while intermediate areas are defined as entities where at least 50% but no more than 80% 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 the 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 United Kingdom, they are from its Office for National Statistics. The analysis factors in population growth and ageing, based on regional projections from Eurostat and the abovementioned 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 a polar stereographic projection centered on 60°N, and up to 10 hPa with

54 vertical layers. The study domain covers continental Europe at 25°–72°N, 25°W–45°E. 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 needed by the WRF preprocessor, we have modified and used the cam_to_wps utility available online (https://github.com/shortwavetrough/cam_to_wps). Boundary conditions of 3D temperature, humidity, horizontal winds, and geopotential height are updated every 6 h 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 the western Balkans, along with the United Kingdom and 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 the 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 (25 km × 25 km) Agri4Cast database of the JRC (2023) since Eurostat CDD data do not cover this period.

Out of the SSPs scenarios, SSP2 describes medium socioeconomic 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 socioeconomic 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 preassigned. 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 twenty-first century cause the OECD and the World Bank to refrain from economic forecasts extending beyond 2060.

Air pollution data for recent (2021) city-level background concentrations of $PM_{2.5}$ stem from a database hosted by the EEA (2023b), covering EU27, EEA, and the western Balkans. With several cities of each NUTS2 region included, we calculated averages weighted by population numbers. For the United Kingdom, we rely on the most recently published data from the U.K. 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 metareview of international literature, the OECD (2012) identified and recommended an average VSL of USD 3.6 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 2023b), subject to an income elasticity of 0.8, we find an updated average EU27 VSL of EUR 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 the OECD. The exchange rate in 2005 was USD 1.22/EUR (PPP adjusted). Real GDP per capita figures from Eurostat for country-level adjustment of VSL generally refer to 2022, though to 2019 for the United Kingdom, 2020 for Switzerland and North Macedonia, and 2021 for Albania. We developed our 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 (2023b), UN Population Division (2022), OECD (2021), and from national statistical institutes of non-EU/EEA countries (Republic of Albania Institute of Statistics 2014; Statistical Office of the Republic 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, United Kingdom, and Türkiye. Economic projections for the western Balkans, Croatia, Malta, and Cyprus are from the World Bank (2023a).

3. Results

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 subsection, 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 Figs. 3a–c 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, Figs. 4a–f 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 the 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 midcentury (2045–49) (see Figs. 4c,d), 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 found in Hungary. By midcentury, 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 heat-wave-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 modeling indicates how even in near future, some regions could experience strong heat waves in specific years, and that summer warming will intensify further as we approach midcentury. Figures 4e and 4f show how four of the above NUTS2 regions (e.g., Craiova, Plovdiv, Skopje, Novi Sad) within the next 10 years, i.e., by the early 2030s, should expect to see heat-wave-related CPD fatalities above 60 per 100 000, 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 heat-wave-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 heat waves. As for the United Kingdom, our modeling 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 toward midcentury*

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 5000 annual fatalities 35 years ago, it is projected to increase to about 14 900 within the next decade, with 1600 more toward midcentury—peaking up to about 20 700 in these five countries alone, when considering individual heat wave 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 3500 within the next decade—and a further 1400 by midcentury. The total EU27 annual average will more than double from 6200 in 1990 to 17 900 by midcentury—peaking at up to 26 000 when considering individual heat wave years across regions.

The six countries of the western Balkans have seen a doubling from about 1000 to 2000 fatalities from 1990 to the present and are projected to experience a further increase to 2500 by midcentury—peaking at 3500 in heat wave years.

EEA countries Norway and Switzerland that previously hardly experienced heat-related CPD fatalities will by midcentury be likely to experience large relative increases (compared to the present), as shown in Fig. 5. Within the EU27, large ratio changes (>10) can be expected for Cyprus and Slovenia. The ratio change will also be considerable in individual heat wave 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 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 midcentury, exceeding 2.5% of annual GDP, is 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% of annual GDP. In fact, they are all expected to exceed that level within the next decade. However, for heat wave years by midcentury, costs are estimated to peak at above 3.5% of annual GDP in Serbia, Northern Macedonia, Cyprus, and Malta, with costs in Bosnia-Herzegovina going above 2.5% (as shown in Fig. 6). In Croatia, along with Hungary and Greece, they

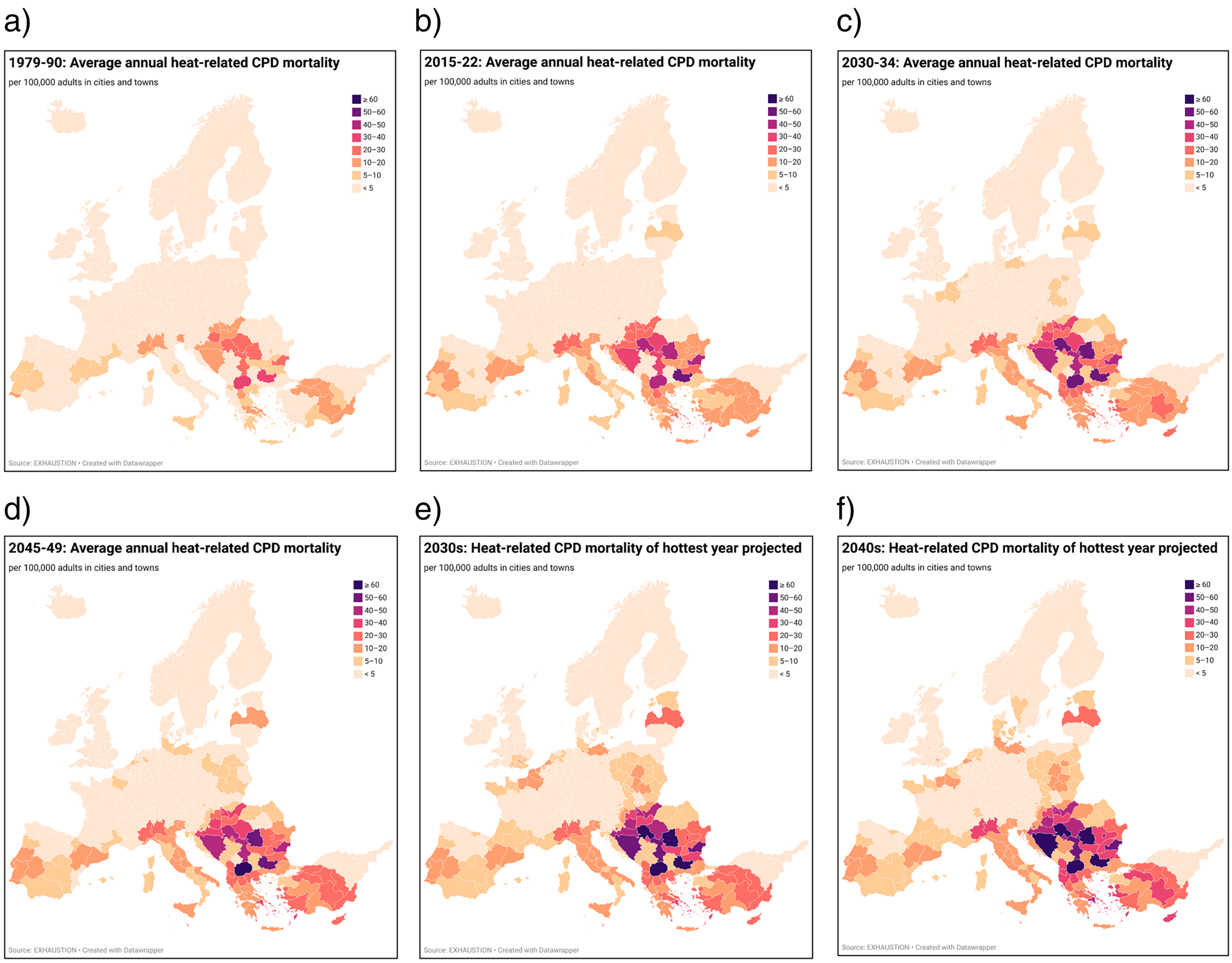

FIG. 4. (a)–(c) Heat-related CPD mortality per 100 000 adults in cities and towns (SSP245). (a) Baseline (1979–90). (b) Recent past (2015–22). (c) Short-term scenario (2030–34). (d)–(f) Heat-related CPD mortality per 100 000 adults in cities and towns (SSP245). (d) Midcentury scenario (2045–49). (e) *Heat wave scenario 2030s. (f) *Heat wave scenario 2040s. (*specific year varies by region).

will exceed 1.8%. Figure 6 provides the accumulated changes, with the sum of the GDP share indicated always with reference to the respective period (i.e., middecade estimates of GDP for the 2030s and 2040s).

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 Fig. 5), even if fatalities are valued relatively more due to citizen's higher levels of income. Costs generally do not exceed the EU27 average of 0.7% of GDP, except for the United Kingdom 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 EUR 22 billion, followed by Italy at about EUR 19 billion by the 2040s. The highest figures relating to specific heat wave years are found in Türkiye, at EUR 29 billion, and Italy, at EUR 26 billion, followed by a projected heat wave year of the 2030s in the United Kingdom at EUR 15 billion.

The EU27 is facing average annual welfare economic costs attributable to heat-related CPD premature mortality in the range of EUR 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 EUR 80–99 billion when considering and summing maximum impact years per decade across NUTS2 regions.

d. Adaptation with air pollution abatement

It is evident from the exposure-response functions identified with our dataset (see Fig. 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)

TABLE 2. Estimated annual heat-related CPD fatalities in urban areas. The # indicates imputed climate projections; * indicates annual fatalities during the summer period (May–September) among adults in cities; ** indicates the sum of 1-yr maximum decadal heat spell fatalities of all individual NUTS2 regions, notwithstanding specific year.

	Fatalities					
Country	1979–90* (historical)	2015–22* (recent)	2030–34* (next decade)	2045–49* (midcentury)	Max 2030s**	Max 2040s**
Cyprus (EU)	10	103	134	158	154	209
Italy (EU)	2193	4895	6121	6260	6907	7675
Malta (EU)	16	68	90	107	108	131
Portugal (EU)	245	531	548	563	750	763
Spain (EU)	732	1698	1899	2024	2291	2315
w-Türkiye	785	3679	3879	5066	4871	6434
Albania	67	234	306	314	348	400
Bosnia-H.#	237	432	546	539	700	824
Bulgaria (EU)	413	787	824	882	1038	1143
Croatia (EU)	188	389	536	536	631	754
Greece (EU)	412	1120	1279	1420	1609	1679
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	1275	1542	1657	2015	2335
Serbia	390	808	1015	1020	1310	1534
Austria (EU)	113	219	274	287	324	370
Czechia (EU)	20	81	119	131	196	211
Hungary (EU)	712	1185	1433	1509	1858	2024
Lithuania (EU)	5	12	14	22	28	33
Poland (EU)	136	463	770	1033	1465	1675
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	1428	1335
Germany (EU)	129	499	754	901	1241	1535
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
United Kingdom	12	365	670	434	2715	1700
EU27 sum	6191	14 391	17 933	19 285	(23 662)	(26 113)
All countries, sum	8025	20 483	25 045	27 417	(34 475)	(37 923)

recommends aiming for an exposure level not higher than 5 μg $PM_{2.5}$ m^{-3} to reduce health impacts and premature mortality (WHO 2021b). Only 10 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 μg $PM_{2.5}$ m^{-3} in urban background (see Fig. 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 by about 7500, down from

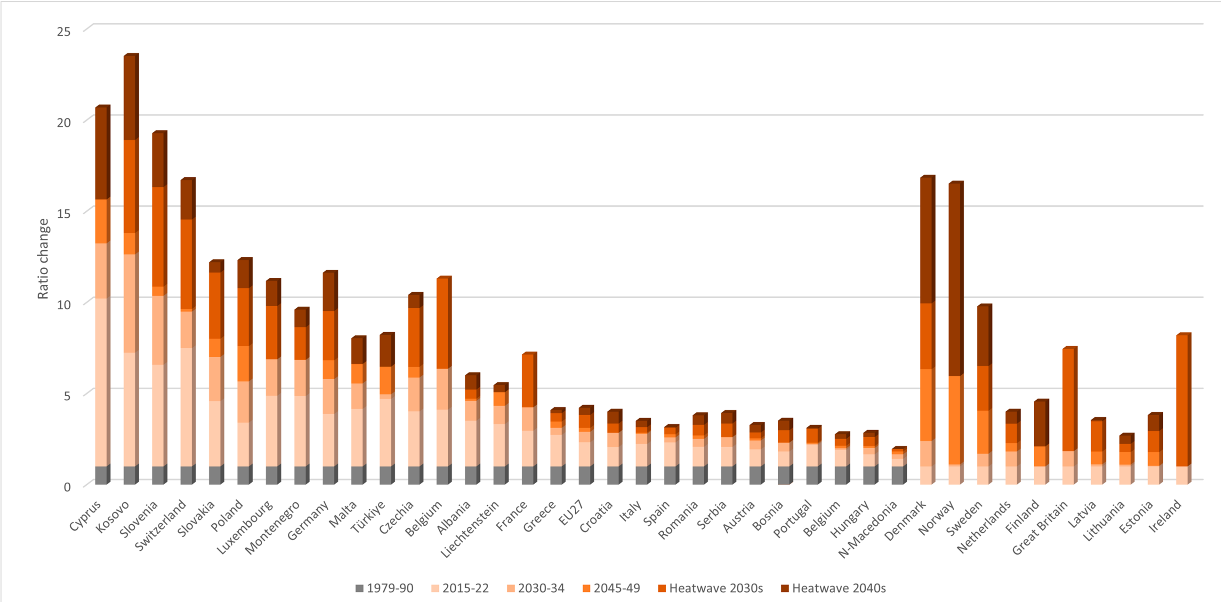

FIG. 5. Ratio change with respect to heat-related CPD fatalities in cities and towns among adults (>25 years) attributable to post-1990 global warming (SSP245) in countries of EU27, EEA, western Balkans, and Türkiye. For Nordic and Baltic countries, plus the Netherlands, Ireland, and the United Kingdom,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

the projection of annually about 19–21 000 to about 12–13 000 in these countries (cf. Tables 2 and 4). In other words, with 2021 levels of air pollution maintained in this region, the number of CPD fatalities would be about 50% 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.

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 μg

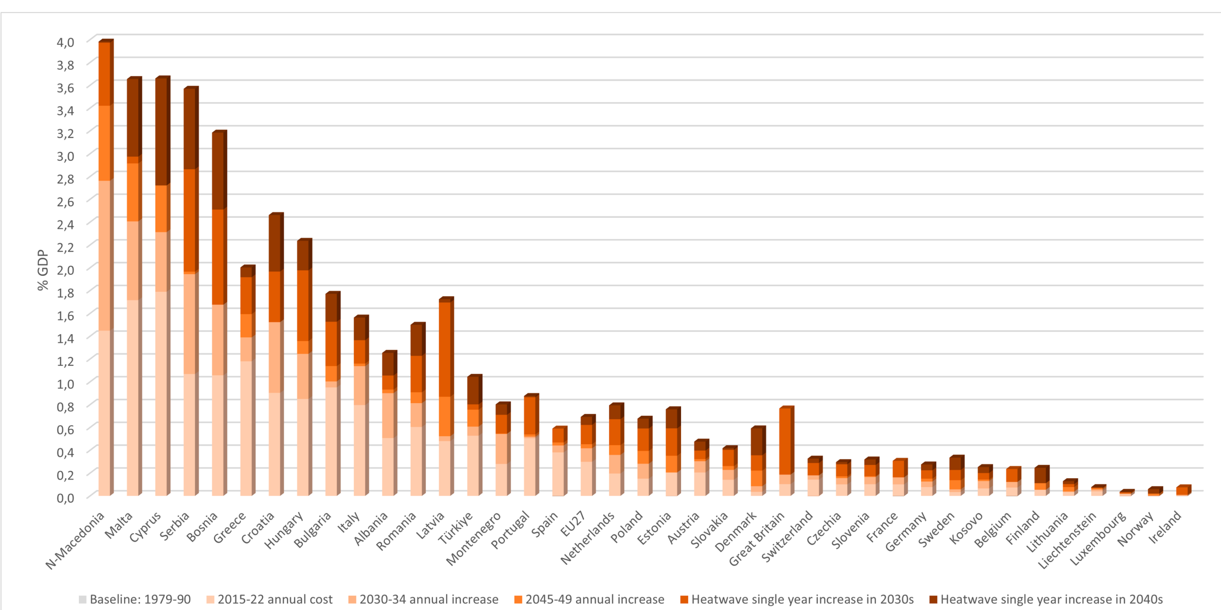

FIG. 6. Annual costs of CPD fatalities in cities and towns among adults (>25 years) attributable to post-1990 increasing summer heat (SSP245) relative to national GDP in countries of EU27, EEA, western Balkans, plus Türkiye and the United Kingdom (including Northern Ireland)—adjusted for population changes and projected economic growth.

TABLE 3. Annual welfare economic costs above pre-1990 baseline of heat-related CPD fatalities. The # indicates imputed CDD; * indicates the sum of the maximum decadal heat spell costs of all individual NUTS2 regions, notwithstanding the specific year.

	Costs				
Country	2015–22 (M€)	2030–34 (M€)	2045–49 (M€)	Max 2030s* (M€)	Max 2040s* (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	1,934	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
United Kingdom	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

$PM_{2.5}$ 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; Díaz 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). The study by Lüthi 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

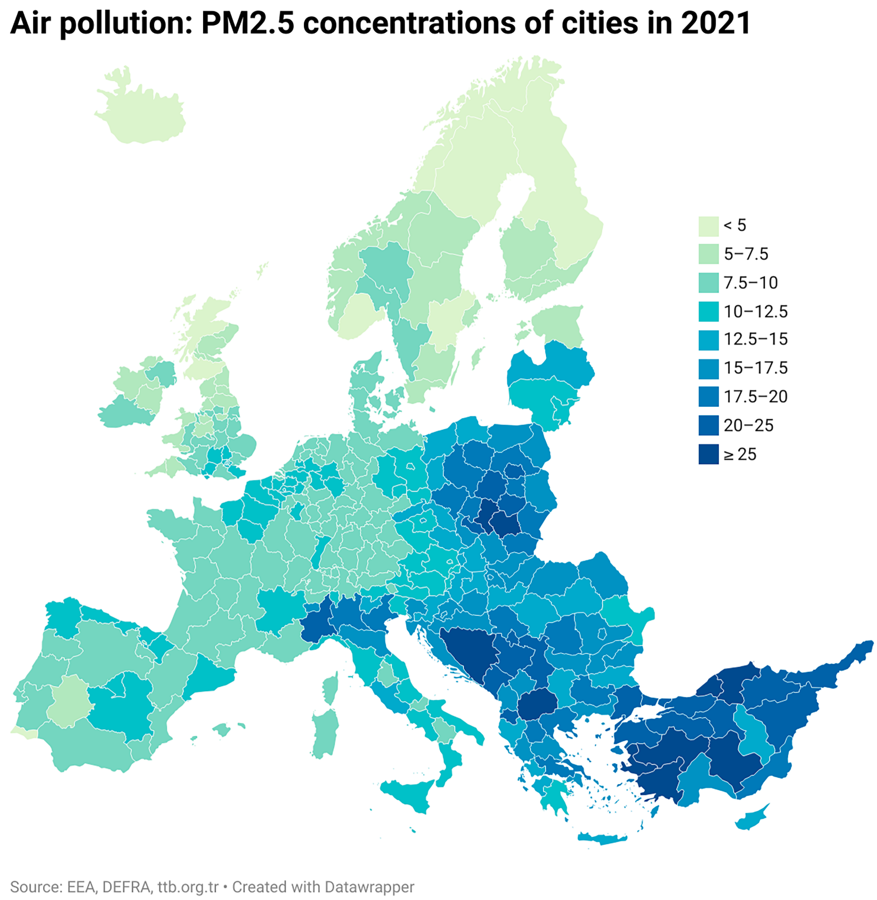

FIG. 7. Background concentrations with particles (μg m^{-3} of $PM_{2.5}$) in cities and towns.

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 ERFs 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 ERFs may overestimate impacts on smaller cities, even if this is mitigated by our CDDs having been calculated at the 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 interregionally, 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 are there 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 the United States and Japan.

Differences in preexisting adaptation policies introduced in some of the reference cities are a further source of heterogeneity. Even if we rely on data from a relatively early period, the 2003 heat wave 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 2021a), 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 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 20 years, yet very little is known about the extent to which AC is able to mitigate the mortality

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 $\mu g\ m^{-3}$. Asterisks indicate the sum of 1-yr maximum decadal heat spell fatalities of all individual NUTS2 regions, notwithstanding specific year.

	Fatalities with $PM_{2.5} < 5\ \mu g\ m^{-3}$				
Country	2030-34 (annual)	2045-49 (annual)	Max 2030s* (1 year)	Max 2040s* (1 year)	Midcentury annual fatality reduction (%)
Cyprus (EU)	107	126	123	166	20
Italy (EU)	3493	4175	4564	5072	33
Malta (EU)	83	98	99	120	8
Portugal (EU)	530	543	725	744	4
Spain (EU)	1480	1522	1729	1777	25
w-Türkiye	2.165	2748	2676	3503	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	1024	39
Kosovo	20	22	30	38	38
Montenegro	11	11	13	15	40
N Macedonia	277	298	311	334	50
Romania (EU)	1082	1160	1378	1572	30
Serbia	636	643	805	935	37
Sum	11 882	13 462	14 910	16 927	37

impacts of heat spells (IEA 2018). From 2006 to 2015, the period that our mortality data refer to, AC ownership in Italy already averaged 30% (ISTAT 2021), yet our data demonstrate 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 3 times higher than the average (Henderson et al. 2022).

Davis et al. (2021) show how annual household incomes of about USD 10,000, corresponding to EUR 9,000, constituted an affordability threshold for installation of AC in Italy, 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 midcentury, 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.

TABLE 5. Annual disposable household income in euros 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)].

	Bulgaria	Croatia	Italy (South)	Romania
2030–35	€2,361–2,923	€4,425–4,736	€7,392–8,882	€1,323–3,609
2045–49	€4,310–7,388	€6,901–7,096	€8,598–10,252	€2,137–5,830

The exposure-response functions from heat spells derived from our data (Fig. 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 heat wave, for which 70 000 deaths across Europe have been estimated by a consortium of national statistical agencies. They provide a breakdown of this figure at the 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 in 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°C in Ballester et al. (2023) presumably contributes 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 2015–22, as the minimum mortality temperature identified with statistical significance in this study is well above 18° in most of southern Europe (cf. Table 1). Hence, our estimate of all-cause deaths is about 5000 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 socioeconomic 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 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. 2022), 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 the western Balkans and Türkiye. Measured against GDP, there will be large variations, with the EU27 average at 0.4% of total GDP, while 10 European countries will suffer casualties corresponding to costs well above 1% 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.

Acknowledgments. Funding by the European Union is acknowledged through the project EXHAUSTION, supported by the Horizon 2020 program (Grant 820655). We are grateful for the comments and suggestions from the journal's two anonymous reviewers.

Data availability statement. Data analyzed in this study were largely a reanalysis 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

Table A1 shows a full listing of NUTS2 regions of the European Union and partner countries, and their classification into heat stress zones. The NUTS classification is made up of three hierarchical levels: each country is divided into NUTS 1 regions, which in turn are subdivided into NUTS 2 regions and then divided further into NUTS 3 regions. Each of these regions is allocated a specific code. Some regions appear at more than one level (for example: Luxembourg appears as the country and also for NUTS levels 1, 2, and 3). In such cases, the codes end in zero for a region with an identical territory at the next lower level (Eurostat 2020).

TABLE A1. Inventory of NUTS2 regions classified into heat stress zones, based on reference city ERFs. Implemented in Fig. 2 of the main text. 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; U.K. = United Kingdom; XK = Kosovo.

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; U.K.-all

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 multimodel ensemble simulations based on CMIP5 scenarios (Jacob et al. 2014, p. 20). We focused specifically on the annual maximum temperature (TXx). For consistent 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 RCP2.6 and RCP4.5 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 5th%–95th% 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. B1), 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. B1e). 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. B1). The differences range from 0.9° to 3.2°C across different zones, with the largest differences in the North (Fig. B1e) and the smallest in the South (Fig. B1b). 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.

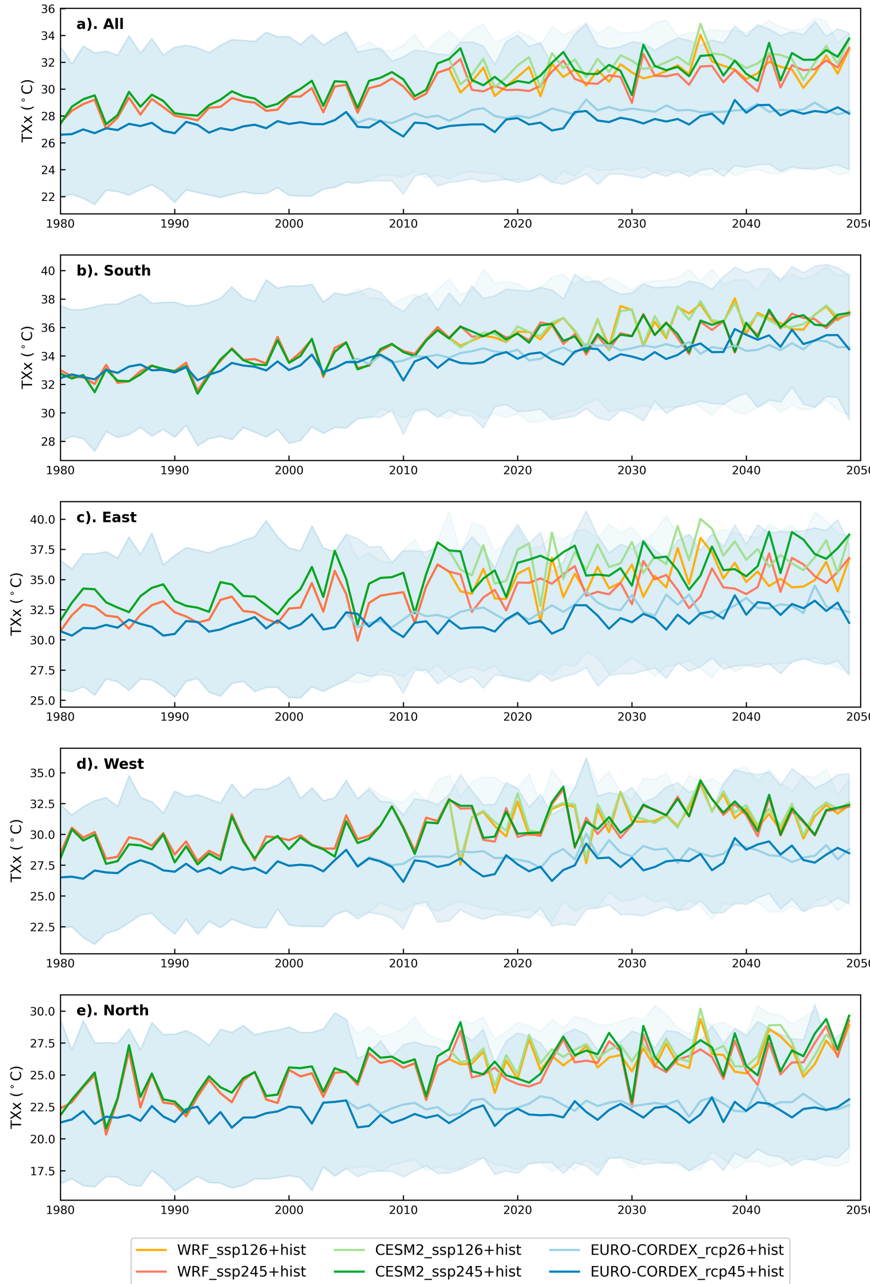

FIG. B1. Interannual variability of region-mean annual maximum temperature (TXx; °C) across the continental Europe and various European climate zones. The data are derived from historical (WRF_CESM2) and future (WRF_ssp126 and WRF_ssp245) simulations from WRF, CESM2 historical and future (CESM2_ssp126 and CESM2_ssp245) simulations, and the EURO-CORDEX ensemble median for historical and future RCP2.6 and RCP4.5 scenarios. The shaded regions represent the interquartile range (5th–95th percentile) of the EURO-CORDEX ensemble, illustrating the spread.

REFERENCES

ADEME, 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? *Ecol. Indic.*, **79**, 11–18, https://doi.org/10.1016/j.ecolind.2017.03.051.

Baccini, M., and Coauthors, 2008: Heat effects on mortality in 15 European cities. *Epidemiology*, **19**, 711–719, https://doi.org/10.1097/EDE.0b013e318176bfcd.

Ballester, J., and Coauthors, 2023: Heat-related mortality in Europe during the summer of 2022. *Nat. Med.*, **29**, 1857–1866, https://doi.org/10.1038/s41591-023-02419-z.

Carleton, T., and Coauthors, 2022: Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Quart. J. Econ.*, **137**, 2037–2105, https://doi.org/10.1093/qje/qjac020.

Chitu, Z., R. Bojariu, L. Velea, and B. Van Schaeybroeck, 2023: Large sex differences in vulnerability to circulatory-system disease under current and future climate in Bucharest and its rural surroundings. *Environ. Res.*, **234**, 116531, https://doi.org/10.1016/j.envres.2023.116531.

Cromar, K. R., and Coauthors, 2022: Global health impacts for economic models of climate change: A systematic review and meta-analysis. *Ann. Amer. Thorac. Soc.*, **19**, 1203–1212, https://doi.org/10.1513/AnnalsATS.202110-1193OC.

Davis, L., P. Gertler, S. Jarvis, and C. Wolfram, 2021: Air conditioning and global inequality. *Global Environ. Change*, **69**, 102299, https://doi.org/10.1016/j.gloenvcha.2021.102299.

DEFRA, 2023: UK AIR background mapping data for local authorities. Accessed 19 December 2023, https://uk-air.defra.gov.uk/data.

Díaz, J., M. Sáez, R. Carmona, I. J. Mirón, M. A. Barceló, M. Y. Luna, and C. Linares, 2019: Mortality attributable to high temperatures over the 2021–2050 and 2051–2100 time horizons in Spain: Adaptation and economic estimate. *Environ. Res.*, **172**, 475–485, https://doi.org/10.1016/j.envres.2019.02.041.

EEA, 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.

——, 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: NUTS and Statistical Regions 2021: 2020 Edition.* Publications Office of the European Union, 196 pp.

——, 2021: *Applying the Degree of Urbanisation.* Publications Office of the European Union, 102 pp.

——, 2023: Online database. Accessed 31 January 2025, https://ec.europa.eu/eurostat/web/main/data/database.

——, 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., and Coauthors, 2020: Climate change impacts and adaptation in Europe. JRC PESETA IV Final Rep. JRC119178, EUR30180EN, 71 pp., https://publications.jrc.ec.europa.eu/repository/handle/JRC119178.

Gasparrini, A., and Coauthors, 2015: Temporal variation in heat–mortality associations: A multicountry study. *Environ. Health Perspect.*, **123**, 1200–1207, https://doi.org/10.1289/ehp.1409070.

——, and Coauthors, 2017: Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet. Health*, **1**, E360–E367, https://doi.org/10.1016/S2542-5196(17)30156-0.

——, B. Armstrong, and M. G. Kenward, 2010: Distributed lag non-linear models. *Stat. Med.*, **29**, 2224–2234, https://doi.org/10.1002/sim.3940.

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/.

Henderson, S. B., K. E. McLean, M. J. Lee, and T. Kosatsky, 2022: Analysis of community deaths during the catastrophic 2021 heat dome. *Environ. Epidemiol.*, **6**, e189, https://doi.org/10.1097/EE9.0000000000000189.

Honda, Y., and Coauthors, 2014: Heat-related mortality risk model for climate change impact projection. *Environ. Health Prev. Med.*, **19**, 56–63, https://doi.org/10.1007/s12199-013-0354-6.

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. *Nat. Commun.*, **14**, 7438, https://doi.org/10.1038/s41467-023-43135-z.

Huang, Z., J. Lim, and M. Skidmore, 2024: The impacts of heat and air pollution on mortality in the United States. *Wea. Climate Soc.*, **16**, 275–301, https://doi.org/10.1175/WCAS-D-23-0001.1.

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. Serv.*, **7**, 78–86, https://doi.org/10.1016/j.cliser.2016.10.004.

IEA, 2018: *The Future of Cooling.* OECD/IEA Publishing, 92 pp.

Ignjacevic, P., W. Botzen, F. Estrada, H. Daanen, and V. Lupi, 2024: Climate-induced mortality projections in Europe: Estimation and valuation of heat-related deaths. *Int. J. Disaster Risk Reduct.*, **111**, 104692, https://doi.org/10.1016/j.ijdrr.2024.104692.

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

ISTAT, 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. *Reg. Environ. Change*, **14**, 563–578, https://doi.org/10.1007/s10113-013-0499-2.

Jones-Lee, M. W., 1989: *The Economics of Safety and Physical Risk.* Basil Blackwell, 318 pp.

JRC, 2023: AGRI4CAST resources portal. Accessed 20 November 2023, https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx?o=d.

Karwat, A., and C. L. E. Franzke, 2021: Future projections of heat mortality risk for major European cities. *Wea. Climate Soc.*, **13**, 913–931, https://doi.org/10.1175/WCAS-D-20-0142.1.

Katsouyanni, K., A. Pantazopoulou, G. Touloumi, I. Tselepidaki, K. Moustris, D. Asimakopoulos, G. Poulopoulou, and

D. Trichopoulos, 1993: Evidence for interaction between air pollution and high temperature in the causation of excess mortality. *Arch. Environ. Health*, **48**, 235–242, https://doi.org/10.1080/00039896.1993.9940365.

Kendrovski, V., M. Baccini, G. S. Martinez, T. Wolf, E. Paunovic, and B. Menne, 2017: Quantifying projected heat mortality impacts under 21st-century warming conditions for selected European countries. *Int. J. Environ. Res. Public Health*, **14**, 729, https://doi.org/10.3390/ijerph14070729.

Kenney, W. L., D. H. Craighead, and L. M. Alexander, 2014: Heat waves, aging, and human cardiovascular health. *Med. Sci. Sports Exercise*, **46**, 1891–1899, https://doi.org/10.1249/MSS.0000000000000325.

Lüthi, S., and Coauthors, 2023: Rapid increase in the risk of heat-related mortality. *Nat. Commun.*, **14**, 4894, https://doi.org/10.1038/s41467-023-40599-x.

Masselot, P., and Coauthors, 2023: Excess mortality attributed to heat and cold: A health impact assessment study in 854 cities in Europe. *Lancet Planet. Health*, **7**, E271–E281, https://doi.org/10.1016/S2542-5196(23)00023-2.

Newman, R., and I. Noy, 2023: The global costs of extreme weather that are attributable to climate change. *Nat. Commun.*, **14**, 6103, https://doi.org/10.1038/s41467-023-41888-1.

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

——, 2021: Long-term baseline projections. Economic Outlook #109. 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. *Environ. Impact Assess. Rev.*, **15**, 421–442, https://doi.org/10.1016/0195-9255(95)00044-F.

Rennert, K., and Coauthors, 2022: Comprehensive evidence implies a higher social cost of CO_2. *Nature*, **610**, 687–692, https://doi.org/10.1038/s41586-022-05224-9.

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

Robine, J.-M., S. L. K. Cheung, S. Le Roy, H. van Oyen, C. Griffiths, J.-P. Michel, and F. R. Herrmann, 2008: Death toll exceeded 70,000 in Europe during the summer of 2003. *C. R. Biol.*, **331**, 171–178, https://doi.org/10.1016/j.crvi.2007.12.001.

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

Skamarock, W. C., and Coauthors, 2019: Description of the Advanced Research WRF Model version 4. NCAR Tech. Note NCAR/TN-556+STR, 145 pp. https://doi.org/10.6084/m9.figshare.7369994.v4.

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

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

UN 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.

WHO, 2021a: Heat and health in the WHO European Region: updated evidence for effective prevention. WHO Regional Office for Europe Rep., 190 pp., https://www.humanitarianlibrary.org/resource/heat-and-health-who-european-region-updated-evidence-effective-prevention.

——, 2021b: WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. WHO guidelines Rep., 300 pp., https://www.who.int/publications/i/item/9789240034228.

WMO, 2023: Guidelines on the definition and characterization of extreme weather and climate events. WMO/TD 1310, 36 pp., https://rcc.dwd.de/DWD-RCC/EN/overview/documents/01_wmo_guidelines.pdf?__blob=publicationFile&v=3.

World Bank, 2023a: Toward sustainable growth. Western Balkans Regular Economic Rep. 24, 116 pp., https://documents1.worldbank.org/curated/en/099101623051741490/pdf/P50064801939bc0a00a0d2077a3883b52c9.pdf.

——, 2023b: Indicators. Accessed 3 November 2022, https://data.worldbank.org/indicator/.

Yamineva, Y., and S. Romppanen, 2017: Is law failing to address air pollution? Reflections on international and EU developments. *RECIEL*, **26**, 189–200, https://doi.org/10.1111/reel.12223.

Yin, B., Y. Chen, and X. Xu, 2024: How does temperature change affect residents' health? A multidimensional health perspective. *Wea. Climate Soc.*, **16**, 723–738, https://doi.org/10.1175/WCAS-D-24-0041.1.

Zhang, S., and Coauthors, 2023: Assessment of short-term heat effects on cardiovascular mortality and vulnerability factors using small area data in Europe. *Environ. Int.*, **179**, 108154, https://doi.org/10.1016/j.envint.2023.108154.