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Climate-induced mortality projections in Europe: Estimation and valuation of heat-related deaths

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ABSTRACT

Extreme heat is becoming more prevalent in Europe and its localized impacts on human health in urban environments are difficult to project. Our main objective was to develop a local-scale integrated assessment model (IAM) to explore the impacts of global warming on heat-related mortality in Europe, with a focus on urban areas. Using the apparent temperature metric, we develop several risk frameworks to project heat-related deaths and help policymakers evaluate future extreme heat risk. We also compute the monetary impact of expected deaths using the value of statistical life. Our results show that the compliance with the Paris agreement targets would limit the cumulative losses during this century to 2.6 million people, compared to almost 5.5 million under alternative climate scenarios. Our analysis suggests that Europe could save more than €150 billion annually through avoided heat-related mortality. We also focus on the relationship between heath-induced mortality and population concentration in urban areas. Limiting the urban heat island effect in compliance with the Paris agreement emissions reduction would lower the number of deaths by up to 40%.

1. Introduction

The balance of ambient temperature is a crucial factor for the survival of all the species on Earth. Anthropogenic climate change is accelerating the rise in temperature and the frequency of heat-waves, increasing the heat-stress and the ecological concerns [1]. Human beings can adapt to climate change and prevent heat-related mortality through, for example, acclimatization[1] and air conditioning [5,6]. However, the effect of such adaptation measures on future excess heat-mortality, has scarcely been evaluated on a local scale under varying climate scenarios. Therefore, policymakers at the national and local level are calling for risk estimations

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[1] Acclimatization is the process by which an organism (e.g. human body) adjusts to a change in its environment. Todd and Valleron [2] find that an increase in 1.6 °C in France led to an increase in the minimum mortality temperature (MMT) by 0.8 °C between 1986 and 2009, suggesting that, in similar climates, humans could acclimatize to about half of the temperature increase. Dessai [3] assume complete acclimatization after three decades to an extra 1 °C warming whereas Kovats et al. [4] assume 0.5 °C for the same time span. Both studies introduce adaptation into the model by increasing the temperature threshold h_i for every 30-year period.

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and evaluation of adaptation plans. To this end, new metrics to measure costs and benefits of such policies are needed. With this study, we aim model the relationship between temperature and excess heat-related mortality under a variety of future climate and socioeconomic scenarios. Our methodology accounts for climate uncertainty, the city-cell scale variability in temperature projections[2] and the impacts on the exposed population. Our framework provides monetized projections of climate change-induced life losses under several scenarios, which could be used as input for cost–benefit analysis of environmental policies.

Previous literature studied the correlation between heat extremes and excess mortality, which adversely affects the most disadvantaged and fragile part of the population, such as the elderly [7–10]. Some works combine meteorological data sourced from stations in Europe with mortality statistics, generating exposure-response relationships [11–13]. Other recent papers estimate the relationship between temperature and mortality using spatially disaggregated data and scaling-up temperature-related deaths. In particular, Vicedo-Cabrera et al. [14] use empirical data from 732 locations in 43 countries during the period 1991–2018, concluding that about 37% of warm-season heat-related deaths can be attributed to anthropogenic climate change. Burkart et al. [15] use the International Classification of Disease-coded deaths from nine countries, estimating that, globally, 1.69 million of people died due to non-optimal temperatures in 2019. Finally, Zhao et al. [16] use deaths from 43 countries in the period 2000–2019, finding that the mortality-temperature relationship is geographically heterogeneous and that in the long-run climate change is expected to worsen the mortality burden. A smaller body of literature focuses on the impacts of heat in urban environments, studying the impact of temperature on mortality across cities [17–20].

However, human thermal strain is not only related to temperature but also to humidity, solar radiation and wind speed [21]. Thermal indices measure human body discomfort combining several of such factors [22].[3] Some works investigate the reliability of thermal variables such as humidity, in predicting mortality [24–26]. Fischer and Knutti [27] emphasize that when considering health-related metrics combining temperature and humidity, the uncertainties are reduced compared to when the uncertainties in the two variables are considered independently. Despite such evidence, the recent epidemiological literature is mixed. Armstrong et al. [28] found little association between humidity and mortality in the summer season, while Hajat et al. [29] explicitly take into account humidity to study the temperature-mortality relationship in Middle Eastern and North African countries.

Following Oleson et al. [30] and Hajat et al. [29], we decided on using apparent temperature (AT) index as a driver of our heat-related mortality in our analysis.[4] AT is computed on the basis of two climate variables e.g., temperature and relative humidity.[5] Depending on the AT, the attributable fraction (AF) of deaths increases conditional to the fact that the realized temperature exceeds the region-specific temperature threshold [34]. We believe this methodology is appropriate given our goal is to flexibly generate heat-mortality projections for different climate scenarios on a granular scale across Europe.

Several studies have explored the severity of heat-related impacts using climate scenario analysis. Watkiss and Hunt [35] used the Intergovernmental Panel on Climate Change (IPCC) SRES A2 climate projections and found that heat-related mortality in Europe (EU-27) on a country level is likely to increase, by 2080, in the range of 20,000 and 160,000 deaths. However, the authors stress that future research should consider spatially disaggregated data to differentiate between local impacts. Kendrovski et al. [34] generate heat-related mortality projections for Europe only at the country level, and for two representative concentration pathway (RCP) scenarios, such as RCP 4.5 and RCP 8.5. Vicedo-Cabrera et al. [36] illustrate the importance of the Paris Agreement in limiting the impacts on temperature-related mortality projections using a Multi-Country Multi-City (MCMC) database for 452 locations in 23 countries. Some papers also study temperature-induced mortality within an integrated assessment model (IAM) framework [37–39]. Moreover, Bressler [40] computes the mortality cost of carbon (MCC) using the global DICE-2016 model. Following the same line of research, Rennert et al. [41] improve the estimates of the social cost of carbon (SCC), accounting for the heat-related mortality channel in the damage function for specific scenarios.[6] Compared to previous studies, we provide spatially explicit estimates ($0.5° x 0.5°$) of heat-related mortality projections and associated costs, since adaptation policies for heat can be targeted to the local level, namely areas where heat impacts are the largest. Thus, we develop a spatially explicit and disaggregated IAM model for Europe, which includes also urban-level heterogeneity.

We explore the impacts of temperature and humidity on mortality under different climate and socioeconomic scenarios, including the urban heat island (UHI) effect [43,44]. The UHI occurs when urban areas experience a larger increase in temperatures than rural areas due to the economic activities and the heat-absorption capacity of concrete and asphalt [45,46]. In particular, we introduce such mechanism and feedback effects between local climate and populations within the spatially-explicit IAM, CLIMRISK.[7] We exploit a wide range of climate and socioeconomic projections available for CLIMRISK to account for uncertainties, including probabilistic temperature projections. The result is the CLIMRISK-EUROHEAT model, which helps users estimate climate-induced heat-related mortality in Europe over the course of the 21st century. Thus, the first goal of this paper is contributing to this stream of research, generating local (city level) projections of heat-related mortality under several scenarios to account for uncertainty. The second

[2] Since the majority of the current and future human population is expected to be concentrated in cities, understanding the health consequences of heat-related mortality in cities is crucial to develop adaptation instruments. See also Taylor et al. [7].

[3] The most common indices are the Wet Bulb Globe Temperature described in International Standardization Organization (ISO) document 7243 and the Personal Heat Strain index described in ISO 7933. Recently, the Universal Thermal Climatic Index (UTCI) was developed to provide a single value for heat and cold circumstances Fiala et al. [23].

[4] See also Cheng et al. [31] and Wiru et al. [32].

[5] See also the systematic literature by Ioannou et al. [33]. Note that other climate variables can also affect apparent temperature (for example, solar radiation). However, such projections are not readily available for the time period of our consideration and would lend false precision in projecting a complex climate phenomenon.

[6] See also Cromar et al. [42].

[7] Estrada and Botzen [43].

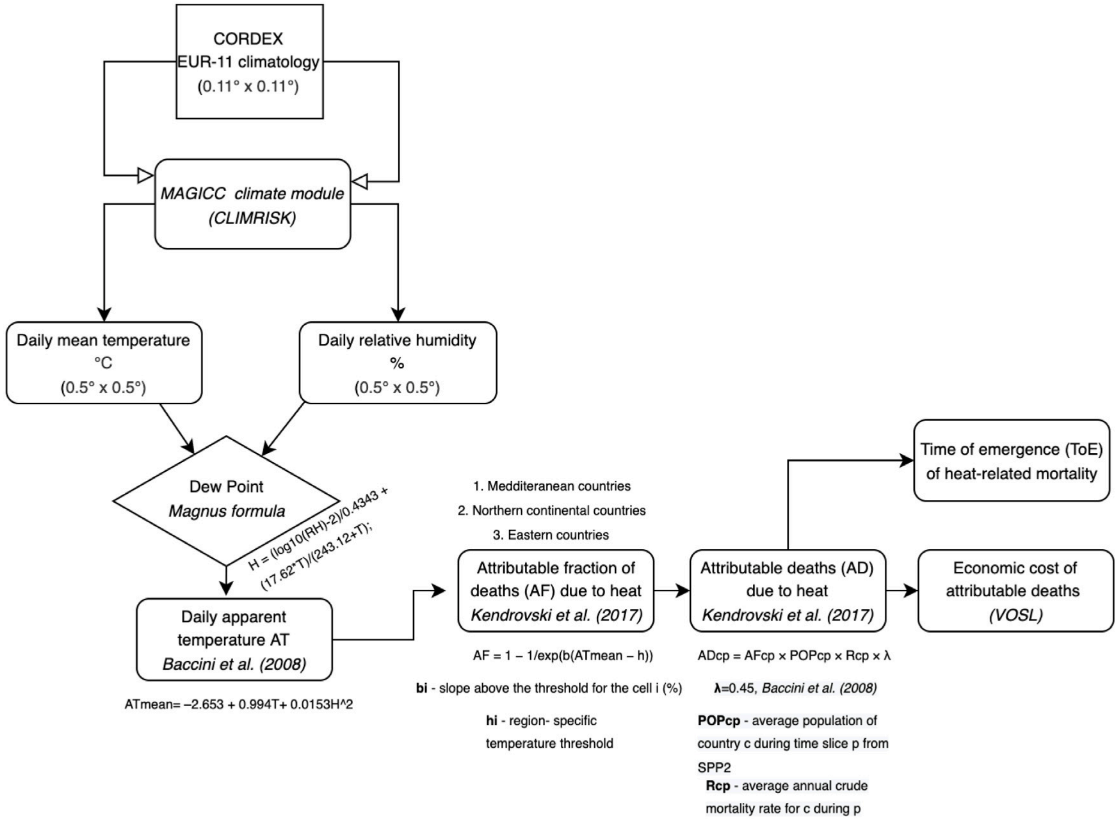

Fig. 1. Main modelling steps for creating the CLIMRISK-EUROHEAT model for generating the heat-related mortality projections presented in this study.

goal, is the integration of local-level temperature-induced mortality projections in the CLIMRISK-EUROHEAT framework. Local-level projections are then coupled with urban-level damage functions, considering the UHI effect [45]. Such values are then used to generate absolute mortality projections with and without UHI, accounting for human acclimatization. Finally, we monetize absolute heat-related mortality using the value of statistical life (VOSL). As a robustness check, we apply the concept of time of emergence (ToE)[8] of heat-related mortality [47] in the context of a recent global health crisis, COVID-19. Our proposed methodology provides the basis for introducing impacts of heat-related mortality in other prominent IAMs.

2. Methodology & data

Fig. 1 presents the main modules of CLIMRISK-EUROHEAT. The methodological flow is drawn from top-to-bottom, and consists of three blocks: (i) climate data (top-half), (ii) heat-related mortality quantification (bottom-left) and (iii) heat-related mortality valuation (bottom-right). While we outline only the high-level methodological steps in this article, the full methodology is available in Appendix A.

First, we use the CORDEX climate projections database[9] to generate estimates of the daily mean temperature and relative humidity for different climate scenarios, with the help of Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) and the CLIMRISK IAM.[10] Here, we use CLIMRISK and MAGICC to generate probabilistic estimates of mean surface-air temperature, which help us proxy other climate variables required for the estimation of daily apparent temperatures (AT).[11]

Next, we generate daily AT estimates using the combination of daily relative humidity and mean temperature projections. In order to achieve this, we use a well-established Magnus formula to get dew point estimates which, in combination with daily temperature, give stylized estimates of apparent temperature.[12]

[8] The ToE concept puts future climate impacts in perspective of other severe impacts or shocks that countries experienced in the past.

[9] See Appendix A.1 for further explanations.

[10] The uncertainties arising from projecting relative humidity estimates in the future are discussed in Appendix A.1. An advantage of CLIMRISK, is that it is able to produce probabilistic climate projections for any RCP-SSP scenario combination at the local scale, while accounting for the UHI effect [43].

[11] Appendix B.

[12] Appendix equation 2 to 4.

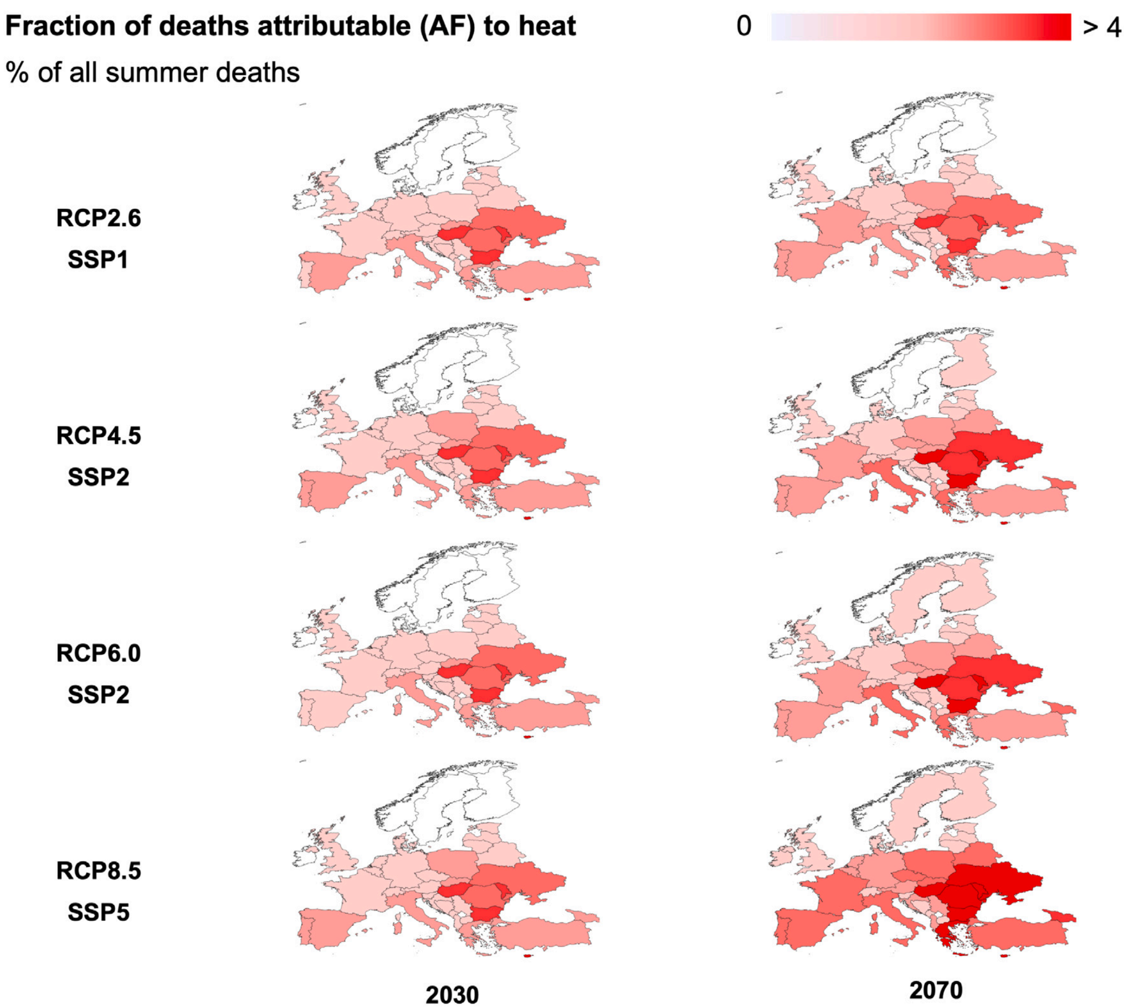

Fig. 2. Country-level distribution of the attributable fraction (AF) of deaths (as % of total summer deaths) in 2030 and 2070 for Northern and Mediterranean countries. Climate and socioeconomic scenarios: RCP2.6 – SSP1, RCP4.5 – SSP2, RCP6.0 – SSP2 and RCP8.5 – SSP5.

We then use the daily apparent temperature estimates to derive the fraction of deaths (in different European regions) which can be attributed to extreme heat. This is done by checking if the regional mortality temperature threshold is exceeded, at which point the slope of mortality determines the fraction of all deaths which can be attributed to extreme heat.[13] This relative mortality metric is combined with population projections and crude mortality statistics to derive the actual number of deaths attributable to heat (AD).[14] Finally, we quantify such impacts using the value of statistical life (VOSL) and compare projected mortality with COVID-19, using our proposed metric of ToE of heat-related mortality.[15]

3. Results

The heat-related mortality results in this section are expressed as annual expected averages for two future time periods;2021–2041 (centered around 2030) and 2061–2081 (centered around 2070). In addition, we also measure cumulative mortality projections between 2021 and 2100 in Fig. 3 and Fig. 4. The combinations of climate and socioeconomic development scenarios include RCP2.6-SSP1, RCP4.5-SSP2, RCP6.0-SSP2 and RCP8.5-SSP5.[16]

[13] Appendix equation 5.

[14] Appendix equation 9.

[15] Explained further in Section 3.4.

[16] Representative concentration pathway (RCP) scenarios are used for temperature projections within the MAGICC model [48]. Shared socioeconomic pathway (SSP) scenarios [49] are used for projecting future population in Europe.

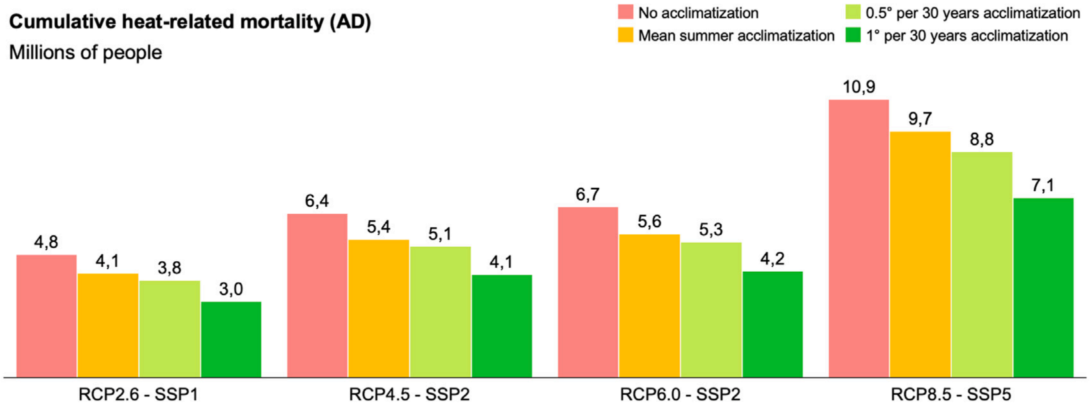

Fig. 3. Cumulative heat-related mortality (AD, in millions of people) between 2021 and 2100 in Europe, for different heat acclimatization assumptions. Climate and socioeconomic scenarios: RCP2.6 - SSP1, RCP4.5 - SSP2. RCP6.0 - SSP2 and RCP8.5 - SSP5.

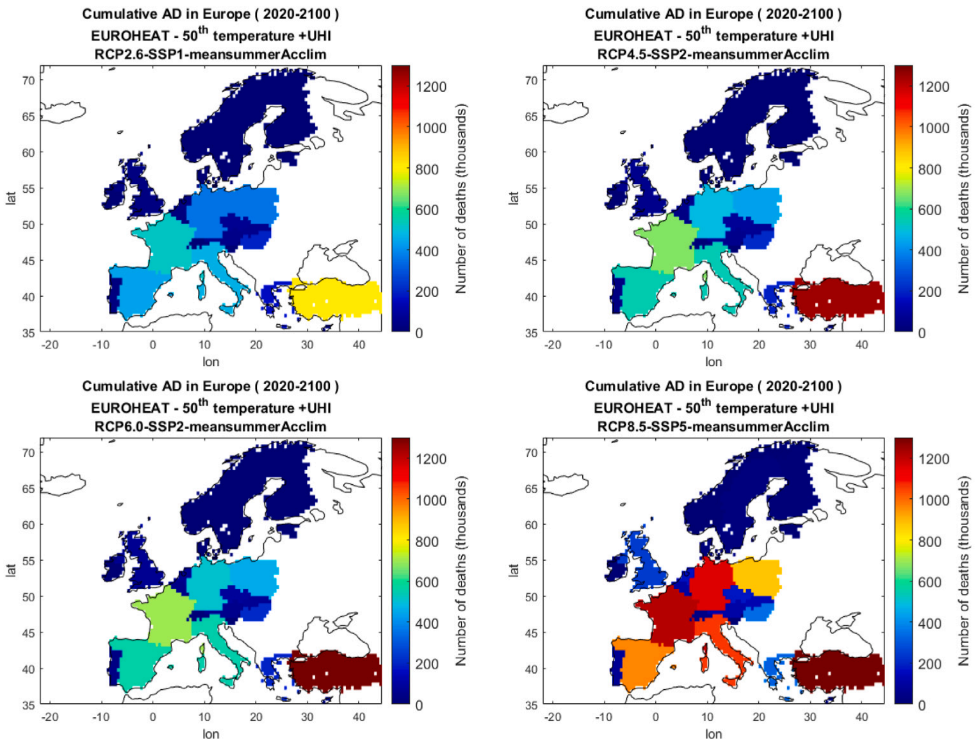

Fig. 4. Country-level distribution of cumulative AD estimates for the period 2020-2100. Climate and socioeconomic scenarios: RCP2.6 – SSP1 (top-left), RCP4.5 – SSP2 (top-right), RCP6.0 – SSP2 (bottom-left) and RCP8.5 – SSP5 (bottom-right).

Fig. 2 presents the AF estimates across European countries.[17] The largest AF estimates are in Cyprus, ranging between 7% (RCP.6-SSP1) and 11% (RCP8.5-SSP5) of total projected summer mortality. Hungary, Bulgaria and Moldova follow with AF estimates of 3% around 2030, reaching 6% by 2070. Overall, the relative mortality estimates appear to be the highest in Southern and Eastern Europe, a result which is also in line with Kendrovski et al. [34].[18] The AF estimates are the highest under the ‘‘business-as-usual’’ scenario (RCP8.5), where temperatures continue to rise over the century. Risk is mainly concentrated in the Eastern Europe. In countries like Romania, Bulgaria and Ukraine, the fraction of total summer season deaths directly attributable to extreme heat

[17] Methodology for calculating AF is outlined in Appendix A.4.

[18] Differences the two models emerge due to the difference in climate model inputs; whereas Kendrovski et al. [34] rely solely on MOHC-HadGEM2-ES projections, we use six different climate models as described in Fig. 1. The original authors' data is reproduced in Appendix D for comparison.

could exceed 10% annually by 2070. Under a stringent climate mitigation policy (RCP2.6),[19] the effect could drop below 8% of total summer deaths across all countries in Europe.

In the following subsections, we explore how heat-related mortality projections are expected to evolve across several scenarios and how impacts would be concentrated in urban areas. Finally, we illustrate our results against a backdrop of COVID-19 using the metric of ToE of heat-related mortality.

3.1. Mortality projections

First, we are interested in measuring the cumulative heat-related mortality projections in Europe until year 2100. Fig. 3 presents the estimates of the number of deaths attributable to heat (AD) in Europe until 2100,[20] for four different acclimatization assumptions:

1. **No acclimatization**: assuming human body does not acclimatize to increasing surface air temperatures
2. **Mean summer acclimatization**: assuming the human body can fully adapt to previous period's mean summer temperatures
3. **0.5 °C per 30 years acclimatization**: following Kovats et al. [4] assumption
4. **1 °C per 30 years acclimatization**: following Dessai [3] assumption

The total projected mortality varies between 4.09 and 9.65 million under mean summer acclimatization (orange bar). Assuming human acclimatization follows Dessai [3] assumption, total projected mortality could vary between 3 and 7 million (dark green bar).

The distribution of country-level cumulative AD estimates for Northern and Mediterranean countries is mapped in Fig. 4. The results show that Turkey could experience the highest total amount of deaths in the 21st century, over 1 million. Countries such as France, Italy and Germany, instead, could experience the same mortality impacts under the RCP8.5 scenario. Our analysis shows that the number of deaths could be reduced by more than one half if greenhouse gas emissions are dramatically reduced, in line with the Paris Agreement (RCP2.6 scenario). The lowest mortality impacts are observed in Northern Europe, where extreme heat days are expected to become more frequent but less intense than in Southern Europe.

Country-level results of total climate change induced mortality are presented in Fig. 5. The total number of casualties in Europe exceeds 50,000 per year by the middle of the century under all scenarios and is closer to 100,000 under RCP8.5. In the near term (around 2030), the average annual heat-related mortality in Europe is projected to be between 40,000 and 50,000 deaths per year, which increases to between about 60,000 and 220,000 in the second part of the century. The lower estimate in this interval is almost 3.7 times lower than the highest estimate. This illustrates the effectiveness of stringent mitigation policies in line with the Paris agreement (RCP2.6) in reducing climate induced mortality compared with RCP8.5 scenario emissions.

Population growth is an important factor in projecting absolute heat-related mortality. Therefore, we estimate cumulative AD by keeping temperature constant at 2010 levels to isolate the impact of increasing exposure of population to extreme heat on mortality. Fig. 6 suggests that population increase alone does lead to an increase in mortality. However, when compared to Fig. 3, this effect is several times smaller than accounting for climate change. The constant temperature scenario leads to 3.62 million cumulative AD under SSP5, which corresponds to 9.65 million deaths under the RCP8.5 – SSP5 scenario, which is 2.67 times larger. The ratio of deaths from climate change and socioeconomic development is somewhat lower under the Paris Agreement; namely, climate change effect is 1.4 times that of population growth alone. These results highlight the relevance of climate change adaptation and mitigation policies as population growth is only partly responsible for the increasing projected mortality due to heat.

3.2. Heat-related mortality evaluation

In order to help understanding the economic impact of heat-induced mortality, the value of statistical life (VOSL) metric is commonly used, with several VOSL estimates available in literature [50–52]. The value of VOSL for the European Union ranges from €1.14 to €1.3 millions.[21] The OECD [51] generated base estimates of the VOSL for the EU-27 region at $USD 3.6 million, with estimates ranging between 1.8 million and 5.4 million (2005 prices). In our study we assume a VOSL value for Europe of €1.3 million.[22]

The results of the VOSL valuation of heat-mortality impacts are presented in Fig. 7. The total annual losses in Europe, measured as monetized heat-related mortality, range between €59 billion (RCP2.6-SSP1) and €66 billion (RCP8.5-SSP5) around 2030 and between €86 billion (RCP2.6-SSP1) and €209 billion (RCP8.5-SSP5) around 2070. This implies that stringent mitigation policies in line with the Paris agreement (RCP2.6-SSP1) could prevent more than €150 billion losses each year in Europe in the later part of the century. The distribution of losses follows the distribution of AD losses presented earlier in Fig. 5. Around 2070, the highest absolute losses could be experienced in Turkey (€40 billion, RCP8.5-SSP5), France and Germany (€23 billion each, RCP8.5-SSP5).

[19] This scenario assumes a rapid decrease in mean global temperature to below 2 °C by 2100, in line with the Paris Climate Agreement.

[20] Methodology for calculating AD is outlined in Appendix A.4.

[21] PESETA III project (2007 prices) and PESETA IV project (2015 prices).

[22] Detailed sensitivity analysis using different VOSL estimates, including the OECD estimate, can be found in Appendix C.5.

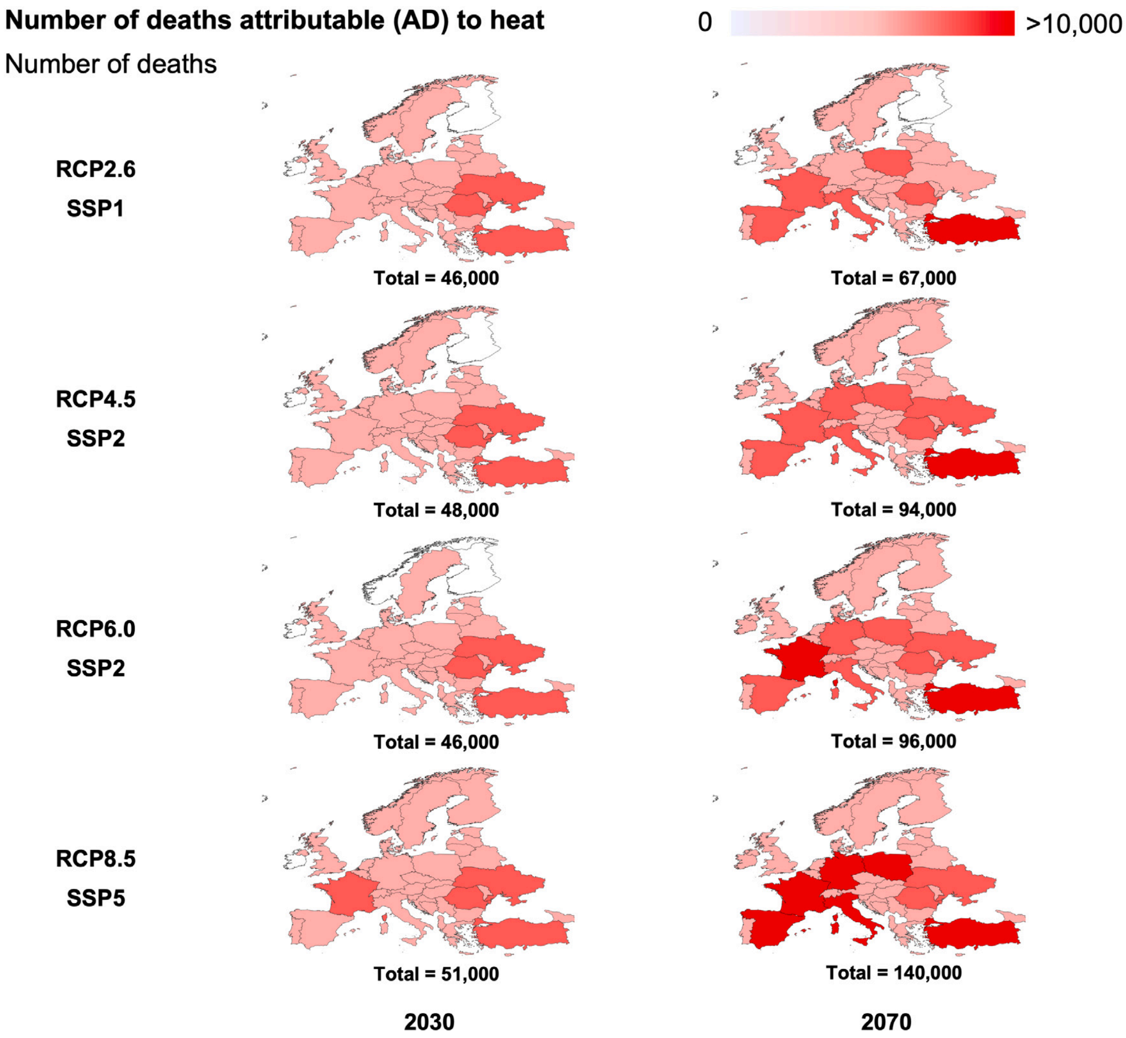

Fig. 5. Annual average number of deaths attributable (AD) to heat across Europe in 2030 and 2070. Estimates generated using mean summer acclimatization assumption. Climate and socioeconomic scenarios: RCP2.6 – SSP1, RCP4.5 – SSP2, RCP6.0 – SSP2 and RCP8.5 – SSP5.

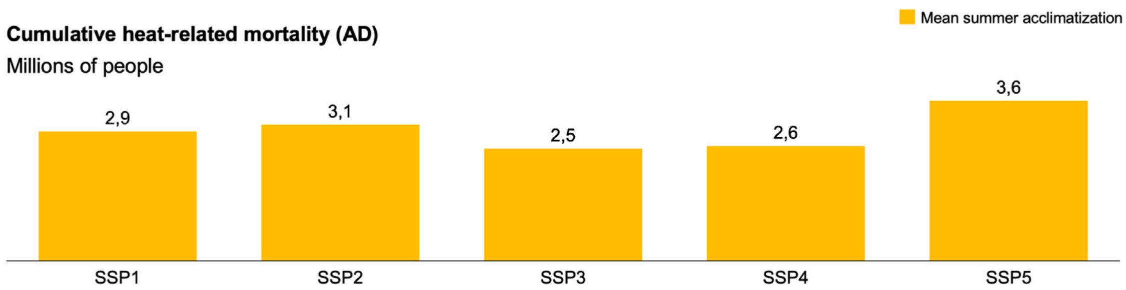

Fig. 6. Cumulative heat-related mortality (AD, in millions of people) between 2021 and 2100, keeping temperatures constant at 2010 levels. Heat acclimatization assumes to follow previous period's mean summer temperatures. Socioeconomic scenarios: SSP1-SSP5.

3.3. City-level results

The benefit of a local-scale IAM such as CLIMRISK is the ability to project impacts on near-city level granularity. Wr present such city-level results in Fig. 8 across several future climate and socioeconomic scenarios. In case global temperatures are reduced in accordance with the Paris Agreement, the heat-related mortality could decrease by 57% in top 10 most affected cities in Europe

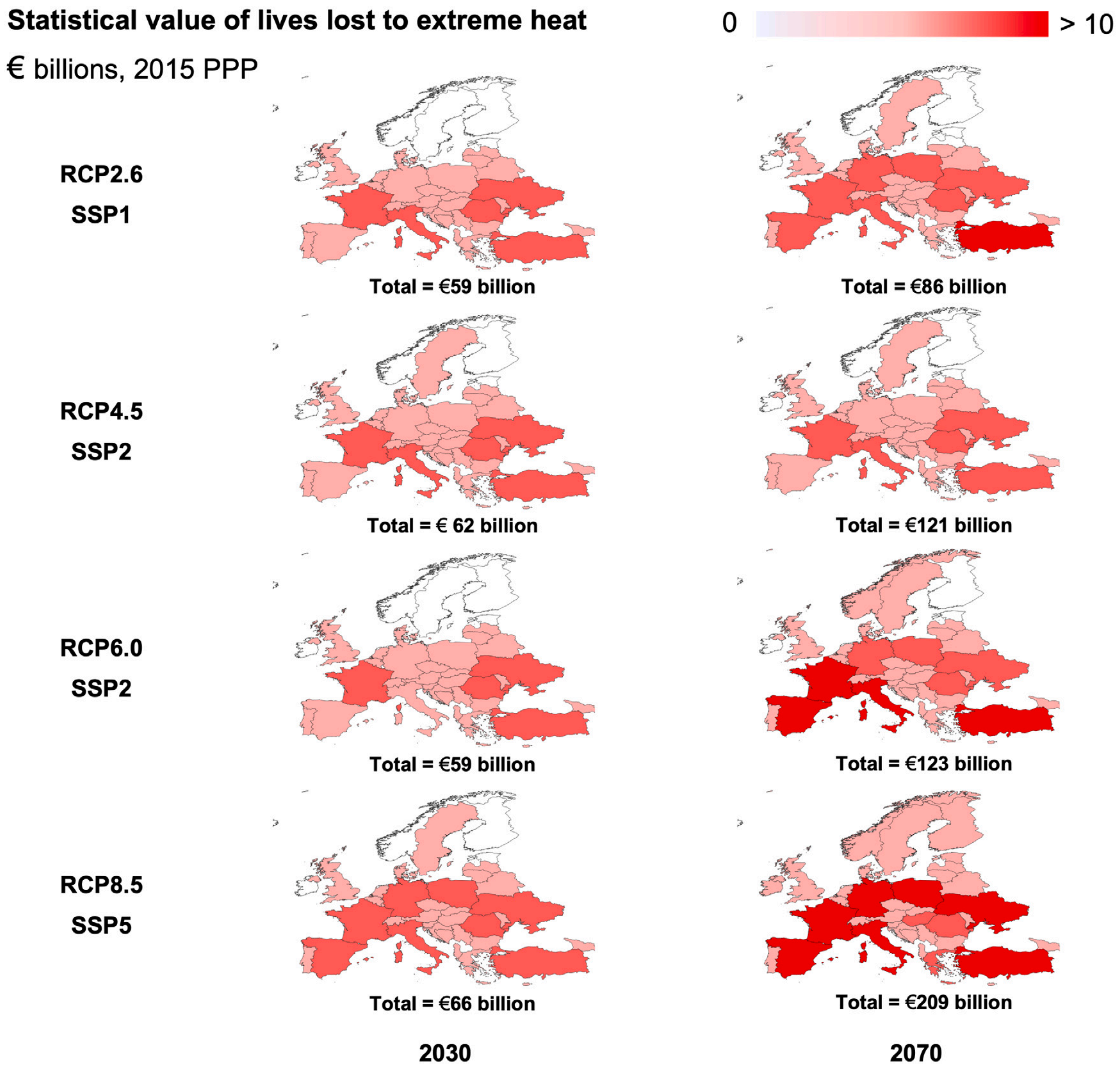

Fig. 7. Annual average economic impact of heat-related mortality in Europe in 2030 and 2070, using the value of statistical life (VOSL) (€ billion, 2015 PPP). Climate and socioeconomic scenarios: RCP2.6 - SSP1, RCP4.5 - SSP2, RCP6.0 - SSP2, RCP8.5 - SSP5.

by 2070, compared to "business-as-usual" RCP8.5 - SSP5 scenario. This means that the number of projected annual deaths in Europe would decrease from 154,000 (RCP8.5-SSP5) to around 66,000 (RCP2.6 - SSP1).[23] Whereas Bucharest is expected to experience the highest annual heat-related mortality in the near term (2030), Istanbul and Paris could both reach 10,000 annual deaths by 2070.

The UHI effect is an important contributing factor to the high number of heat-related mortalities in cities. If the UHI effect were to be neutralized (e.g., through urban greening and cooling adaptation measures), the death toll could drop by over 50% in some cities (Paris, Istanbul, Cologne) under RCP8.5 - SSP5 scenario.[24] The benefits of urban heat adaptation stand even more out within a high mitigation scenario (e.g. RCP2.6). For example, cities such as Paris, Istanbul and Cologne, could see a threefold or fourfold reduction in death toll through limiting the UHI effect through heat adaptation actions. This illustrates the potential synergies for risk reduction when climate mitigation is combined with effective climate adaptation action.

Fig. 9 shows the cumulative heat-related mortality on a grid-cell level across Europe for the period 2021-2100. The results show the relatively high AD risk across Europe under the RCP6.0 - SSP2 and RCP8.5 - SSP5 scenarios, compared to alternative scenarios. Specifically, many local areas in Central and Western Europe could exceed 10,000 total heat-related deaths by 2100. The drastically

[23] Even with lower global temperatures, the local temperatures in urban environments could still be higher than surrounding rural temperatures and would continue to induce mortality, especially among the elderly population.

[24] While considered extremely challenging, we consider UHI effect neutralization to imply no difference in local temperatures between urban and local rural areas, for the purposes of measuring the maximum potential benefits of heat adaptation.

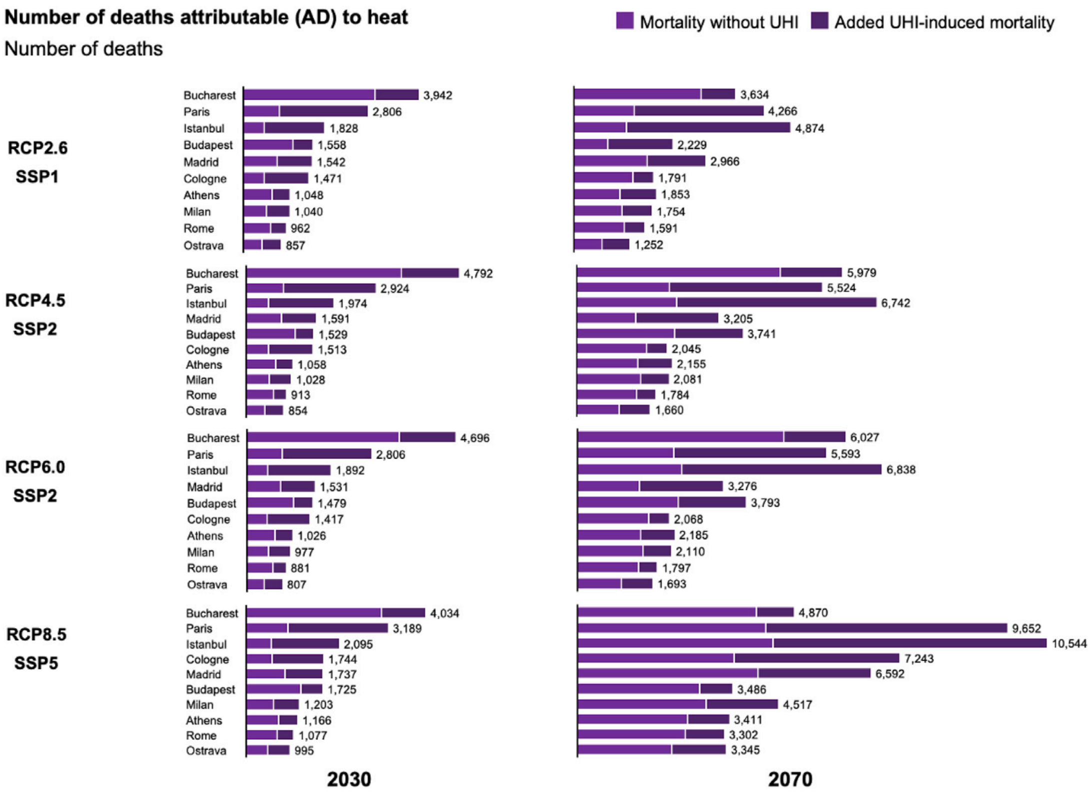

Fig. 8. Annual average deaths attributable to heat (AD) for 10 most impacted city-cells in Europe, in 2030 and 2070. Climate and socioeconomic scenarios: RCP2.6 - SSP1, RCP4.5 - SSP2, RCP6.0 - SSP2, RCP8.5 - SSP5.

lower cumulative AD under RCP2.6 - SSP1 scenario, which is in line with the Paris Agreement targets, illustrates the benefits of climate change mitigation for local populations.

3.4. Time of emergence of heat-related mortality

While the absolute valuation of mortality is a useful metric for cost–benefit analysis, it relies on the value of statistical life (VOSL) or other forms of valuing human life which are subject to an ongoing public debate. In order to provide an alternative metric of comparison, we explore the ToE of heat-related mortality.[25] This measure places future climate impacts in perspective of other severe impacts or shocks that countries experienced in the past. Once annual AD estimates are produced,[26] we can generate cumulative values of AD, CAD_{iy}, for subsequent years using the following equation:

$$CAD_{iy} = \begin{cases} AD_{iy} & if \quad y == 1 \\ CAD_{iy-1} + AD_{iy} & if \quad y > 1 \end{cases} \tag{1}$$

In order to illustrate the severity of health shocks brought about by extreme heat, we compare our projected annual impacts to COVID-19 cumulative deaths by August 1st, 2021. COVID-19 mortality is chosen as a comparison statistic due the large negative health and economic consequences it brought about. The date is set to August 1st, 2021 because widespread vaccination became available everywhere in Europe around by that date. Prior to this, national governments mainly relied on severe lockdown measures, indicating a large willingness to prevent huge societal costs to limit the risk of a health crisis. Hence it is of interest to estimate if climate change can cause similar fatalities, when this would occur, and which kind of climate policies can prevent such an impact from climate change. The first year in which the cumulative number of heat-related deaths exceeds the COVID-19 deaths is the ToE of heat-related mortality. Since mortality projections of COVID-19 are available at the country level, the results of this experiment are also expressed on the same scale.

[25] The procedure for estimating the ToE is explained in full detail in Ignjacevic et al. [47].

[26] Appendix equation 9.

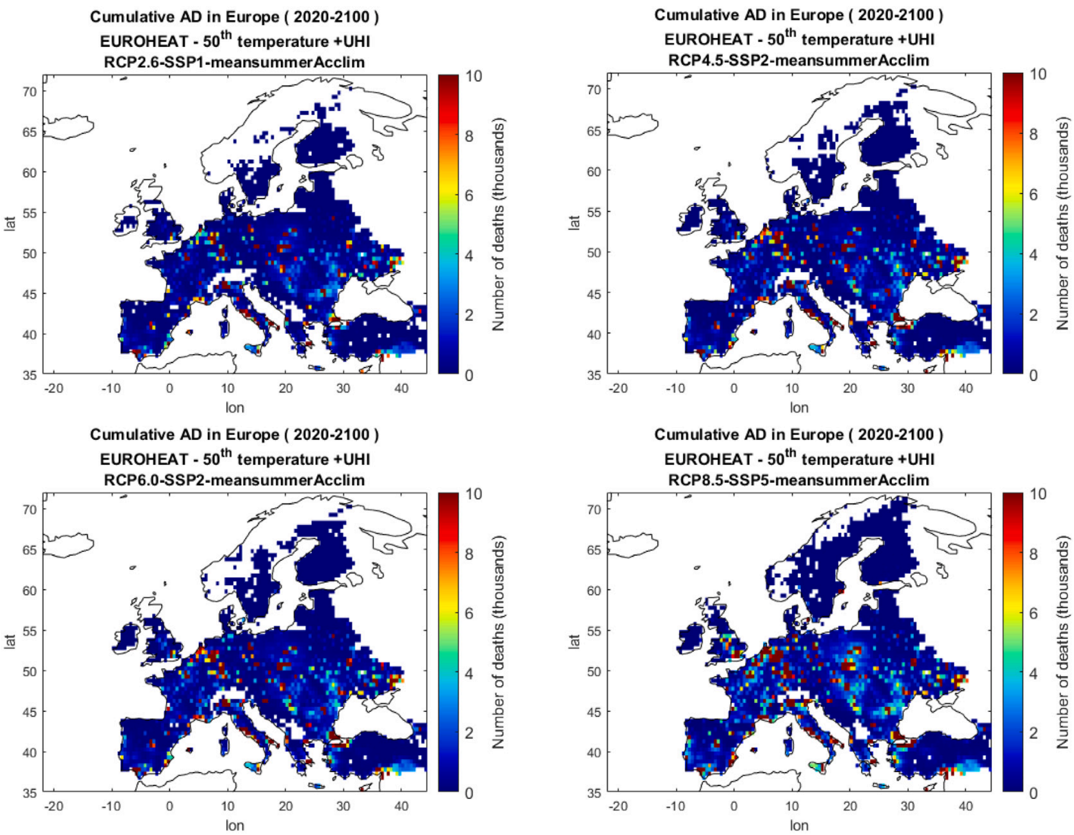

Fig. 9. Local-scale cumulative number of deaths attributable to heat (AD) for the period 2021 – 2100. Climate and socioeconomic scenarios: RCP2.6 - SSP1 (Paris Agreement, top-left), RCP4.5 - SSP2 (top-right), RCP6.0 - SSP2 (bottom-left), RCP8.5 - SSP5 (bottom-right).

The comparison between the heat-related mortality and the total number of deaths from COVID-19 is illustrated in Fig. 10. The figure suggests that, while Scandinavian countries are expected to exceed the number of COVID-19 fatalities by 2080 or 2090 under the RCP8.5 – SSP5 scenario (bottom-right figure), this would not occur by 2100 under the RCP4.5 – SSP2 scenario combination (top-right map). The results are nearly identical for the UK and Iceland. Southern Europe is facing a much higher risk with an earlier ToE. For example, Turkey is facing the highest risk of heat-related mortality, with a ToE estimate of 2035 under the RCP8.5 scenario, closely followed by the rest of Southern Europe. This is in line with the July 2021 events of extreme heat across the Balkans (Serbia, Greece) and Turkey with many forest fires and temperatures reaching 40°C. Overall these results suggest that climate change induced mortality could exceed COVID-19 mortality in several countries before the mid-century. This projection could be a reason for putting stringent policies in place to try to limit these deaths as many governments around the world tried to do for COVID-19. Reducing greenhouse gas emissions in line with the Paris Agreement could be an effective policy, especially in Northern Europe, but could not limit heat-related mortality in many EU-28 countries below current COVID-19 mortality statistics.

Country-level ToE results of heat-related mortality are also presented in Fig. 11. The figure shows results for different RCP-SSP scenario combinations (left) and with keeping the temperature constant at 2010 levels (right), illustrating the impact of climate change on the year of exceeding COVID-19 mortality. On average, the ToE is shortened by 5 - 13 years, with some countries facing a significantly shorter period. For example, Belgium would expect its ToE in 2071 under the RCP8.5 – SSP5 scenario and past 2100 under the constant temperature scenario, about 30 years earlier.

4. Discussion

4.1. Limitations

There are several limitations to our approach of estimating extreme heat-induced mortality. The main limitation refers to the construction of heat-mortality functions used in our calculations. First, the functions do not allow us to consider changes in demographic structure of the population across time. A previous study suggests that the older segment of the population is more vulnerable to heat, and under scenarios of ageing population impacts from heat-related mortality are expected to be even greater [53]. Moreover, while the input-response functions are derived from local-scale data, they are aggregated to three major

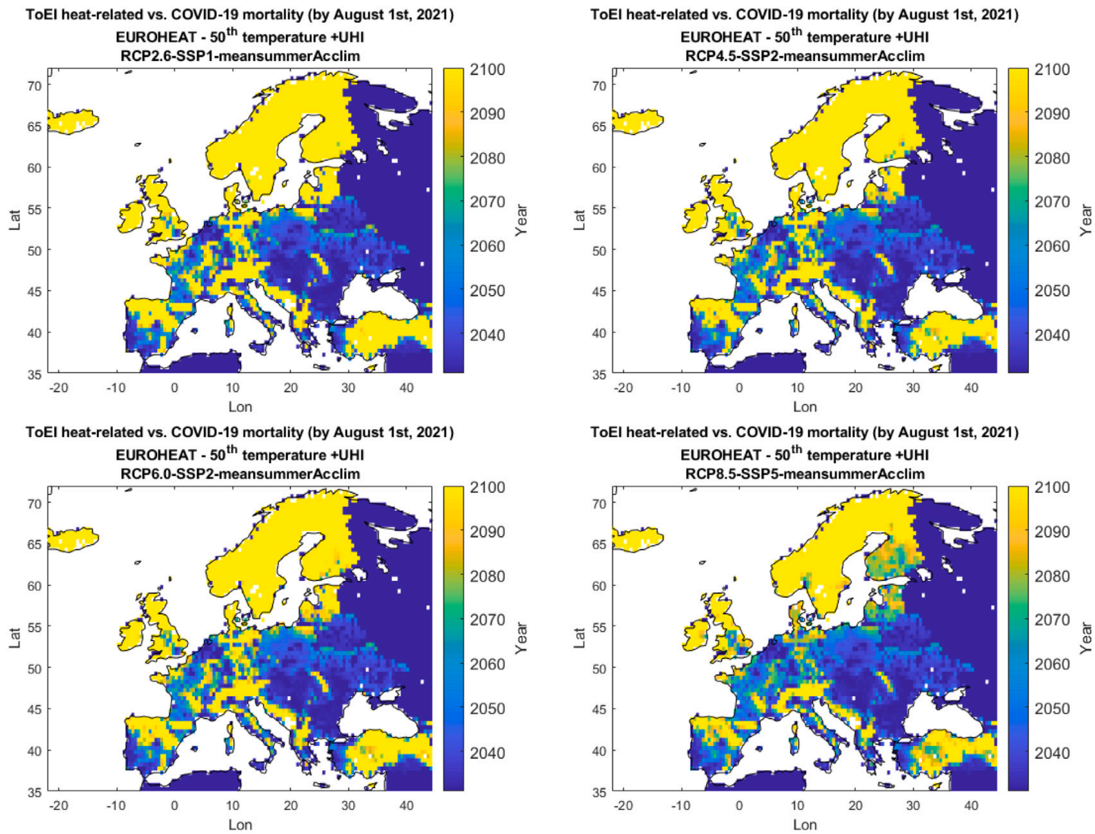

Fig. 10. ToE of heat-related mortality, indicating the year when cumulative heat-related mortality could exceed total COVID-19 number of deaths by August, 2021. Results indicate that the ToE is expected to exceed that of the most recent global health crisis around the world. Climate and socioeconomic scenarios: RCP2.6 – SSP1 (top-left), RCP4.5 – SSP2 (top-right), RCP6.0 – SSP2 (bottom-left) and RCP8.5 – SSP5 (bottom-right).

European regions, rendering local scale temperature and socioeconomic inputs from CLIMRISK less effective. However, we account for this uncertainty in the sensitivity analysis section of the Appendix. Finally, the input-response functions relate AT to temperature and humidity through a specific weighing factor. We acknowledge that other thermal indices including factors like solar radiation and wind speed, may better represent the relationship with mortality. However, such indices would be difficult to include in IAMs that mainly project climate impacts based on temperature change. Future research could use alternative heat-mortality functions and explore the sensitivity of the results to input-response functions.

The second limitation relates to the choice of heat adaptation assumption. While we account for heat acclimatization, we do not include any additional heat adaptation. The reason lies in the lack of local scale data on adaptation measures and in the effectiveness of those in place in limiting the impacts of climate change. Examples of such adaptation include the use of air-conditioning systems, city cooling strategies and various heat warning systems that are already in place in Europe [54]. However, since future projections of such adaptation strategies are not available and since it is unclear how they would affect the heat-mortality curve, we have decided not to include them in the present work. Future studies could focus on estimating such information on local adaptation in order to produce better estimates of heat-related mortality. One realistic form of adaptation is that based on past heat-related mortality. This assumption implies that higher observed mortality leads to larger adaptation to increasing future temperatures as policymakers respond to increasing death tolls due to heat. Further research should focus also focus extending such projections and valuation to other regions and local scale effects, including adaptation policies.

Finally, the limited set of climate scenarios available in the CORDEX climate dataset implies that important probable scenarios, such as RCP6.0, are excluded from the analysis. Future research could use alternative model inter-comparison projects (e.g. CMIP6) to better account for alternative climate scenarios as they evolve over time.

4.2. Results sensitivity

The results presented in this study depend on a multitude of factors such as climate uncertainty, socioeconomic development and the underlying acclimatization assumptions. These types of uncertainties are further explored in Appendix C and summarized in this subsection.

2020 - 2040 | 2040 - 2060 | 2060 - 2080 | 2080 - 2100

Country	RCP2.6 – SSP1	RCP4.5 – SSP2	RCP6.0 – SSP2	RCP8.5 – SSP5	Constant temperature SSP1	SSP2	SSP3	SSP4	SSP5
Austria	2044	2043	2044	2041	2050	2051	2053	2052	2049
Belgium	2099	2084	2085	2071	2100				
Bulgaria	2037	2035	2036	2036	2042	2040	2042	2043	2042
Cyprus	2027	2026	2026	2026	2028	2027	2028	2027	2027
Czechia	2052	2052	2054	2046	2069	2074	2081	2076	2064
Denmark			2094	2071					
Estonia				2095					
Finland				2073					
France	2044	2044	2044	2042	2050	2050	2052	2051	2049
Germany	2047	2046	2047	2043	2059	2060	2067	2063	2055
Greece	2039	2039	2040	2039	2041	2041	2041	2041	2041
Hungary	2033	2033	2034	2032	2035	2036	2036	2035	2034
Iceland									
Ireland									
Italy	2052	2052	2053	2049	2058	2060	2062	2061	2056
Luxembourg	2093	2086	2085	2062					
Netherlands	2067	2059	2062	2052					2084
Norway				2081					
Poland	2044	2045	2046	2042	2050	2052	2053	2052	2048
Portugal	2076	2070	2072	2061	2097				2086
Romania	2026	2025	2025	2026	2026	2026	2026	2027	2026
Slovakia	2041	2041	2042	2039	2045	2047	2048	2047	2045
Slovenia				2080					
Spain	2044	2043	2044	2042	2049	2049	2051	2050	2048
Sweden				2089					
Switzerland		2087	2087	2067					
Turkey	2035	2034	2034	2034	2037	2036	2037	2037	2037
UK				2087					

Fig. 11. ToE of heat-related mortality vs. COVID-19 mortality. The left half of the table represents ToE results using alternative climate-socioeconomic scenarios whereas the right half of the table presents results for alternative socioeconomic scenarios keeping temperature fixed at the 2010 level. Empty fields indicate that ToEI has not occurred by 2100 in the model run.

The sensitivity to differences in climate outcomes can be explored through the choice of a climate scenario, temperature realization and the severity of the UHI effect.[27] When climate mitigation is in line with the Paris Agreement, about 50% (2.6 million, RCP2.6) of AD is prevented compared to alternative climate scenarios (5.5 million, RCP4.5, RCP6.0 and RCP8.5) under the SSP2 assumption, delaying the ToE by two decades in some cases.

Socioeconomic development also plays a role in heat-related mortality projections by influencing the temperature rise from the UHI effect[28]; with the RCP4.5 climate scenario, development in line with SSP3 scenario yields 4.44 million deaths compared to 6.48 million under the SSP5 scenario, delaying the ToE in many countries by one decade.

Different realizations of future temperature within a climate scenario have a large effect on projected AD.[29] In case that the 5th percentile temperature is realized from the triangular climate sensitivity distribution, this would correspond to 3.24 million and 6.89 million deaths under the RCP2.6 and RCP8.5 scenarios. If the 95th percentile is realized instead, this would correspond to 4.89 million and 12.4 million deaths, almost twice as high in the low mitigation scenario RCP8.5.

Acclimatization and adaptation are the most important determinants of future heat-related mortality but also least well understood [55]. There is little consensus in literature about temperatures to which humans will be able to adapt in the future and the uncertainty range is very large. When no acclimatization assumption is made, the projected mortality (AD) is higher than our estimates with acclimatization, but only by 3-4 percentage points.[30] On the other hand, if we assume more serious acclimatization of humans to heat, the expected number of deaths drops significantly. For example, using Dessai (2003)'s assumption the heat-related mortality is about 40% lower on average than when the mean summer temperature acclimatization assumption is used.

The valuation of projected AD is dependent on the VOSL chosen.[31] In this research, VOSL was valued following the PESETA IV estimate. However, alternative values available from the OECD are explored. Overall, the PESETA IV VOSL value is the lowest

27 Appendix C.1.
28 Appendix C.2.
29 Appendix C.4.
30 Appendix C.3.
31 Appendix C.5.

among alternatives explored, leading to a loss of approximately €100 billion in 2080 compared to €350 billion under the median OECD VOSL estimate and €525 billion under the high OECD VOSL estimate. This represents a large range of projected impacts owing to the uncertainty in valuing human life lost.

The spatial distribution of results under different assumptions in the sensitivity analysis does not change noticeably. Most parameters apply to cells equally; the choice of acclimatization assumption, VOSL, socioeconomic scenario, temperature realization and climate scenario. Nevertheless, an important cell-dependent parameter is the UHI impact which affects highly urbanized cells, leading to higher projected AD in cities. When the UHI effect is accounted for in the model and not mitigated, it would lead to 9.65 million deaths under the RCP8.5 - SSP5 scenario combination. Alternatively, omitting such an effect from the model or effectively mitigating it would reduce cumulative AD to 6.5 million deaths under the exact same other parameters in the model. The difference is also noticeable under a high mitigation scenario RCP2.6 - SSP1 whereby the UHI effect leads to 4.09 million cumulative deaths whereas the no-UHI scenario would result in 2.5 million deaths.

Finally, the choice of the input-response function parameters has a large effect on projected mortality, specifically the choice of temperature threshold and slope above the threshold as defined in Equation 5. The results are most sensitive in the Mediterranean region where under the RCP2.6 scenario, low threshold - high slope impact functions lead to four times as many death in Spain, five times in Italy and six times in Turkey compared to the high threshold - low slope scenario. The difference is larger under RCP8.5 scenario, with most deaths in the Mediterranean region under low threshold - high slope scenario being six or more times higher than under the high threshold - low slope scenario.[32]

CLIMRISK-EUROHEAT model results, highlight the relevance of heat-related mortality in estimating the impacts of climate change. Nevertheless, it is worth drawing some comparisons with other similar studies to understand the distribution of heat-mortality estimates. First, we compare the annual average AD results with Watkiss and Hunt [35] study country-level mortality estimates. Whereas the authors use 30-year periods time period averages (2011–2040 and 2071 – 2100), their results are still comparable to ours since they estimate the change in heat-related mortality in Europe over the current century. Our projections range between 42,000 and 53,000 annual deaths around 2030 whereas they project a range from 37,900 to 60,400. The findings also exhibit a similarity in the second half of the century. Our results range from 25,650 to 220,000 deaths, while theirs fall within the range of 31,000 and 221,000, depending on the climate model used.[33] A recent study by Ballester et al. [56], estimate around 61,000 deaths in Europe in the summer of 2022, which exceeds our 2030 estimates under the pessimistic RCP8.5 - SSP5 scenario (51,000 deaths, Fig. 5). This suggests that our model could be underestimating the true mortality impacts in Europe. The PESETA IV project [57] estimates around 90,000 heat-related deaths in Europe under a 3 °C temperature scenario, which is lower than our projected 140,000 under similar climate conditions in 2070. Regarding city-level estimates, Masselot et al. [58] find around 20,000 deaths attributable to heat in European cities between 2000–2019. Regarding relative mortality, Vicedo-Cabrera et al. [59] project that between 0%–4% of total mortality is caused by human-induced climate change heat-related mortality in European countries, which is in line with our projections in Fig. 2. Wu et al. [60] project an average 1.7% of total mortality in 2019 to be the result of climate change-induced extreme heat, which is somewhat higher than our average estimate across Europe in 2030 (0.93%, RCP2.6-SSP1).

Whilst the total European mortality projections are similar, our local scale estimates provide additional insights compared with these previous studies on heat-related mortality. First, we provide estimates on a higher spatial resolution than country or regional level. This allows for a city-cell level analysis of climate impact inequality across Europe. Second, we can contextualize climate impacts using a selection of risk measures such as the ToE of heat-related mortality. In that way, heat-related mortality impacts are placed in the perspective of other impacts (e.g. COVID-19), and we can compute the time period available for climate adaptation. Third, specialized UHI functions allow us to improve the impact estimates for city-cells and determine adaptation benefits resulting from urban cooling policies and city level adaptation strategies. Finally, we can generate estimates for a wide range of climate and socioeconomic scenarios, both present and future. This allows us to capture a wider range of uncertainties involved in climate change impact assessment and conduct sensitivity analyses for a wide range of factors.

5. Conclusion

Heat-related mortality is expected to increase due to climate change. In this paper, we present such mortality estimates within the framework of a local-scale IAM. CLIMRISK-EUROHEAT makes use of the CORDEX EUR-11 projections of climate change when generating mortality estimates. Together with granular socioeconomic projections, we are able to project heat-related mortality impacts on a higher spatial resolution for several RCP and SSP scenario combinations than was previously possible. CLIMRISK-EUROHEAT can produce results for alternative scenarios on a local scale in order to highlight areas that would benefit the most from heat adaptation, especially urban areas. Our results are aligned with similar studies in the field, and show in most countries in Europe up to 4% of total mortality could result from heat-related causes. This translates into around 50,000 annual deaths by 2030 and around 140,000 annual deaths by 2070 under the "business-as-usual" climate scenario.

In addition to estimating the severity of heat-related impacts in Europe, we also show that there are significant potential benefits of climate mitigation. For example, if global climate mitigation is in line with the Paris Agreement, around 2 million lives could be saved in Europe in the 21st century which would otherwise be lost to heat-related causes. This could potentially save €150

[32] Appendix C.7.

[33] These results refer to period 2081-2100, tables available in Appendix C.3.

billion annually in losses to human life across Europe. Finally, we focus on estimating the heat-related mortality in European cities with specific attention for the UHI effect. We show that the most significant heat-related impacts could occur in Paris, Istanbul and Cologne, where around 25,000 lives could be lost every year around 2070 due to heat stress. These cities could see a threefold or fourfold reduction in heat-related mortality if investments are made in UHI adaptation measures, such as installing green roofs, building cool pavements, or increasing green spaces, all of which can help bring urban temperatures in line with surrounding rural area levels.

CRediT authorship contribution statement

Predrag Ignjačević: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Wouter Botzen:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Francisco Estrada:** Supervision, Methodology, Data curation, Conceptualization. **Hein Daanen:** Methodology. **Veronica Lupi:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104692.

References

[1] IPCC, Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Technical Report, Cambridge University Press, 2022.
[2] N. Todd, A.J. Valleron, Space–time covariation of mortality with temperature: A systematic study of deaths in France, 1968–2009, Environ. Health Perspect. 123 (7) (2015) 659–664.
[3] S. Dessai, Heat stress and mortality in Lisbon part II. An assessment of the potential impacts of climate change, Int. J. Biometeorol. 48 (1) (2003) 37–44.
[4] S. Kovats, S. Lloyd, A. Hunt, P. Watkiss, The Impacts and Economic Costs on Health in Europe and the Costs and Benefits of Adaptation, Technical Report, Results of the EC's directorate general research and innovation (DG RTD) climate cost project. Final report, The climate cost project, 1, 2011.
[5] B. Ferreira, L. Alfesio, A. Zanobetti, J. Schwartz, The time course of weather-related deaths, Epidemiology 12 (6) (2001) 662–667.
[6] I.T. Commission, Glossary of terms for thermal physiology, Jpn. J. Physiol. 51 (2001) 245–280.
[7] J. Taylor, P. Wilkinson, M. Davies, B. Armstrong, Z. Chalabi, A. Mavrogianni, P. Symonds, E. Oikonomou, S.I. Bohnenstengel, Mapping the effects of urban heat island, housing, and age on excess heat-related mortality in London, Urban Clim. 14 (2015) 517–528.
[8] A. Bunker, J. Wildenhain, A. Vandenbergh, N. Henschke, J. Rocklöv, S. Hajat, R. Sauerborn, Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence, EBioMedicine 6 (2016) 258–268.
[9] H. Achebak, D. Devolder, J. Ballester, Heat-related mortality trends under recent climate warming in Spain: A 36-year observational study, PLoS Medicine (2018).
[10] W.J. Botzen, M.L. Martinius, P. Bröde, M.A. Folkerts, P. Ignjacevic, F. Estrada, C.N. Harmsen, H.A. Daanen, Economic valuation of climate change–induced mortality: age dependent cold and heat mortality in the Netherlands, Clim. Change 162 (2) (2020) 545–562.
[11] A. Gasparrini, Y. Guo, M. Hashizume, Mortality risk attributable to high and low ambient temperature: a multicountry observational study, Environnement, Risques Sante 14 (6) (2015) 464–465.
[12] Y. Guo, A. Gasparrini, B.G. Armstrong, B. Tawatsupa, A. Tobias, E. Lavigne, M.d.Z.S. Coelho, X. Pan, H. Kim, M. Hashizume, Y. Honda, Y.L. Guo, C.-F. Wu, A. Zanobetti, J.D. Schwartz, M.L. Bell, A. Overcenco, K. Punnasiri, S. Li, L. Tian, P. Saldiva, G. Williams, S. Tong, Temperature variability and mortality: A multi-country study, Environ. Health Perspect. 124 (10) (2016) 1554–1559.
[13] Y. Guo, A. Gasparrini, B.G. Armstrong, B. Tawatsupa, A. Tobias, E. Lavigne, M. De Sousa Zanotti Stagliorio Coelho, X. Pan, H. Kim, M. Hashizume, Y. Honda, Y.L. Leon Guo, C.F. Wu, A. Zanobetti, J.D. Schwartz, M.L. Bell, M. Scortichini, P. Michelozzi, K. Punnasiri, S. Li, L. Tian, S.D.O. Garcia, X. Seposo, A. Overcenco, A. Zeka, P. Goodman, T.N. Dang, D. Van Dung, F. Mayvaneh, P.H.N. Saldiva, G. Williams, S. Tong, Heat wave and mortality: A multicountry, multicommunity study, Environ. Health Perspect. 125 (8) (2017).
[14] A. Vicedo-Cabrera, N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D.M. Hondula, R. Abrutzky, S. Tong, M.d.Z.S. Coelho, P.H. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, H. Orru, E. Indermitte, J.J. Jaakkola, N. Ryti, M. Pascal, A. Schneider, K. Katsouyanni, E. Samoli, F. Mayvaneh, A. Entezari, P. Goodman, A. Zeka, P. Michelozzi, F. De'Donato, M. Hashizume, B. Alahmad, M.H. Diaz, C.D.L.C. Valencia, A. Overcenco, D. Houthuijs, C. Ameling, S. Rao, F. Di Ruscio, G. Carrasco-Escobar, X. Seposo, S. Silva, J. Madureira, I.H. Holobaca, S. Fratianni, F. Acquaotta, H. Kim, W. Lee, C. Iniguez, B. Forsberg, M.S. Ragettli, Y.L. Guo, B.Y. Chen, S. Li, B. Armstrong, A. Aleman, A. Zanobetti, J. Schwartz, T.N. Dang, D.V. Dung, N. Gillett, A. Haines, M. Mengel, V. Huber, A. Gasparrini, The burden of heat-related mortality attributable to recent human-induced climate change, Nat. Clim. Change 11 (6) (2021) 492–500.

[15] K. Burkart, M. Brauer, A. Aravkin, W. Godwin, S. Hay, J. He, V. Iannucci, S. Larson, S. Lim, J. Liu, C. Murray, P. Zheng, M. Zhou, J. Stanaway, Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the global burden of disease study, Lancet 398 (10301) (2021) 685–697.
[16] Q. Zhao, Y. Guo, T. Ye, et al., Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling studyy, Lancet Planet Health 5 (2021) e415–e425, http://dx.doi.org/10.1016/S2542--5196(21)00081--4.
[17] M. Stafoggia, F. Forastiere, D. Agostini, A. Biggeri, L. Bisanti, E. Cadum, N. Caranci, F. De'Donato, S. De Lisio, M. De Maria, P. Michelozzi, R. Miglio, P. Pandolfi, S. Picciotto, M. Rognoni, A. Russo, C. Scarnato, C.A. Perucci, Vulnerability to heat-related mortality: A multicity, population-based, case-crossover analysis, Epidemiology 17 (3) (2006) 315–323.
[18] D. D'ippoliti, P. Michelozzi, C. Marino, F. De'donato, B. Menne, K. Katsouyanni, U. Kirchmayer, A. Analitis, M. Medina-Ramón, A. Paldy, R. Atkinson, S. Kovats, L. Bisanti, A. Schneider, A. Lefranc, C. Iñiguez, C.A. Perucci, The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project, Technical Report, 2010.
[19] M. Leone, D. D'Ippoliti, M. De Sario, A. Analitis, B. Menne, K. Katsouyanni, F. De' Donato, X. Basagana, A. Salah, E. Casimiro, Z. Dörtbudak, C. Iñiguez, C. Peretz, T. Wolf, M. P., A time series study on the effects of heat on mortality and evaluation of heterogeneity into European and Eastern-Southern Mediterranean cities: results of EU CIRCE project, Environ. Health 55 (12) (2013).
[20] F. Sera, B. Armstrong, A. Tobias, A.M. Vicedo-Cabrera, C. Åström, M.L. Bell, B.-Y. Chen, M. de Sousa Zanotti Stagliorio Coelho, P. Matus Correa, J.C. Cruz, T.N. Dang, M. Hurtado-Diaz, D. Do Van, B. Forsberg, Y.L. Guo, Y. Guo, M. Hashizume, Y. Honda, C. Iñiguez, J.J.K. Jaakkola, H. Kan, H. Kim, E. Lavigne, P. Michelozzi, N.V. Ortega, S. Osorio, M. Pascal, M.S. Ragettli, N.R.I. Ryti, P.H.N. Saldiva, J. Schwartz, M. Scortichini, X. Seposo, S. Tong, A. Zanobetti, A. Gasparrini, How urban characteristics affect vulnerability to heat and cold: a multi-country analysis, Int. J. Epidemiol. 48 (4) (2019) 1101–1112.
[21] J.D. Périard, T.M.H. Eijsvogels, H.A.M. Daanen, Exercise Under Heat Stress: Thermoregulation, Hydration, Performance Implications, and Mitigation Strategies, vol. 101, (no. 4) American Physiological Society Rockville, MD, 2021, pp. 1873–1979, http://dx.doi.org/10.1152/PHYSREV.00038.2020.
[22] G. Havenith, D. Fiala, Thermal indices and thermophysiological modeling for heat stress, Compr. Physiol. 6 (2016) 255–302.
[23] D. Fiala, G. Havenith, P. Bröde, B. Kampmann, G. Jendritzky, UTCI-fiala multi-node model of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (3) (2011) 429–441.
[24] S. Hajat, S. Sheridan, M. Allen, M. Pascal, K. Laaidi, A. Yagouti, U. Bickis, D. Tobias, B. Armstrong, T. Kosatsky, Heat–health warning systems: A comparison of the predictive capacity of different approaches to identifying dangerously hot days, Am. J. Public Health 100 (6) (2010).
[25] A. Barnett, S. Tong, A. Clements, What measure of temperature is the best predictor of mortality? Environ. Res. 110 (6) (2010) 604–611.
[26] K. Zhang, Y. Li, J.D. Schwartz, M.S. ONeill, What weather variables are important in predicting heat-related mortality? A new application of statistical learning methods, Environ. Res. 132 (2014) 350–359.
[27] E. Fischer, R. Knutti, The energetic basis of the urban heat island robust projections of combined humidity and temperature extremes, Nature Clim. Change (3) (2013) 126–130.
[28] B. Armstrong, et al., The role of humidity in associations of high temperature with mortality: A multicountry, multicity study, Environ. Health Perspect. 127 (10) (2019).
[29] S. Hajat, Y. Prestos, J. Araya-Lopez, T. Economou, J. Lelieveld, Current and future trends in heat-related mortality in the mena region: a health impact assessment with bias-adjusted statistically downscaled CMIP6 (SSP-based) data and Bayesian inferences, Lancet Planet. Hearth 7 (4) (2023) E282–E290.
[30] K.W. Oleson, A. Monaghan, O. Wilhelmi, M. Barlage, N. Brunsell, J. Feddema, L. Hu, D.F. Steinhoff, Interactions between urbanization, heat stress, and climate change, Climatic Change 129 (3) (2015) 525–541.
[31] Y.T. Cheng, S.C.C. Lung, J.S. Hwang, New approach to identifying proper thresholds for a heat warning system using health risk increments, Environ. Res. 170 (2019) 282–292.
[32] K. Wiru, F.B. Oppong, O. Agyei, C. Zandoh, O.E. Nettey, R. Adda, A. Gasparrini, K.P. Asante, The influence of apparent temperature on mortality in the kintampo health and Demographic Surveillance Area in the middle belt of ghana: A retrospective time-series analysis, J. Environ. Public Health 2020 (2020).
[33] L.G. Ioannou, K. Mantzios, L. Tsoutsoubi, S.R. Notley, P.C. Dinas, M. Brearley, Y. Epstein, G. Havenith, M.N. Sawka, P. Bröde, I.B. Mekjavic, G.P. Kenny, T.E. Bernard, L. Nybo, A.D. Flouris, Indicators to assess physiological heat strain - part 1: Systematic review, Temperature 3 (9) (2022) 227–262.
[34] V. Kendrovski, M. Baccini, G.S. Martinez, T. Wolf, E. Paunovic, B. Menne, Quantifying projected heat mortality impacts under 21st-centurywarming conditions for selected European countries, Int. J. Environ. Res. Public Health 14 (7) (2017).
[35] P. Watkiss, A. Hunt, Projection of economic impacts of climate change in sectors of europe based on bottom up analysis: human health, Clim. Change 112 (2012) 101–126.
[36] A. Vicedo-Cabrera, Y. Guo, F. Sera, V. Huber, C.F. Schleussner, D. Mitchell, S. Tong, M.d.Z.S. Coelho, P.H.N. Saldiva, E. Lavigne, P.M. Correa, N.V. Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, J.J. Jaakkola, N.R. Ryti, M. Pascal, P.G. Goodman, A. Zeka, P. Michelozzi, M. Scortichini, M. Hashizume, Y. Honda, M. Hurtado-Diaz, J. Cruz, X. Seposo, H. Kim, A. Tobias, C. Íñiguez, B. Forsberg, D.O. Åström, M.S. Ragettli, M. Röösli, Y.L. Guo, C.f. Wu, A. Zanobetti, J. Schwartz, M.L. Bell, T.N. Dang, D. Do Van, C. Heaviside, S. Vardoulakis, S. Hajat, A. Haines, B. Armstrong, K.L. Ebi, A. Gasparrini, Temperature-related mortality impacts under and beyond Paris agreement climate change scenarios, Clim. Change 150 (3–4) (2018) 391–402.
[37] D. Anthoff, R.S. Tol, The climate framework for uncertainty, negotiation and distribution (FUND), technical description, version 3.9, Www.Fund-Model.Org 26 (2014) 1–69.
[38] M. Ikefuji, J.R. Magnus, H. Sakamoto, The effect of health benefits on climate change mitigation policies, Clim. Change 4467 (126) (2014) 229–243.
[39] V. Lupi, S. Marsiglio, Population growth and climate change: A dynamic integrated climate-economy-demography model, Ecol. Econom. 107011 (184) (2021) 229–243.
[40] R. Bressler, The mortality cost of carbon, Nature Commun. 4467 (12) (2021).
[41] K. Rennert, F. Errickson, B.C. Prest, et al., Comprehensive evidence implies a higher social cost of CO2, Nature 107011 (610) (2022) 687–692.
[42] K.R. Cromar, et al., Global health impacts for economic models of climate change: A systematic review and meta-analysis, Ann. Am. Thorac. Soc. 7 (19) (2022) 1203—-1212.
[43] F. Estrada, W.J.W. Botzen, Economic impacts and risks of climate change under failure and success of the Paris agreement, Ann. New York Acad. Sci. (2021) nyas.14652.
[44] P. Ignjacevic, W.J.W. Botzen, F. Estrada, O. Kuik, P. Ward, T. Tiggeloven, CLIMRISK-RIVER: Accounting for local river flood risk in estimating the economic cost of climate change, Environ. Model. Softw. 132 (2020) 104784.
[45] F. Estrada, W.J.W. Botzen, R.S. Tol, A global economic assessment of city policies to reduce climate change impacts, Nature Clim. Change 7 (6) (2017) 403–406.
[46] A. Hunt, P. Watkiss, Climate change impacts and adaptation in cities: A review of the literature, Clim. Change 104 (1) (2011) 13–49.
[47] P. Ignjacevic, F. Estrada, W.J.W. Botzen, Time of emergence of economic impacts of climate change, Environ. Res. Lett. 16 (7) (2021) 074039.
[48] M. Meinshausen, S.C.B. Raper, T.M.L. Wigley, Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6–part 1: Model description and calibration, Atmos. Chem. Phys. 11 (4) (2011) 1417–1456.

[49] K. Riahi, D.P. van Vuuren, E. Kriegler, J.A. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K.L. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, M. Tavoni, The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environ. Change 42 (2017) 153–168.

[50] A. Alberini, A. Hunt, A. Markandya, Willingness to pay to reduce mortality risks: Evidence from a three-country contingent valuation study, 2006.

[51] OECD, Mortality risk valuation in environment, health and transport policies, in: Mortality Risk Valuation in Environment, vol. 9789264130807, OECD Publishing, Paris, 2012, pp. 1–139.

[52] W. Szewczyk, J. Ciscar, I. Mongelli, A. Soria, JRC PESETA III Project: Economic Integration and Spillover Analysis, Technical Report, Publications Office of the European Union, Luxembourg, 2018.

[53] K. Chen, A.M. Vicedo-Cabrera, R. Dubrow, Projections of ambient temperature- and air pollution-related mortality burden under combined climate change and population aging scenarios: a review, Curr. Environ. Health Rep. 7 (3) (2020) 243–255.

[54] G. Toloo, G. Fitzgerald, P. Aitken, K. Verrall, S. Tong, Evaluating the effectiveness of heat warning systems: Systematic review of epidemiological evidence, Int. J. Public Health 58 (5) (2013) 667–681.

[55] P.L. Kinney, Temporal trends in heat-related mortality: Implications for future projections, Atmosphere 9 (10) (2018) 409.

[56] J. Ballester, M. Quijal-Zamorano, R.F. Méndez Turrubiates, F. Pegenaute, F.R. Herrmann, J.M. Robine, X. Basagaña, C. Tonne, J.M. Antó, H. Achebak, Heat-related mortality in Europe during the summer of 2022, Nature Med. 29 (7) (2023) 1857–1866.

[57] L. Feyen, J.C. Ciscar Martinez, S. Gosling, D. Ibarreta Ruiz, A. Soria Ramirez, A. Dosio, G. Naumann, S. Russo, G. Formetta, G. Forzieri, et al., Climate Change Impacts and Adaptation in Europe. JRC PESETA IV Final Report, Technical Report, Joint Research Centre (Seville site), 2020.

[58] P. Masselot, M. Mistry, J. Vanoli, R. Schneider, T. Iungman, D. Garcia-Leon, J.-C. Ciscar, L. Feyen, H. Orru, A. Urban, et al., Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in europe, Lancet Planet. Health 7 (4) (2023) e271–e281.

[59] A.M. Vicedo-Cabrera, N. Scovronick, F. Sera, D. Royé, R. Schneider, A. Tobias, C. Astrom, Y. Guo, Y. Honda, D. Hondula, et al., The burden of heat-related mortality attributable to recent human-induced climate change, Nat. Clim. Change 11 (6) (2021) 492–500.

[60] Y. Wu, S. Li, Q. Zhao, B. Wen, A. Gasparrini, S. Tong, A. Overcenco, A. Urban, A. Schneider, A. Entezari, et al., Global, regional, and national burden of mortality associated with short-term temperature variability from 2000–19: a three-stage modelling study, Lancet Planet. Health 6 (5) (2022) e410–e421.