

Future heat-related mortality in Europe driven by compound day-night heatwaves and demographic shifts

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This study attempts to investigate the future burden of humid-heat related mortality in the context of aging and day-night warming. In general, the paper is interesting and important, but I still have a lot of questions and comments.

Abstract. It is not clear what you mean with day-night compound hot extremes. Heat extreme at day and night using percentiles? You should give some more insights here.

L61. I would be more precise since not for all locations it will be so: "Climate model projections suggest that the percentage of area where heat wave magnitude and peak are amplified by humidity increases with increasing warming levels." (<https://www.nature.com/articles/s41598-017-07536-7>)

L69. I mean that's not correct for all European countries, there is high variability (exceptions are Spain, Italy, Greece). According to a recent report, the rate has already doubled.

<https://www.oecd.org/about/publishing/TheFutureofCooling2018Corrigendumpages.pdf>

There is a better indicator for Europe: share of population living in a dwelling not comfortably cool in summer: <https://www.eea.europa.eu/data-and-maps/figures/percentage-of-households-unable-to>

In addition, it also depends on socioeconomic factors.

L105-106. If I understand correctly, you estimated the humidex for daytime and day-night? I would suggest adding more details on definition for day-night. In the same context, it would be better to extend the methods used in the results section (time series regression models using a distributed lag non-linear model over lags of 0-3 days?) and data (mortality, temperature data, CMIP5, etc). Until results it is unclear which temporal scale you are using. If I understand correctly, weekly or days? If daily, does it seem the humidex is estimated on a weekly basis? Why?

L112. See also recent study on aging and climate change heat and cold related mortality: <https://www.nature.com/articles/s41467-024-45901-z>

L131. Strongest effects in the same week? As you use a weekly scale it is more limited to evaluate lag effects which for heat are usually only of a lag 0 to 7 days.

L136. You should be more clear when you change from weekly to daily scales, I guess it should be "When heat duration exceeds 3 days in a week". I am not sure if you have stated the analysis of consecutive days. If not, you should do it. What are the results for 1, 2 or even more than 3 consecutive or not consecutive days? As you work at weekly basis, it could be interesting to see differences between several hot day-night events in one week but not necessary consecutive.

L160. Have you defined what you consider heat? I guess all index ranges above the minimum mortality threshold? See https://journals.lww.com/epidem/fulltext/2023/03000/heat_attributable_mortality_in_the_summer_of_2022.19.aspx

L177. Regions are defined on which criteria? Maybe you should use the UN definition.

L188. The list of all combinations of SSP and RCP doesn't really help.

L289. It is misleading to talk about 2024-2080 when actually only 2025-2030, 2075-2080 is meant. Or have you analysed the whole period? It's not really clear for me.

L301. Here you mention warm season, but you analysis was mainly summer (Jun-Aug).

L295. I am wondering how it is with 1, 2, 3 or even more consecutive days. What happens at the beginning and end in summer (usually risks decrease with seasonal adaptation).

L310-. See also other non-european studies: <https://pubmed.ncbi.nlm.nih.gov/37495061/>, <https://pubmed.ncbi.nlm.nih.gov/37172196/>, [https://www.thelancet.com/journals/lanph/article/PIIS2542-5196\(22\)00139-5/fulltext](https://www.thelancet.com/journals/lanph/article/PIIS2542-5196(22)00139-5/fulltext)
Maybe another limitation to discuss would be the exposure indoor vs outdoor.

L386. As you use weekly mortality data you will clearly lose a lot of daily variability. This is a huge limitation. See

[https://www.thelancet.com/journals/lanep/article/PIIS2666-7762\(23\)00198-9/fulltext](https://www.thelancet.com/journals/lanep/article/PIIS2666-7762(23)00198-9/fulltext)

In this context, it is not clear for me which kind of statistical summary you use at weekly scale for humidex? maximum, mean? It would even be interesting to conduct sensitivity analysis changing the kind of metric used.

L399. I would recommend to use a population weighted approach for the humidex estimation based on gridded data (see

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GH000363>)

You should find a better way to guide the reader in the steps here. Maybe a summary first, explaining several steps for climate data, analysis etc. Figure 5 could be a good place to start.

L406. For me the use of CESM-LENS is not enough justified, particularly, because it is based on CMIP5. The same community has already finished the second version from the CMIP6, hence I would recommend updating to the new version. This would also make it more coherent with the used SSP in population age estimations.

L448. It would be better to use night definition based on local sunrise/sunset, to account on sessional and latitudinal variation.

L450. Which is the threshold? I would add reference to the definition.

L454. Why don't you use 95P of hourly diurnal temperatures and the same for the night period.

L455. Why 15 days? You should justify the decision. I guess it is to consider the idea that people acclimate to their local climate with respect to its temperature variation throughout the year. I would even go to the window of 30 days or at least try how it changes the results. <https://pubmed.ncbi.nlm.nih.gov/35460514/>, <https://www.mdpi.com/1660-4601/12/1/227>

Some other general comments:

Methods: I couldn't read any formula as they were strange symbols

I find the study period very short (2015-2019). Wouldn't it be possible to control pandemic the COVID pandemic? In particular for a seasonal analysis (weeks 22-35) and on a weekly scale. Why don't you use the local warm season? Is the definition fixed for the projections? I mean the warm season is changing in the future. So I am not sure if it would be right to use a fixed period. In the same sense, do you really have enough statistical power for all locations within only 6 years?
<https://bmcmmedresmethodol.biomedcentral.com/articles/10.1186/s12874-019-0894-6>

The role of humidity is still under discussion and appears to be site-dependent: <https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.8160>, and see also: <https://ehp.niehs.nih.gov/doi/full/10.1289/EHP5430>

You should explain and discuss more in detail the physiological standpoint with the biological mechanisms for hot temperature and humidity.

Figures:

1a. I would add the baseline for RR at 1.

1d. I suggest using column fill for region groups instead of symbols. Actually, I would also place the region legend below and make it smaller in order to reduce clutter. I am not really sure if there is a second light gray bar, if so, it is a good idea to place overlapping symbols.

2. I don't remember if you defined the used periods (2075-2080), why those? Why only 6 years? What about the mid-century?

2a The symbol for the RCP8.5 as a not filled circle isn't easy to see.

2b. If SSP5 is the worst scenario, why do you use a dark red color for SSP1? You should select coherent coloring. Legend for RCP is not needed as you use different facets. I would place the legend of SSP below both facets.

3. Please use ETRS89-extended / LAEA Europe. Country labelling is really helping, I would remove them all. Maybe you can highlight some regions with highest risks. Border lines between countries look better using white color. I recommend adding a title to each facet, since without the reader has to go to the caption. Finally, a single colorbar as legend would be better, instead of a two row legend. I don't see the need to add a scale. Maybe a graticulate could be useful. A diverging color palette is not recommended if there isn't any midpoint. In this case a sequential palette would be ideal or define a reference midpoint. You must also report here death by population, if not, it is a population map. For instance, in Spain Madrid and Barcelona both have high death numbers because they are the most populated regions.

4. From my point of view the use of line-area chart is not really helping to understand the difference between both (dashed and solid line). The meaning of both lines should be included in the graph.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

This is potentially an interesting and important study that tries to unpick the role of demographic and climate change on the evolving mortality burden from extreme humid heat. However, there are a number of significant issues with the paper. I highlight the 'major' concerns below; more minor comments are included as PDF annotations (attached with my review).

On the basis of these, recommend rejection and resubmission at this stage – due to the significant issues related to model validation and the deployment of the climate scenarios. These aspects require modifications to the analysis, and I cannot anticipate how substantially this will affect the results/conclusions (e.g., it might be that integrating humidity via the Humidex does not lead to more skilful predictions after all, and hence the key results/significance would change).

Encouraging resubmission would enable the authors to take their time to revisit the key issues, whilst leaving the door open for publication if their findings (which are of interest) remain robust.

Major comments

1. Model calibration and validation

The authors present in the calibration the results of their cross-validation procedure in Supplementary Figure 5, which shows a comparison between predicted and observed mortality in the 954 regions. However, so far as I understand, this shows total mortality, which is highly dependent on the baseline population. The comparison should be between observed and predicted excess (heat) mortality. For example, I imagine one could get quite close to the observed mortality in any one year for a particular region by simply using the long-term (all, non-pandemic years) mean mortality?

The significant issue above is highlighted quite clearly when the authors 'test' their model when forced with 2023 projections of climate change (from RCP4.5 and RCP8.5) against observed mortality. Unfortunately this is nonsensical: the weather "which actually occurred in 2023" will of course be different from the random ensemble generated by the climate model simulations for that year. Agreement between your projected mortality and observed mortality therefore mostly represents everything "but" the impact from the heat/humidity that prevailed during that year. This issue seems to represent a misunderstanding of what the climate model simulations represent (explained in point #2) – it goes beyond an inappropriate method of validation.

To summarise, then, the model validation needs to be rethought. First, "excess" deaths should be compared between simulations and observations. Second, rather than 2023, a far more convincing test would be to assess to what extent your calibrated models could capture the excess mortality in 2022 – an extreme year more similar (in temperature and humidity distributions) to the future, warmer climates that you're investigating. And please note that you can't validate using the RCPs as they're storylines – not predictions.

2. The 'humid' heat component

The authors contend that their analysis moves beyond earlier work by asserting that inclusion of humidity (through the humidex) improves the modelling of heat related mortality. However:

The statistical significance of this very small reduction in the RMSE is not commented on (unless I missed it)?

The authors seem to neglect the very substantial body of work that has probed this topic at length (and which concludes that, in general, adding a humidity term does not improve model skill). Please see: Baldwin, J.W., Benmarhnia, T., Ebi, K.L., Jay, O., Lutsko, N.J. and Vanos, J.K., 2023. Humidity's role in heat-related health outcomes: a heated debate. *Environmental health perspectives*, 131(5), p.055001 for a recent overview. At the very least, the authors need to interpret their results in the context of such work.

Related to the above: why did the authors choose the Humidex versus any one of the other many combined temperature-humidity measures (e.g., wet-bulb temperature, simplified wet-bulb globe temperature, wet-bulb globe temperature, heat index, equivalent temperature, universal thermal climate index)?

3. Deployment of the climate scenarios

The RCPs and SSPs are combined inappropriately. For example, RCP8.5 is incompatible with SSP1. Please read the relevant literature and either justify the approach taken here, or reconsider the scenarios considered. A readable overview of this issue is available courtesy of the Carbon Brief: <https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/>

4. Headline findings

The headline messages need reconsideration, regardless of the other concerns raised above. Concluding that declining total population can 'offset' the climate induced rise in heat mortality is, I contend, an unhelpful framing. 'Impact' will surely be felt by the change in heat mortality per capita rather than the total? That is, if global population declined by a factor of 10, and the likelihood of dying from extreme heat increased by a factor of 10, would we really regard that as no change in the heat mortality burden? To avoid any such interpretation, I suggest that the authors reconsider their framing throughout.

(Remarks on code availability)

I have looked at the database, but have not reviewed the code in detail. What I can see, though, is that there is a README that describes (albeit very briefly) what the different scripts do. However, there is insufficient integration with the datasets (or explanation about which data should be fed into which script) to make the work reproducible.

In the context of the above, I do wonder how authors are supposed to satisfy such requirements -- given that often datasets will be far too large to be managed locally. In such cases, some code may be run on a remote server to cut out/manage data there, and other code would be used to process derived data locally. Really, everything would be required for reproducibility, but so too would the access to the remote server!

Reviewer #3

(Remarks to the Author)

I was kindly asked to review the manuscript: Future burden of humid-heat related mortality in Europe aggravated by compound day-night warming and aging. This is a well written and well detailed manuscript. Such study is highly relevant as it could add to the scientific body of knowledge and address a pressing public health issue, but I would encourage them to consider the following:

The introduction section should be reorganized, provide additional information related to the methods followed in previous studies and highlight the gap of knowledge that this study seeks to fill.

Please, provide a statement of why this research is particularly novel aside from the study area.

Methods:

Could the authors provide more information on the control the validity of the results?

A)Rodrigues, M., Santana, P. & Rocha, A., 2019. Bootstrap approach to validate the performance of models for predicting mortality risk temperature in Portuguese Metropolitan Areas. Environ Health 18, 25. <https://doi.org/10.1186/s12940-019-0462-x>

B)Rodrigues, M., Santana, P. & Rocha, A., 2019. Effects of extreme temperatures on cerebrovascular mortality in Lisbon: a distributed lag non-linear model. Int J Biometeorol 63, 549–559.

Discussion

Overall, the discussion of findings is complete and concise. The results are adequately compared with previous work, explanations are proposed for the results observed and limitations are well discussed.

Conclusions

Include suggestions for how the analyses could be incorporated into public health programs.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have satisfactorily answered my questions.

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)

I found the paper interesting and well written.

However, I have here few comments for improvement:

- there is a recent paper at [https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667\(24\)00179-8/fulltext](https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667(24)00179-8/fulltext) on a similar topic. Please reference it, explaining also the differences between the 2 (yours, this one) proposed approaches

- fig 1: the "Italy" case is much higher then the other countries...please explain why, and better describe this behavior

- fig 3: why some countries (i.e. Ireland) are missing from the map?

- fog 4: it is not clear how the decomposition approach works...can you elaborate more on this, in the text?

(Remarks on code availability)

Reviewer #5

(Remarks to the Author)

This is a study in which the authors aim to analyse the "Future heat-related mortality in Europe driven by compound day-night heatwaves and demographic shifts". In my opinion, this study has two major methodological shortcomings that detract from the scientific validity of the results obtained.

Firstly, the authors define a heat wave on the basis of the 95th percentile of the average temperature series for the summer months.

Defining a heat wave with a similar percentile for all European countries means admitting that socio-economic, demographic and adaptation factors do not influence mortality attributable to temperature, which goes against scientific evidence and the WHO itself, which states in chapter 3 of this document on prevention plans in Europe that the health effects of heat waves cannot be based on fixed percentiles but on previous epidemiological studies of temperature-mortality that determine the temperatures above which mortality increases : "Threshold levels in heat waves should be based on health risks and not only on meteorological conditions" <https://iris.who.int/bitstream/handle/10665/339462/9789289055406-eng.pdf>.

A good example of this is the Spanish Plan de Prevención de Prevención ante altas temperaturas in which up to 182 different regions with different temperatures and percentiles are determined in a single country.

https://www.sanidad.gob.es/areas/sanidadAmbiental/riesgosAmbientales/temperaturasExtremas/planAltasTemperaturas/2024/docs/Plan__Excesos_Temperaturas_2024.pdf

The second major methodological deficiency is that the authors maintain the RR calculated for the period 2010-2019 constant over time and only allow changes in the population for the calculation of attributable mortality. This goes against the scientific evidence that shows that in Europe and around the world there is a decrease in the risks attributable to high temperatures as a consequence of adaptation processes.

I recommend that the authors read these articles together with others that calculate the impact of heat waves on the 2050-2100 horizon taking into account adaptation processes and how to consider them in impact projections.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #5

(Remarks to the Author)

I thank the authors for their responses to my comments on the original manuscript.

However, the two substantive issues raised (the first regarding the choice of a fixed percentile and the second regarding the assumption of constant RRs over time) have not been resolved.

These are not mere limitations of the study as the authors would have us believe by including some paragraphs in the revised version of the manuscript.

'It is important to emphasise that the thresholds used in this study were not definitive health-based heatwave definitions.

definitive health-based heatwave definitions but were instead intended to identify extreme weather conditions relative to historical status. These thresholds served as a tool to explore the relationship between extreme heat and health impacts, but we acknowledge the need for localised and health risk-based definitions of heatwaves.

These are substantive issues that detract from the validity of the results presented.

My decision is to again reject the manuscript for publication in Nature Communications until these shortcomings are resolved.

(Remarks on code availability)

Version 4:

Reviewer comments:

Reviewer #5

(Remarks to the Author)

I thank the authors for their efforts in answering the questions raised.

From my point of view, the comments have been satisfactorily resolved this time. From my point of view the manuscript can be accepted for publication.

(Remarks on code availability)

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Reviewers' comments:

Reviewer #1 (Remarks to the Author):

This study attempts to investigate the future burden of humid-heat related mortality in the context of aging and day-night warming. In general, the paper is interesting and important, but I still have a lot of questions and comments.

Response: We are grateful for the reviewer's valuable suggestions and constructive comments, which significantly improved the quality and clarity of our manuscript. We have tried our best to address the concerns you raised, hoping that the readability of the revised manuscript has been improved.

Abstract. It is not clear what you mean with day-night compound hot extremes. Heat extreme at day and night using percentiles? You should give some more insights here.

Response: Sorry for the confusion. We have revised the abstract to clarify the concept of "day-night compound hot extremes." We now define it as **"day-night compound hot extremes (where both day and night temperatures exceed certain percentiles)."**

L61. I would be more precise since not for all locations it will be so: "Climate model projections suggest that the percentage of area where heat wave magnitude and peak are amplified by humidity increases with increasing warming levels. "[\(\(https://www.nature.com/articles/s41598-017-07536-7](https://www.nature.com/articles/s41598-017-07536-7)

Response: We appreciate your comment. We have revised the relevant sentence to more accurately reflect the variability across different locations. To make it clearer, the related content has been revised as: **"Climate models consistently predict that as the world warms, more land will be exposed to humid heat and compound hot extremes"**

L69. I mean that's not correct for all European countries, there is high variability (exceptions are Spain, Italy, Greece). According to a recent report, the rate has already doubled.

<https://www.oecd.org/about/publishing/TheFutureofCooling2018Corrigendumpages.pdf>

There is a better indicator for Europe: share of population living in a dwelling not comfortably cool in summer: <https://www.eea.europa.eu/data-and-maps/figures/percentage-of-households-unable-to>

In addition, it also depends on socioeconomic factors.

Response: Thank you for your insightful comments and for pointing out a more accurate indicator. We agree that using the share of the population living in a dwelling

not comfortably cool in summer is a better measure, as it considers income and urbanization levels. Following your suggestion, we have revised the relevant description to: **“ Although Europe's developed economy allows for better adaptation to extreme heat, nearly 21.4% of the population lived in dwellings that were not comfortably cool during summers until 2020 ”**

L105-106. If I understand correctly, you estimated the humidex for daytime and day-night? I would suggest adding more details on definition for day-night.

Response: Sorry for any confusion caused by the expression used in the manuscript. Actually, we have estimated the hourly Humidex and then categorized it into daytime and nighttime periods. To clarify, daytime and nighttime periods are defined based on local sunrise and sunset times. We have updated our Methods section to provide detailed explanations for these definitions **“Each day was divided into two subperiods: the day, which lasted from sunrise to sunset and the night, which lasted from sunset to sunrise. The Google Earth Engine platform’s SunCalc package was used to determine the precise sunrise and sunset times for each day and location.”**

Also, it is important to note that daytime, nighttime, and day-night categorizations are not used to divide the Humidex estimates but rather to classify the types of extreme heat. We have provided further explanations in the Introduction and Methods sections **“To address these challenges, we developed a comprehensive, Europe-wide fine-grained dataset that incorporates an integrated metric of temperature and humidity (i.e., the Humidex) and a range of heat extremes categories. ...**

Previous studies showed that human thermoregulation varies with environmental conditions, indicating that long-term evolution may lead to adaptive diversification to hot extremes. Thus, we defined a hot day/night threshold as the mean temperature throughout the day or night exceeding the 95th percentile of its local daily climatology. The period-based percentile for a specific location was determined using a 15-day-long time window centered on each calendar day over 1961 – 2022. If the mean temperature of either the daytime or nighttime sub-period was higher than the threshold, we identified it as a hot extreme. If the hot extreme occurred solely during the daytime or nighttime, we labeled it as a daytime-only hot extreme (DH) or nighttime-only hot extreme (NH). If the hot extreme occurred throughout the daytime and nighttime, we defined it as a day-night compound hot extreme (CH). Additionally, we divided the DH, NH, and CH within the week into consecutive (CDH, CNH, CCH) and non-consecutive (NDH, NNH, NCH) events.”

In the same context, it would be better to extend the methods used in the results section (time series regression models using a distributed lag non-linear model over

lags of 0-3 days?) and data (mortality, temperature data, CMIP5, etc). Until results it is unclear which temporal scale you are using. If I understand correctly, weekly or daily? If daily, does it seem the humidex is estimated on a weekly basis? Why?

Response: Thank you for pointing out the need for additional clarity regarding the methods and temporal scale used in our study. In fact, limited by the availability of mortality data, our study was conducted on a weekly basis. To address your concern, we have added more detailed explanations of our methodology and the data used. Specifically, we have revised the following description “**To address these challenges, we developed a comprehensive, Europe-wide, fine-grained dataset that incorporates an integrated metric of temperature and humidity (i.e., the Humidex) and a range of extreme heat categories. Using data aggregated from hourly to weekly intervals, a Quasi-Poisson generalized regression combined with a distributed lag non-linear model was employed to estimate location-age specific associations between weekly mortality and Humidex, consecutive and inconsecutive daytime, nighttime and diurnal compound hot extremes across 955 NUTS3-level (the most detailed level of the Nomenclature of territorial units for statistics classification) regions in 34 European countries. After validating the robustness and prediction accuracy of the model, we projected future heat-related mortality per capita at different levels of global warming from 2024 to 2100, by combining single-model large-ensemble simulations with population size and age-structure projections. Finally, a decomposition approach was used to identify the roles of climate change, population growth, and aging in the future burden of heat-related mortality in Europe.**”

L112. See also recent study on aging and climate change heat and cold related mortality: <https://www.nature.com/articles/s41467-024-45901-z>

Response: Thanks for highlighting this valuable work. This insightful research has further informed our understanding and approach to the effects of aging and climate change on mortality. We have incorporated relevant findings and citations from this study into our manuscript.

L131. Strongest effects in the same week? As you use a weekly scale it is more limited to evaluate lag effects which for heat are usually only of a lag 0 to 7 days.

Response: Yes. Our findings indicate that the strongest effects of hot extremes occur within the same week. Actually, it doesn't conflict with your point that the heat lag effect generally spans 0-7 days. We have reviewed numerous studies to ensure our approach is consistent with existing research. For instance, the referenced article from Nature Medicine (<https://www.nature.com/articles/s41591-023-02419-z#Sec9>) considers a lag of up to 3 weeks on a weekly scale. Additionally, studies based on

daily scales also account for lag effects up to 21-30 days, such as those found in (<https://www.sciencedirect.com/science/article/pii/S2542519621000814#cesec20>) and (<https://ehjournal.biomedcentral.com/articles/10.1186/s12940-019-0462-x#Sec2>). These references confirm that the most significant lag effects are indeed within the 0-7 days, although some regions may exhibit lag effects beyond this period. Therefore, we opted to retain the consideration of lag effects in our analysis.

L136. You should be more clear when you change from weekly to daily scales, I guess it should be “When heat duration exceeds 3 days in a week”. I am not sure if you have stated the analysis of consecutive days. If not, you should do it. What are the results for 1, 2 or even more than 3 consecutive or not consecutive days? As you work at weekly basis, it could be interesting to see differences between several hot day-night events in one week but not necessary consecutive.

Response: Thank you for bringing this to our attention. Yes, since our work is based on a weekly scale, we previously focused on observing the impact of the number of days with diurnal events occurring within a week and did not consider whether these events were consecutive. Following your suggestion, the model has been further modified in the reviewed version. We observed that when heat events exceed three days within a week, they are usually consecutive. Therefore, we mainly compared the risk differences between non-consecutive 1 day, 2 days and consecutive 1 day, 2 days, and ≥ 3 days of hot extreme.

And the results have shown as: “We classified heat events within a week into six types: consecutive daytime-only hot extreme (CDH), consecutive nighttime-only hot extreme (CNH), consecutive compound day-night hot extreme (CCH), non-consecutive daytime-only hot extreme (NDH), non-consecutive nighttime-only hot extreme (NNH), and non-consecutive compound day-night hot extreme (NCH). This allows us to observe the impacts of consecutive and non-consecutive extreme heat on mortality. As extreme heat events usually occur consecutively when they last more than three days within a week, our results suggest that non-consecutive extreme heat does not significantly increase mortality risk (Fig. 1b). Consecutive daytime-only heat is linked to a 1.5-fold increased risk of death in individuals of working-age and children compared to consecutive day-night compound hot extremes (Fig. 1c). However, this effect is reversed in older adults for consecutive day-night compound hot extremes, the relative mortality risk is 2.9 times higher than for consecutive daytime-only hot extremes with the same duration (Fig. 1c)”

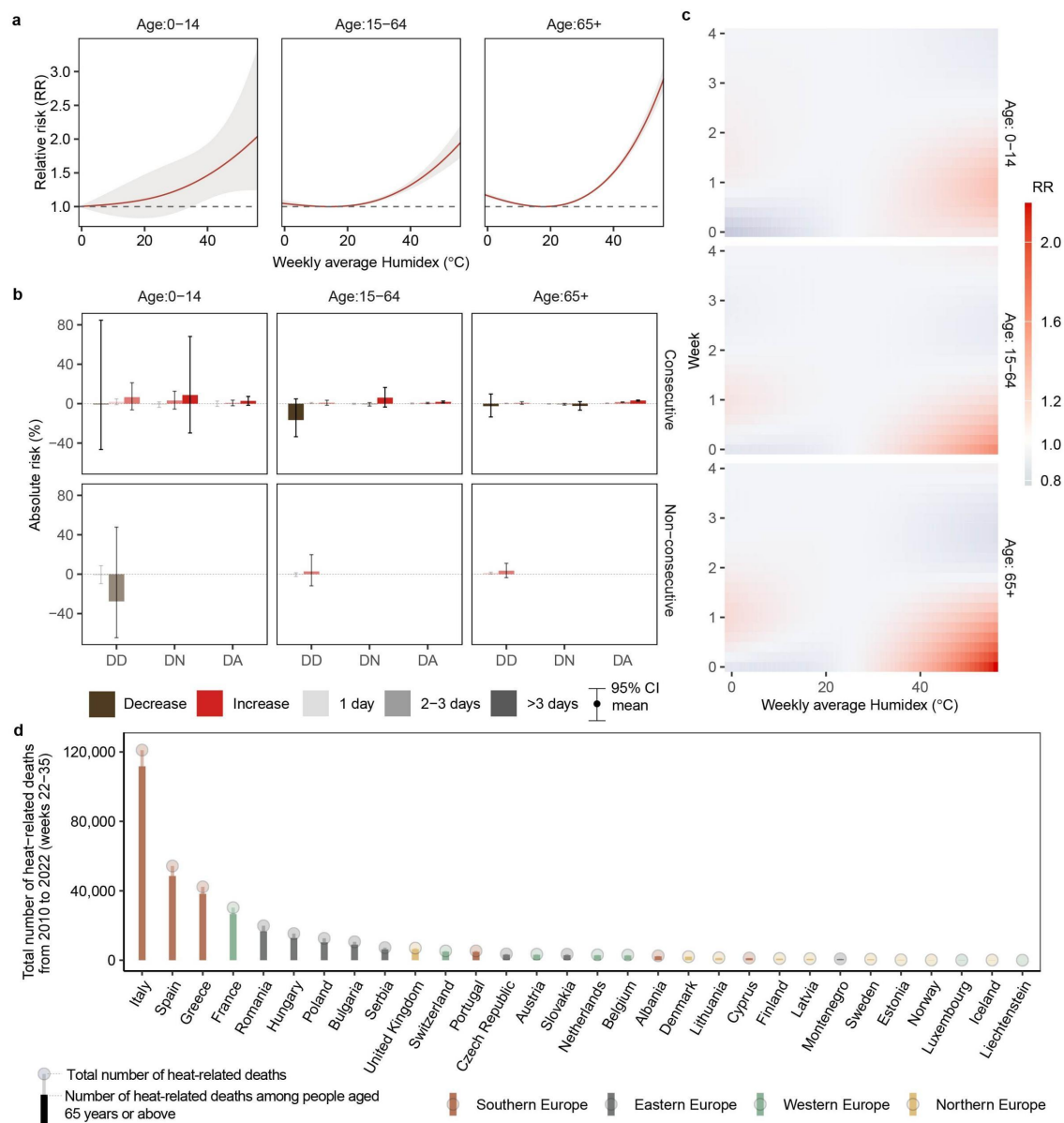


Fig. 1. Heat-mortality associations and heat-related deaths in Europe. (a) Cumulative relative risk-weekly humidex response curves for three age groups: children (aged 0–14 years), the working-age population (aged 15–64 years), and the elderly (aged 65 years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group. (b) Heat map showing the lagged effects of heat exposure on mortality. The red indicates an increased mortality risk ($RR > 1$), while the blue indicates a decreased mortality risk ($RR < 1$). (c) Bar chart of the variation of mortality risk with the duration of heat exposure. It shows the absolute mortality risk of the day-night compound (CH) hot extremes compared to the daytime-only (DH) hot extremes. The absolute risk means the increased mortality risk in the exposure of a heat day relative to normal days. (d) The estimated total heat-related mortality in 30 European nations during the summers of 2010–2023 (weeks 22–35). These

nations are geographically divided into 4 regions: Northern, Southern, Eastern, and Western Europe, according to the United Nations Geoscheme. The dark and light grey bars represent the number of heat-related excess deaths in the elderly group and in the all-age population, respectively.

L160. Have you defined what you consider heat? I guess all index ranges above the minimum mortality threshold?

See https://journals.lww.com/epidem/fulltext/2023/03000/heat_attributable_mortality_in_the_summer_of_2022.19.aspx

Response: Thank you for raising this question. We have reviewed the reference you provided. Following a consistent methodology, we have further classified heat-related mortality estimates from 2010 to 2022. For each age group, we defined the cumulative deaths estimated to be attributable to moderate heat as the sum of deaths occurring in summer weeks with a Humidex between the optimal minimum mortality Humidex and the weekly 95th percentile threshold. We defined the cumulative deaths attributable to extreme heat as the sum of deaths in summer weeks above the weekly 95th percentile threshold. The weekly 95th percentile threshold was calculated as the average daily 95th percentile threshold within one week. The daily 95th percentile threshold was defined as the mean temperature during the daytime/nighttime exceeding the 95th percentile of its local daily climatology. The period-based percentile for a specific location was determined using a 15-day-long time window centered on each calendar day over 1961 – 2022. We summarized the number of deaths attributable to moderate and extreme heat from 2010 to 2022 among three age groups in Supplementary Table 5. Since 2015, the number of deaths caused by extreme heat has been observed to surpass those caused by moderate heat. In 2022, the cumulative deaths estimated to be attributable to moderate heat were 22,120 (95% CI 19,182-25,332), while 24,809 (21,915-27,872) heat-related deaths were estimated to be attributable to extreme heat. Among these, the number of deaths among the elderly due to extreme heat reached 22,571 (20,378-24,840). For Spain, we estimated 5,113 (4,512-5,735) deaths attributable to extreme heat, which is similar to the results obtained in the reference you provided (5316, 95% CI 5,050-6,825).

The related results have been added in results section as **“We estimated the cumulative deaths associated with moderate heat as the totality that occurs in the summer weeks with the Humidex falling between the minimum mortality Humidex and the weekly 95th percentile threshold. The cumulative deaths owing to extreme heat were calculated as those during the summer weeks with Humidex surpassing the 95th percentile threshold. The weekly 95th percentile threshold was defined as the mean value of the daily 95th percentile threshold within that week. We summarized the number of deaths among three age groups attributable to moderate and extreme heat from 2010 to 2022 (Supplementary**

Table 5). The number of heat-related excess deaths in Europe during the summer of 2022 was estimated to be 47,182 (95% CI: 41,242 – 53,664), which accounts for 12.9% (95% CI: 11.3 – 14.7%) of all summer heat-related deaths from 2010 to 2022. Extreme heat was estimated to be responsible for 24,809 (95% CI: 21,915 – 27,872) deaths, whilst moderate heat was responsible for 22,120 (95% CI: 19,182 – 25,332) deaths. It is noted that since 2015, more people have died from extreme heat than from moderate heat (Supplementary Table 5). We estimated that 5,113 (95% CI: 4,512 – 5,735) deaths in Spain were associated with extreme heat, which in line with another recent assessment that attributed 5,316 (95% CI: 5,050 – 6,825) excess deaths in Spain to extreme heat in the summer of 2022.”

Supplementary Table 5. Number of deaths attributable to moderate and extreme heat among three age group (0-14, 15-64, 65+) from 2010 to 2022.

		Humidex (°C)	Moderate heat		Extreme heat	
Age	Year	Mean	Deaths	(95% CI)	Deaths	(95% CI)
0-14	2010	20.9	28	2-93	23	0-71
15-64			632	389-941	919	635-1,218
65+			3,761	3,261-4,306	5,166	4,641-5,709
0-14	2011	21.4	35	4-108	11	0-38
15-64			786	530-1,120	475	314-650
65+			6236	5,546-7,006	3,978	3,538-4,439
0-14	2012	21.8	45	4-134	30	0-89
15-64			1112	747-1,547	992	683-1,323
65+			8358	7,444-9,326	8,160	7,333-9,021
0-14	2013	21.3	51	5-148	20	0-61
15-64			1,189	817-1,627	686	466-920
65+			9,177	8,211-10,211	5,494	4,910-6,101
0-14	2014	20.8	41	6-120	6	0-20
15-64			959	651-1,331	205	131-286
65+			6532	5,815-7,305	1,812	1,596-2,037
0-14	2015	21.1	61	4-211	72	0-213
15-64			1613	1,051-2,311	2,454	1,751-3,208
65+			11762	10,369-13,281	22,779	20,663-24,971
0-14	2016	21.6	63	7-204	43	0-136
15-64			1,560	1,063-2,180	1,378	956-1,844
65+			12,111	10,771-13,558	11,677	10,478-12,933
0-14	2017	21.9	65	5-222	48	0-149
15-64			1,720	1,144-2,433	1,866	1,319-2,461
65+			13,880	12,282-15,606	17,007	15,379-18,706
0-14	2018	22.7	78	9-243	48	0-157
15-64			2,053	1,396-2,874	1,851	1,283-2,490
65+			15,362	13,647-17,254	16,971	15,265-18,767
0-14	2019	22.4	72	5-233	64	0-197

15-64			1,931	1,281-2,710	2,368	1,655-3,131
65+			15,529	13,755-17,413	21,377	19,305-23,516
0-14	2020	22.3	51	6-145	37	0-106
15-64			1,680	1,165-2,289	1,279	914-1,674
65+			13,938	12,455-15,510	13,286	12,031-14,584
0-14	2021	22.7	64	6-179	43	43
15-64			2,051	1,416-2,777	1,988	1,988
65+			16,517	14,762-18,376	17,609	17,609
0-14	2022	23.5	65	6-184	47	0-140
15-64			2136	1,445-2,930	2,192	1,538-2,892
65+			19,920	17,732-22,219	22,571	20,378-24,840

L177. Regions are defined on which criteria? Maybe you should use the UN definition.

Response: Thanks for the reminder. Following your suggestion, we have updated the definition of regions in accordance with UN definition.

L188. The list of all combinations of SSP and RCP doesn't really help.

Response: Deleted.

L289. It is misleading to talk about 2024-2080 when actually only 2025-2030, 2075-2080 is meant. Or have you analysed the whole period? It's not really clear for me.

Response: Thank you for pointing out the potential confusion. We have indeed conducted annual predictions for each year from 2024 to 2100, not just for the periods 2025-2030 and 2075-2080. The misunderstanding arises from the fact that in the second part of results, we primarily compared the mean changes between 2025-2030 and 2075-2080.

It is important to note that our analysis includes annual predictions for each year from 2023 to 2080. To ensure a smooth trend and to minimize the impact of any anomalous years, we averaged the mortality numbers over 5-year windows. This method helps in providing a more stable estimate of the trends over time. In the revision, we have reorganized the presentation of this part of the results to prevent any confusion. Here is the revised text:

“The aforementioned exposure-response functions of heat-related mortality by three age groups were utilized to project future changes in heat-related excess mortality per capita in Europe from 2024 to 2100 (Methods). We integrated

population estimates that align with four shared socioeconomic pathways (SSP1, SSP2, SSP4, and SSP5) with single-model large-ensemble simulations under four future emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) (Methods). We found that as global warming intensifies, the per capita heat-related mortality rate increases faster (Fig. 2). Specifically, the rates are projected to rise by 109.8% (95% confidence interval: 38.0-145.7%) for SSP1-2.6, 126.4% (61.5-169.9%) for SSP2-4.5, 211.9% (121.7-270.0%) for SSP3-7.0, and 273.3% (165.0-344.7%) for SSP5-8.5 with every degree of global warming.

We compared the growth rates of heat-related deaths per capita before and after the middle of the twenty-first century (Fig. 2a). The difference between 2045-2050 and 2025-2030 (between 2095-2100 and 2045-050) was used to represent the growth rate before (after) the middle of the twenty-first century. Under the high-emission scenarios (SSP3-7.0 and SSP5-8.5), the growth rate of heat-related deaths per capita in the post-mid-century is 2.2-2.8 times higher than that in the pre-mid-century. Heat-related deaths are projected to increase by about 1 per 10,000 people per degree of global warming under SSP1-2.6 and SSP2-4.5, compared to about 2 per 10,000 people under SSP3-7.0 and about 3 per 10,000 people under SSP5-8.5 (Fig. 2b). Specifically, more than 77.0% of heat-related deaths are experienced by individuals aged 65 years or above. The growth rates of heat-related mortality with each degree of global warming show a strong spatial diversity in response to climate change and population dynamics (Fig. 2c). The largest increase in heat-related mortality per capita is found in Western Europe and Northern Europe, with an increase of rate of 266.2-600.1% and 327.3-573.2% per degree of global warming, respectively. For an additional 1°C of global warming, Southern Europe shows the lowest growth rates at 57.1-163.3%.

To better understand the spatial distribution of future health burdens, the cumulative number of heat-related deaths per 10,000 people is illustrated in Fig. 3. For various population-emission combinations, the cumulative number of heat-related summer deaths per 10,000 inhabitants in Europe might surpass 56.2-119.5 if the global warming exceeds 2.5°C. Summer heat might lead to more than 244.3 per 10,000 individuals in Europe if global warming keeps rising and surpasses 4°C. Until the end of the twenty-first century, a disproportionate increase in the negative effects of heat on health is predicted for the nations with fast-aging populations, such as Germany, Italy, Spain, France, and Slovenia. With rising global carbon emissions, new hotspots with high cumulative heat-related mortality per 10,000 persons will emerge, which include Spain (85.7-372.6), Denmark (127.0-313.1), Finland (73.5-161.2), Romania (52.9-396.1), and Bulgaria (81.4-535.4).

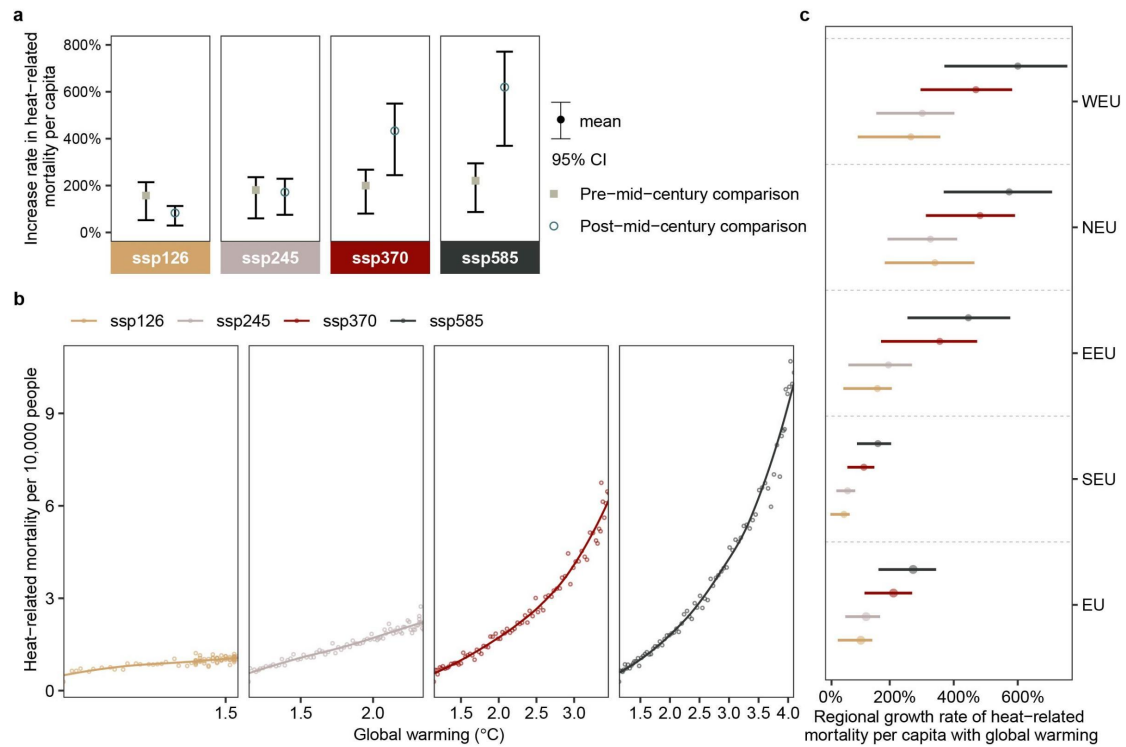


Fig 2. Projected changes in heat-related mortality in Europe. (a) The growth rate of heat-related excess mortality per capita under different climate-population scenarios. Squares and circles indicate the comparison for near-mid-century and mid-end-century, respectively. The pre-mid-century growth rate is calculated by comparing the mean mortality per capita between 2045-2055 and 2025-2030. The post-mid-century growth rate is calculated by comparing the mean mortality per capita between 2095-2100 and 2045-2055. The black bars represent the 95% confidence interval of the projected growth rate of heat-related mortality per capita. (b) The variation of heat-related deaths per 10,000 people with global warming. The global warming levels are determined by the years in which the 20-year moving average global mean surface temperature anomaly (relative to the pre-industrial period 1850-1900) exceeds specific warming levels. (c) Regional growth rates of heat-related excess mortality per capita with global warming. The growth rate is represented by the linear slope of heat-related mortality against the levels of projected global warming, i.e., the percentage change in added heat-related mortality per capita with each degree of global warming. The percentage changes are estimated relative to the 2022 baseline of 1.07 heat-related deaths per 10,000 capitals. Europe (EU) is divided into four regions: Northern (NEU), Western (WEU), Eastern (EEU), and Southern Europe (SEU), with baseline heat-related excess deaths of 0.25, 0.38, 0.74, and 2.59 per 10,000 capitals, respectively. Note that the baselines reported in 2022 differ from the previous section due to the exclusion of regions with missing data in the projections.

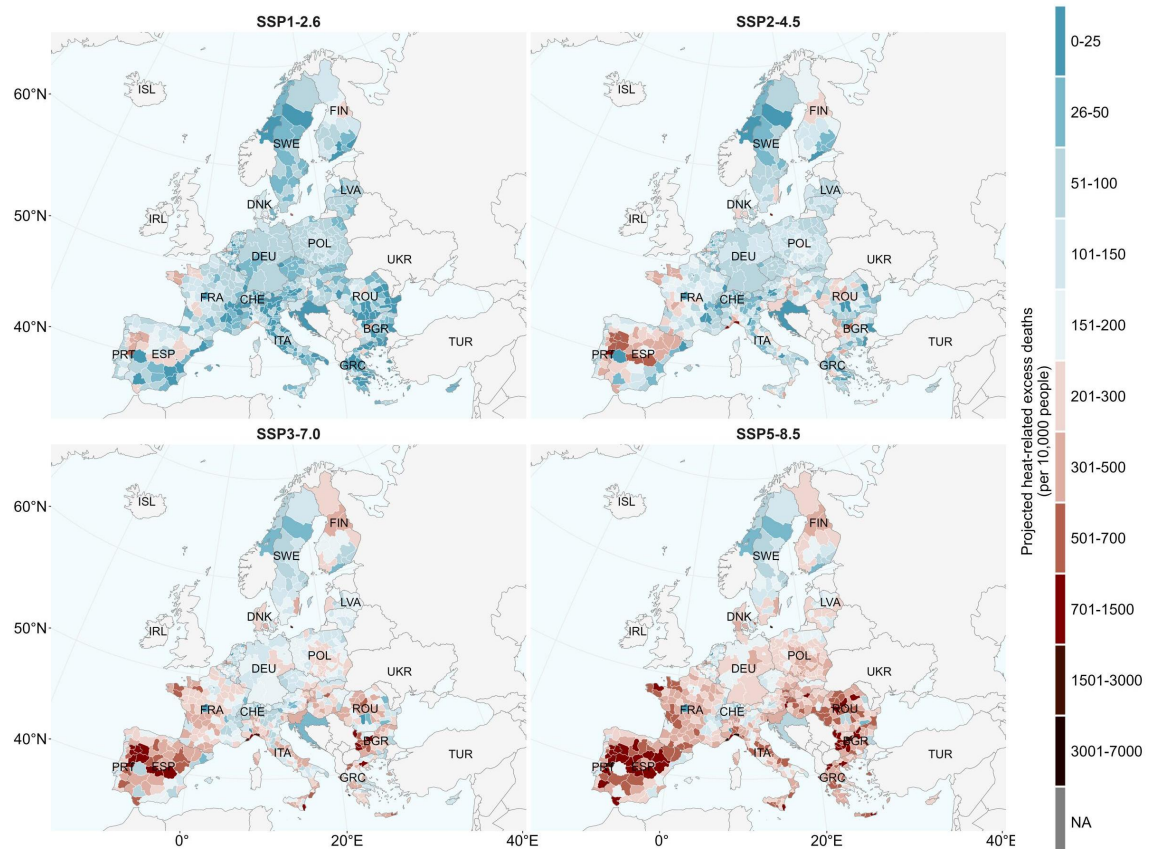


Fig 3. Geographic distributions of expected cumulative heat-related excess deaths per 10,000 people. The projected heat-related excess deaths per 10,000 people at the NUTS3 level from 2024 to 2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The regions with missing data are shaded in grey.”

L301. Here you mention warm season, but you analysis was mainly summer (Jun-Aug).

Response: Thank you for pointing this out. We have revised the relevant descriptions in the article to specify "summer (weeks 22-35)" instead of "warm season" to maintain consistency.

L295. I am wondering how it is with 1, 2, 3 or even more consecutive days. What happens at the beginning and end in summer (usually risks decrease with seasonal adaptation).

Response: It’s an insightful suggestion regarding the impact of consecutive hot days and seasonal adaptation. To address this, we have conducted additional experiments by including a seasonal factor in our model. We divided the summer into two parts (weeks 22-28 and 29-35) to examine whether the risk of heat-related mortality

decreases with seasonal adaptation. If the coefficient for this seasonal factor is negative, it would indicate the presence of seasonal adaptation.

The coefficients obtained from the model for different age groups are summarized in Table 1. Although these coefficients are negative, indicating some degree of adaptation, the actual reduction in excess mortality due to this factor is less than 1.5%. Therefore, we conclude that the effect of seasonal adaptation on mortality can be considered negligible.

Table 1. Coefficients for seasonal adaptation factor among three age group models.

Age	Coefficient	Effect
0-14	-0.0146	-1.5%
15-64	-0.0019	-0.2%
65+	-0.0029	-0.3%

L310-. See also other non-european studies: <https://pubmed.ncbi.nlm.nih.gov/37495061/>, <https://pubmed.ncbi.nlm.nih.gov/37172196/>, [https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196\(22\)00139-5/fulltext](https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00139-5/fulltext)

Maybe another limitation to discuss would be the exposure indoor vs outdoor.

Yes, we agreed the discussion of this problem is necessary. Following your suggestion, we have added some discussions, as “**Additionally, our study is lack of distinction between indoor and outdoor exposure, which may lead to an overestimation of predicted mortality rates. Individuals who spend more time indoors may benefit from cooling measures and thus be better adapted to heat-related threats. Future research should incorporate indoor exposure data to provide a more accurate estimation of heat-related health risks and to better understand how different living environments influence vulnerability to extreme heat.**”

L386. As you use weekly mortality data you will clearly lose a lot of daily variability. This is a huge limitation. See [https://www.thelancet.com/journals/lanepi/article/PIIS2666-7762\(23\)00198-9/fulltext](https://www.thelancet.com/journals/lanepi/article/PIIS2666-7762(23)00198-9/fulltext)

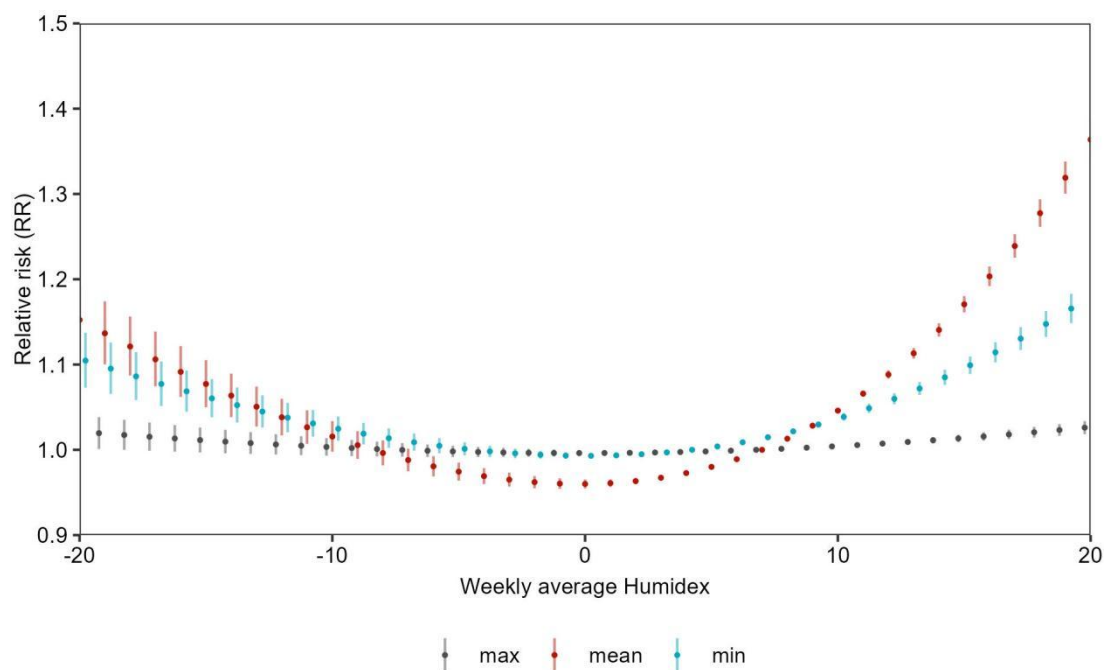
In this context, it is not clear for me which kind of statistical summary you use at weekly scale for humidex? maximum, mean? It would even be interesting to conduct sensitivity analysis changing the kind of metric used.

Response: We agree the weekly mortality may lead to the limitation in underestimating the heat-related mortality as previous studies proved. Unfortunately,

due to data availability constraints, we cannot analyze the impact of extreme heat on mortality at a finer temporal scale. Actually, we have discussed this limitation as **“First, using weekly data may lead to an underestimation of the number of heat-related deaths due to limitations in identifying the effect of continuous hot extremes. In the absence of finer-resolution mortality data, we employed weekly humidex and mortality data in our epidemiological model, categorically aggregating different durations of continuous heat events on a weekly basis.”**

Additionally, we have included more detailed explanations about the aggregation of weekly data, as **“Specifically, a distributed lag nonlinear model (DLNM) with a quasi-Poisson distribution was used to quantify the geographically dependent relationship between weekly counts of all-cause mortality and weekly mean Humidex, as well as consecutive and non-consecutive daytime-only, nighttime-only and day-night compound hot extremes...”** ,

Furthermore, we added sensitivity analyses using different statistical summaries (maximum and minimum values) at the weekly scale. The results have been included in the **supplementary information (SI)**. It indicates that the model is sensitive to the characteristics of the input meteorological variables, but using the mean value provides the highest model accuracy. Therefore, we used the mean value as the primary metric for analysis in this study.



Supplementary Fig 8. Relative risk variation under different characteristics of the input meteorological variables of weekly min, mean and max Humidex. Sensitivity analysis results are exemplified by modelling data from the elderly (aged 65 years or above). Please note that the x-axis has been shifted to the left by the minimum mortality Humidex (MMH) for comparison. The MMH

estimated using different statistical variables are 33(max),18(mean), and 11(min), respectively.

Supplementary Table 3. Model accuracy using different statistical summaries. Here, the validation results were reported by root mean square error (RMSE).

	Age:0-14	Age:15-64	Age:65+
Weekly mean Humidex	0.75	4.23	11.92
Weekly min Humidex	0.75	4.28	13.02
Weekly max Humidex	0.75	4.25	12.47

L399. I would recommend to use a population weighted approach for the humidex estimation based on gridded data (see <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GH000363>)

Response: Thanks for this comment. Based on the reference you provided, we have adopted a similar approach to extract all gridded humidex data. The methodology has been revised as “**The population-weighted approach performed better in detecting the effects of climate change, particularly in regions with large climate and population variability, as Evan et al. (2021)⁶⁰ suggested. Therefore, climate variables from ERA5-Land were retrieved as hourly population-weighted means at the NUTS3 level. The population weighting for historical data was determined based on gridded population data with a 1 km horizontal resolution (from <https://www.worldpop.org/>). We calculated the weight of each grid cell using the ratio of the population residing in each grid cell to the total population in the corresponding NUTS3-level region. Gridded climate variables were simply resampled to a 1 km grid to match the population.**”

You should find a better way to guide the reader in the steps here. Maybe a summary first, explaining several steps for climate data, analysis etc. Figure 5 could be a good place to start.

Response: Thank you for your suggestion. We have reorganized the Data and Methods section to guide the reader more effectively. A brief overview of the flowchart has been added at the beginning, as follows “**We used historical weekly all-cause mortality records and climate data at the NUTS3-level from 2010 to 2019 to construct the connection between summer heat and mortality. Based on these data, we built a distributed lag nonlinear model (DLNM) with a quasi-Poisson distribution, which considers consecutive and non-consecutive daytime-only, nighttime-only, and day-night compound hot extremes (Fig. 5). We devised a three-step procedure to assess the model’s generalization ability and robustness. A model-based prediction was conducted to estimate future heat-related excess deaths until 2100 using climate projections under four emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and population**

sizes from the Gridded Population of the World (GPW) v4 and EUROPOP2019 baseline projections. Lastly, we examined the relative contributions of climate change, population size change, and population aging to future heat-related mortality burdens using a decomposition approach.

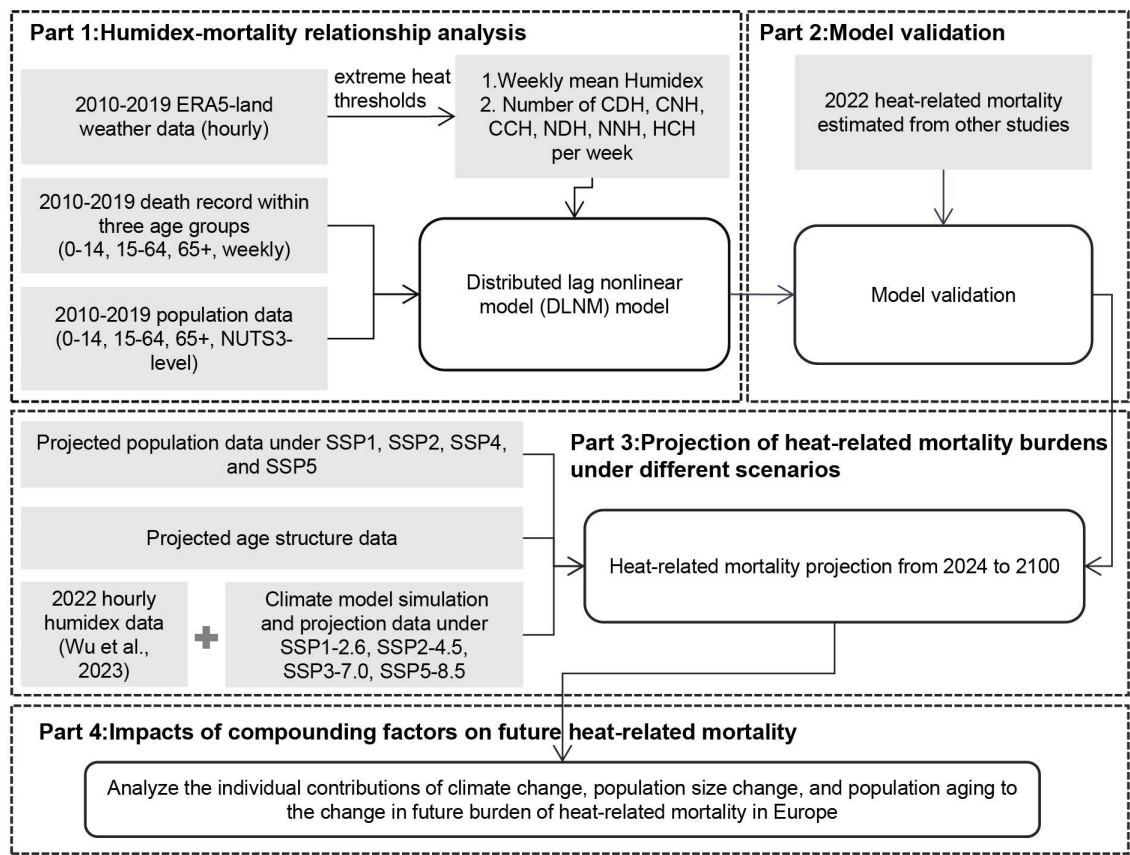


Fig. 5. Schematic flowchart of data and models for this study. CDH, CNH, CCH, NDH, NNH, and NCH denote the consecutive daytime-only hot extremes, consecutive nighttime-only hot extremes, consecutive day-night compound hot extremes, non-consecutive daytime-only hot extremes, non-consecutive nighttime-only hot extremes, and non-consecutive day-night compound hot extremes, respectively. The regression model was trained based on the Humidex and mortality data during the summers (weeks 22-35) of 2010 – 2019. The data from 2020 to 2021 were excluded from the model’s training and validation to eliminate the influence of the COVID-19 pandemic on mortality.”

L406. For me the use of CESM-LENS is not enough justified, particularly, because it is based on CMIP5. The same community has already finished the second version from the CMIP6, hence I would recommend updating to the new version. This would also make it more coherent with the used SSP in population age estimations.

Response: We agree and have reviewed the inappropriate combination of RCPs and SSP as the reminder from reviewer 2. Following this suggestion, we have modified

the future projected data to the new version of CMIP6. We have recognized the related content as **“In addition, the monthly relative humidity and surface air temperature derived from the new Max Planck Institute (MPI) grand ensemble with CMIP6 was used. The MPI grand ensemble simulations were performed with combined natural and anthropogenic forcing, including historical runs up to 2014 and future projections under various Shared Socioeconomic Pathways (SSPs), such as SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. For each scenario experiment, there are 50 ensemble members from 2015 to 2100, available at a horizontal spacing of 1.875°×1.875°. Each member has identical external forcing but slightly differing initial conditions.”**

L448. It would be better to use night definition based on local sunrise/sunset, to account on sessional and latitudinal variation.

Response: Thanks for the suggestion. Considering local and seasonal variations in sunrise and sunset can indeed help in more accurately defining day and night. We have employed the SunCalc package to calculate daily sunrise and sunset times based on each region's geographical information. The related description has been updated as follows: **“Each day was divided into two subperiods: the day, which lasted from sunrise to sunset and the night, which lasted from sunset to sunrise. The Google Earth Engine platform’s SunCalc package was used to determine the precise sunrise and sunset times for each day and location.”**

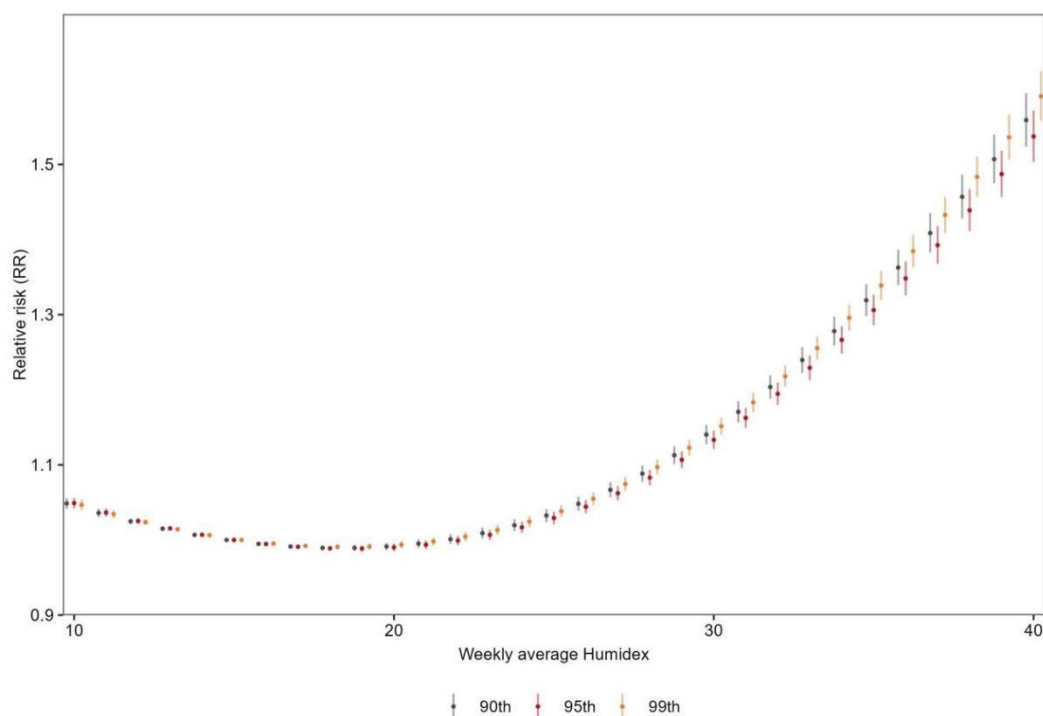
L450. Which is the threshold? I would add reference to the definition.

Response: Sorry for any confusion caused by the expression used in the manuscript. In our revised manuscript, **“Previous studies showed that human thermoregulation varies with the environmental conditions, indicating that long-term evolution may lead to adaptive diversification to hot extremes. Thus, we defined a hot day/night threshold as the mean temperature throughout the day or night exceeding the 95th percentile of its local daily climatology. The period-based percentile for a specific location was determined using a 15-day-long time window centered on each calendar day over 1961-2022. If the mean temperature of either daytime or nighttime sub-period was higher than the threshold, we identified it as a hot extreme. If the hot extreme occurred solely during the daytime or nighttime, we labeled it as a daytime-only hot extreme (DH) or nighttime-only hot extreme (NH). If the hot extreme occurred throughout the daytime and nighttime, we defined it as a day-night compound hot extreme (CH).”**. We reorganized the definition of extreme heat threshold and added more references to prove the universality of the definition.

L454. Why don't you use 95P of hourly diurnal temperatures and the same for the night period.

Response: Thank you for your insightful suggestion. We agree the distinction between daytime and nighttime thresholds do better in capturing extreme hot. Therefore, we have revised our methodology to define extreme daytime- and nighttime- hot using their respective 95th percentile thresholds. Meanwhile, the 90th and 99th percentiles were also used for sensitivity analysis in the revised version. For your easy reference, we pasted the related content here: **“Thus, we defined a hot day/night threshold as the mean temperature throughout the day or night exceeding the 95th percentile of its local daily climatology. The period-based percentile for a specific location was determined using a 15-day-long time window centered on each calendar day over 1961-2022....**

Furthermore, the robustness of the hot extreme definition was confirmed by utilizing the 90th and 99th percentiles.” The results were included in the SI.



Supplementary Fig 6. Relative risk variation under different definitions of extreme daytime- and nighttime- hot using their respective 90th, 95th, and 99th percentile. Sensitivity analysis results are exemplified by modelling data from the elderly (aged 65 years or above).

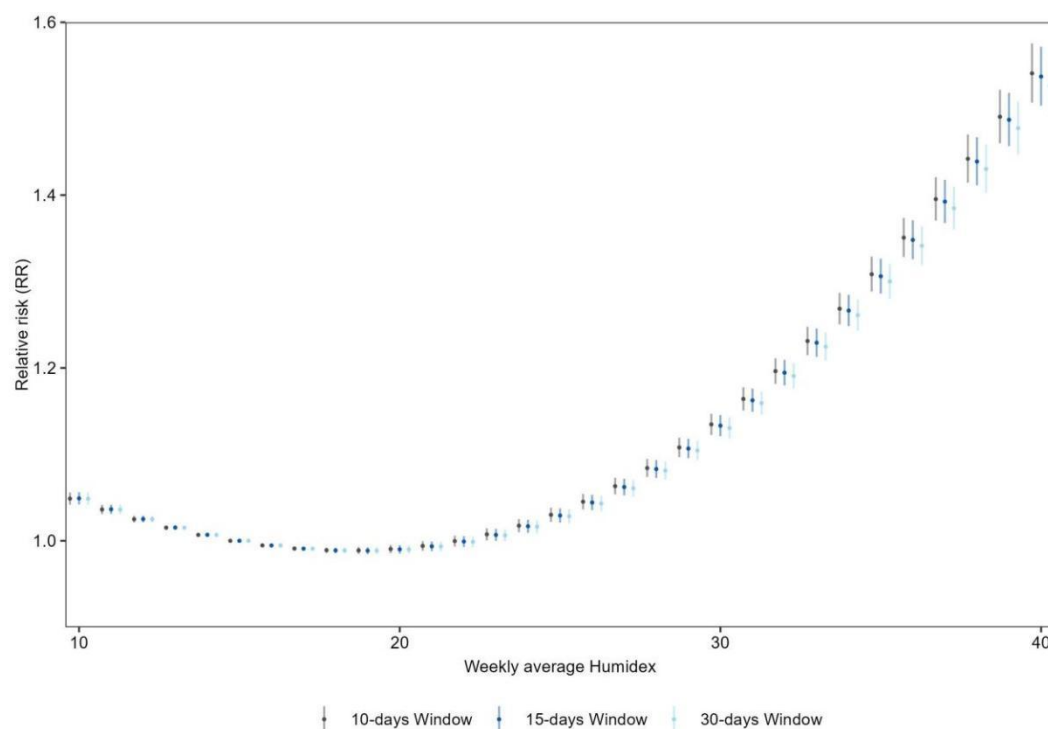
L455. Why 15 days? You should justify the decision. I guess it is to consider the idea

that people acclimate to their local climate with respect to its temperature variation throughout the year. I would even go to the window of 30 days or at least try how it changes the results. <https://pubmed.ncbi.nlm.nih.gov/35460514/>, <https://www.mdpi.com/1660-4601/12/1/227>

Response: Sorry for the confusion caused by our initial description. In fact, we considered the 95th percentile of the daily temperature from 50 years of data (1961-2022) for the target date. However, due to the substantial variability on a daily scale, we introduced a 15-day climatological window. For example, the extreme heat threshold for June 1st is determined by the 95th percentile of temperatures from May 17th to June 15th across the years 1961-2022.

The choice of a 15-day window was random. To ensure the robustness of this window size, we have added sensitivity analyses with window sizes of 5 days, 15 days, and 30 days. The results were included in the supplementary information (SI). In the reviewed manuscript, we reorganized the relevant description in lines 454-464: **“Thus, we defined a hot day/night threshold as the mean temperature throughout the day or night exceeding the 95th percentile of its local daily climatology. The period-based percentile for a specific location was determined using a 15-day-long time window centered on each calendar day over 1961-2022...**

Sensitivity analysis was conducted using window sizes of 5 and 30 days to test the effect of window size on the results.”



Supplementary Fig 7. Relative risk variation under different window sizes of 10, 15 and 30 days. Sensitivity analysis results are exemplified by modelling data from the elderly (aged 65 years or above).

Some other general comments:

Methods: I couldn't read any formula as they were strange symbols ❓

Response: We apologize for the issue with the unreadable formulas in the Methods section. In the original manuscript, the formulas were displayed correctly. It seems there was a formatting issue during the submission process. We have thoroughly reviewed and adjusted the formulas to ensure they are correctly displayed. We hope this resolves the problem.

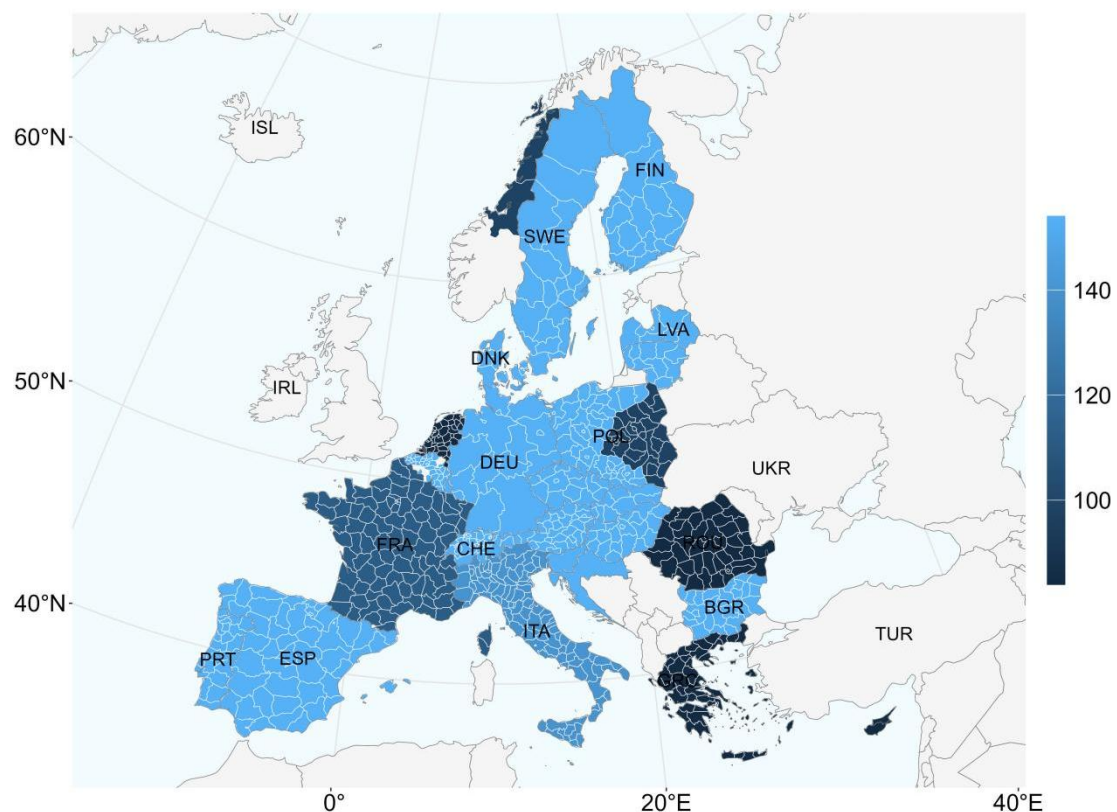
I find the study period very short (2015-2019). Wouldn't it possible to control pandemic the COVID pandemic? In particular for a seasonal analysis (weeks 22-35) and on a weekly scale. Why don't you use the local warm season? Is the definition fixed for the projections? I mean the warm season is changing in the future. So I am not sure if it would be right to use a fixed period. In the same sense, do you really have enough statistical power for all locations within only 6 years? <https://bmcmmedresmethodol.biomedcentral.com/articles/10.1186/s12874-019-0894-6>

Response: Thanks for your insightful comments. We agree that the 2015-2019 period may seem short and may impact the model's stability. The limitation of this period was due to the availability of population proportion data by age groups (0-15, 16-65, 65+), which is only available post-2014. To address this, we have extended the data range to 2010-2019 by applying the 2014 age proportions to the 2010-2013 period (as mortality data is available from 2010 onwards). We have revised the manuscript accordingly in lines 427-430, as **"Since 2014, Eurostat has provided the population statistics by sex, five-year age group, and region of residence at the NUTS3 level. We aggregated them into three age groups: 0-14, 15-64, and 65+. Due to limitations in data availability, the population age structure data from 2010 to 2013 was estimated by multiplying the total population at the NUTS2 level for each specific year by the age proportions in 2014."**

Furthermore, the data from 2020 to 2022 were excluded for two reasons. First, COVID-19 mortality data were unavailable on the NUTS level 3, making it challenging to exclude COVID-19 deaths accurately. Second, the potential interaction or compounded effect of extreme heat and COVID-19 on mortality is uncertain. A simple exclusion of COVID-19 deaths might not yield reliable results. Given that the relationship between extreme heat and mortality is unlikely to change drastically

within two years, we decided to build the model excluding the 2020-2022 data. However, to ensure robustness, we cross-validated our predicted 2022 heat-related mortality with results from other studies.

Regarding the definition of the warm season, we recognize the merit of using the local warm season. However, considering the possible future changes in the local warm season, we followed the fixed period approach proposed by Ballester et al., 2023 (<https://www.nature.com/articles/s41591-023-02419-z>). Also, we have visualized the sample size for each region and added it in Supplementary Fig 13.



Supplementary Fig 13. Sample sizes of each region used for model training. The regions with missing data are shaded in grey.

The role of humidity is still under discussion and appears to be site-dependent: <https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.8160>, and see also: <https://ehp.niehs.nih.gov/doi/full/10.1289/EHP5430>

You should explain and discuss more in detail the physiological standpoint with the biological mechanisms for hot temperature and humidity.

Response: We agree and have added more discussion in Line 308-330, as “To the best of our knowledge, our study may be the first to use a weather indicator that combines dry-bulb air temperature and humidity to model the Europe-wide mortality responses to day-night compound, daytime-only, and nighttime-only

hot extremes across various age groups. A related study³⁴ that examined the relation between hot nights and mortality in four countries in Southern Europe reported an excess mortality risk related to compound heat ranging from 12% to 37%, which aligns with our findings (over 30%). Recent research also highlights the importance of considering humidity when assessing heat stress. Our findings indicate that persistently extreme humid heat during the day and night is associated with a higher mortality rate among the elderly. Sweating is a crucial cooling mechanism for the human body. As a result, a decreased sweating rate due to high ambient humidity may raise body temperature and increase the risk of heat-related illnesses. Nevertheless, a few studies suggested that adding humidity to air temperature does not considerably improve the prediction accuracy of the heat exposure-mortality response model. We note that most of these studies were conducted in predominantly dry conditions, with the possibility of a global shift towards more humid heat unnoticed (Supplementary Fig 12.). In this regard, our results provide a contrasting emphasis on the humid heat burden. Specifically, the validation demonstrates that Humidex gives a more reliable representation of heat-mortality association throughout different periods when compared to dry-bulb air temperature alone. The models that account for humidity show higher accuracy than those using dry-bulb air temperature alone in estimating heat-related mortality ($R^2 = 0.78$ vs. 0.63). Despite this, the role of humidity in modeling heat-related mortality may depend on many other factors, such as local climate conditions and data characteristics. Our study contributes to the ongoing discussion by stressing that humidity should be considered in health effect assessments in the future when humid heat is more prevalent. It also highlights the importance of paying more attention to the potential health impacts of humidity during extreme heat events. Further study is required to determine whether the impacts of humidity are getting more pronounced with time and how they interact with other factors like air temperature and population vulnerability....”

Figures:

1a. I would add the baseline for RR at 1.

Response: Added.

1d. I suggest using column fill for region groups instead of symbols. Actually, I would also place the region legend below and make it smaller in order to reduce clutter. I am not really sure if there is a second light gray bar, if so, it is a good idea to place overlapping symbols.

Response: Thank you for your suggestion. We have made the following modifications to Fig 1:

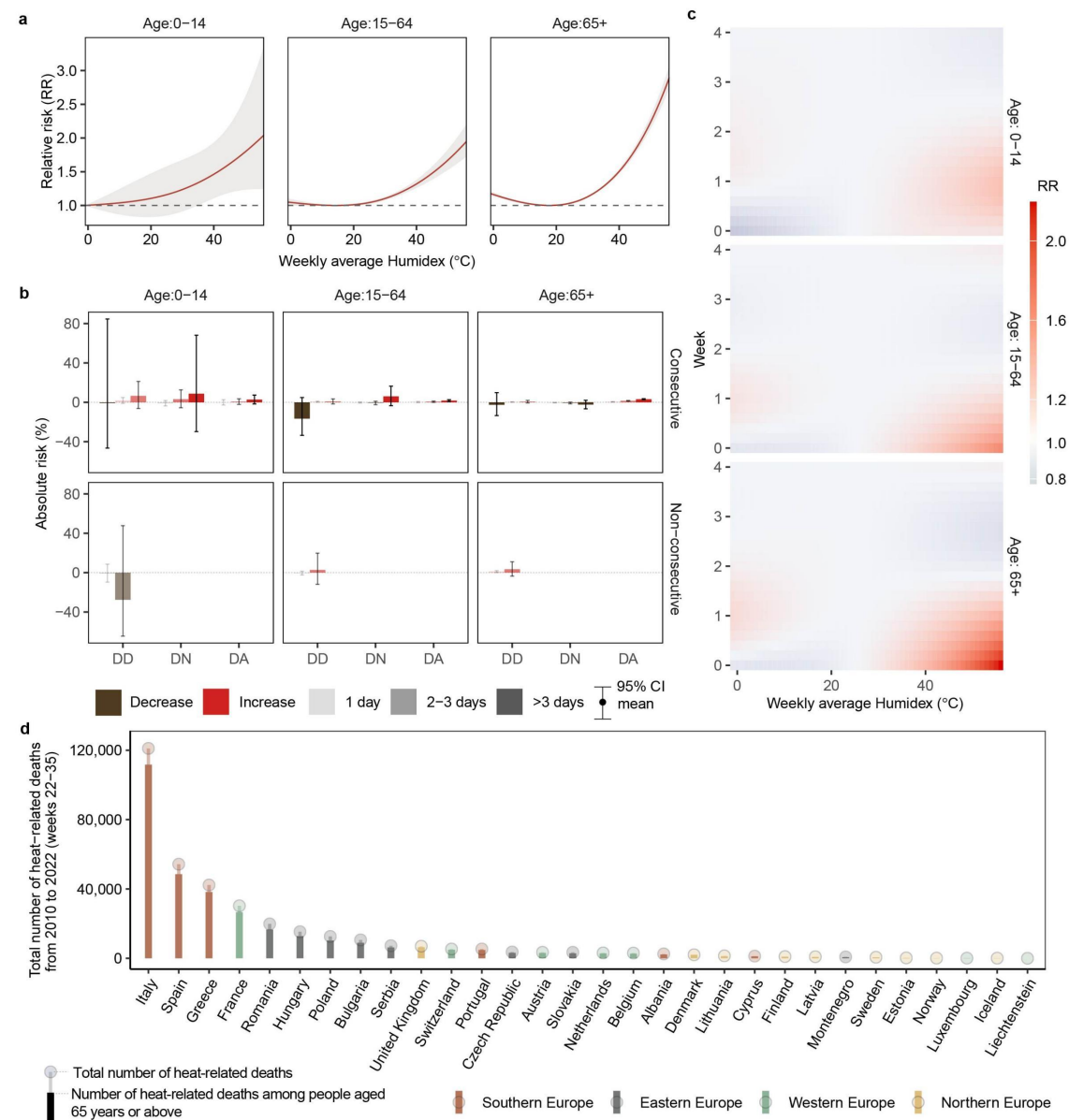


Fig. 1. Heat-mortality associations and heat-related deaths in Europe. (a) Cumulative relative risk-weekly Humidex response curves for three age groups: children (aged 0 - 14 years), the working-age population (aged 15 - 64 years), and the elderly (aged 65 years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group. **(b)** Heat map shows the lagged effects of heat exposure on mortality. The red indicates an increased mortality risk ($RR > 1$), while the blue indicates a decreased mortality risk ($RR < 1$). **(c)** Bar chart of the variation of mortality risk with the duration of heat exposure. It shows the absolute mortality risk of the day-night compound (CH) hot extremes compared to the

daytime-only (DH) hot extremes. The absolute risk means the increased mortality risk in the exposure of a heat day relative to normal days. (d) The estimated total heat-related mortality in 30 European nations during the summers of 2010-2023 (weeks 22-35). These nations are geographically divided into 4 regions: Northern, Southern, Eastern, and Western Europe, according to the United Nations Geoscheme. The dark and light grey bars represent the number of heat-related excess deaths in the elderly group and the all-age population, respectively.

2. I don't remember if you defined the used periods (2075-2080), why those? Why only 6 years? What about the mid-century?

Response: Thank you for raising this important point regarding the chosen periods and their rationale. In this revision, we compared the growth rate of heat-related deaths per capita before and after the mid-century. Specifically:

For the pre-mid-century comparison, we used the average values from 2045-2050 compared to 2025-2030.

For the post-mid-century comparison, we used the average values from 2095-2100 compared to 2045-2050.

To reduce the influence of seasonal fluctuations and ensure a more stable trend analysis, we employed a six-year window average. This approach allows us to capture more consistent and reliable trends over time, rather than being affected by the variability that might occur in shorter periods. We added more details in the manuscript this time, as shown in Line 199-203, **“We compared the growth rates of heat-related deaths per capita before and after the middle of the twenty-first century (Fig. 2a). The difference between 2045-2050 and 2025-2030 (between 2095-2100 and 2045-2050) was used to represent the growth rate before (after) the middle of the twenty-first century. Under the high-emission scenarios (SSP3-7.0 and SSP5-8.5), the growth rate of heat-related deaths per capita in the post-mid-century is 2.2-2.8 times higher than that in the pre-mid-century...”**

2a The symbol for the RCP8.5 as a not filled circle isn't easy to see.

Response: Thanks. Given the changes in the scenarios used, we have modified the presentation of the results. In the new figures, we have ensured that all symbols are clearly visible.

2b. If SSP5 is the worst scenario, why do you use a dark red color for SSP1? You

should select coherent coloring. Legend for RCP is not needed as you use different facets. I would place the legend of SSP below both facets.

Response: We appreciate your suggestion to use coherent coloring for the scenarios. Given the scenario updates, we have adjusted the color scheme in our figures. Now, the colors are consistent with the severity of the scenarios. Additionally, we have removed the redundant legend for RCPs as the different facets make this information unnecessary. And we have noted in the figure title that Figs. 2b and 2c share the same legend, as shown in Fig 2.

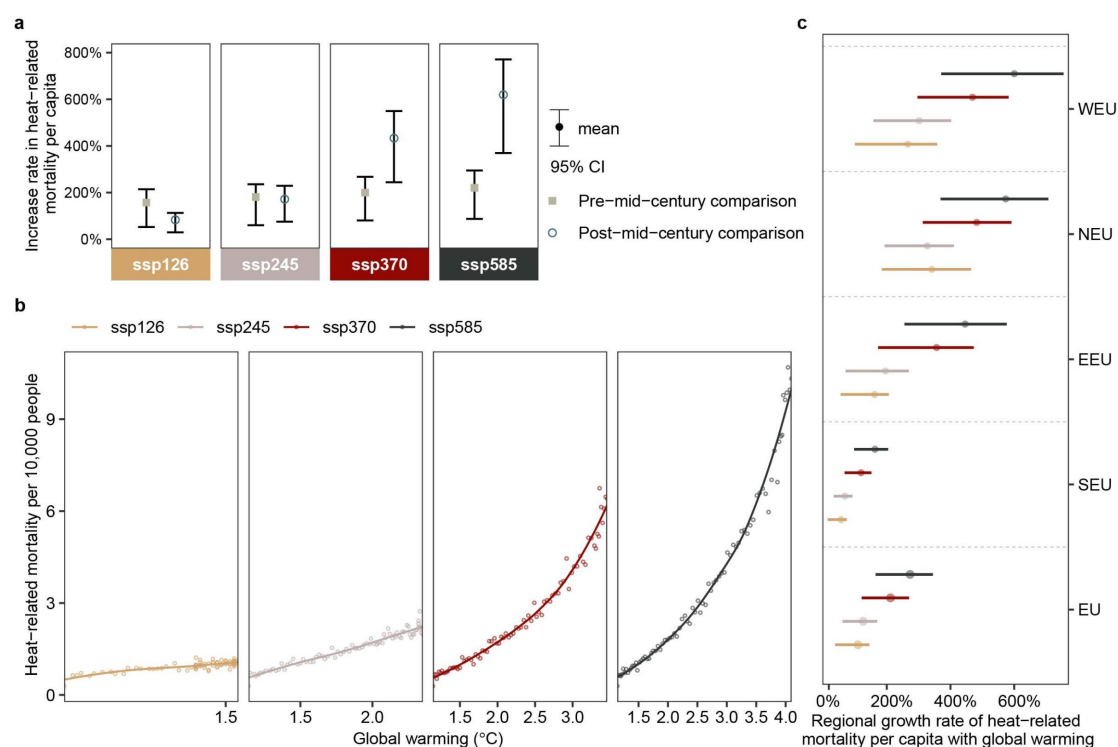


Fig 2. Projected changes in heat-related mortality in Europe. (a) The growth rate of heat-related excess mortality per capita under different climate-population scenarios. Squares and circles indicate the comparison for near-mid-century and mid-end-century, respectively. The pre-mid-century growth rate is calculated by comparing the mean mortality per capita between 2045-2055 and 2025-2030. The post-mid-century growth rate is calculated by comparing the mean mortality per capita between 2095-2100 and 2045-2055. The black bars represent the 95% confidence interval of the projected growth rate of heat-related mortality per capita. **(b)** The variation of heat-related deaths per 10,000 people with global warming. The global warming levels are determined by the years in which the 20-year moving average global mean surface temperature anomaly (relative to the pre-industrial period 1850-1900) exceeds specific warming levels. **(c)** Regional growth rates of heat-related excess mortality per capita with global warming. The growth rate is represented by the linear slope of heat-related mortality against the levels of projected global warming, i.e., the percentage

change in added heat-related mortality per capita with each degree of global warming. The percentage changes are estimated relative to the 2022 baseline of 1.07 heat-related deaths per 10,000 capitals. Europe (EU) is divided into four regions: Northern (NEU), Western (WEU), Eastern (EEU), and Southern Europe (SEU), with baseline heat-related excess deaths of 0.25, 0.38, 0.74, and 2.59 per 10,000 capitals, respectively. Note that the baselines reported in 2022 differ from the previous section due to excluding regions with missing data in the projections.

3. Please use ETRS89-extended / LAEA Europe. Country labelling is really helping, I would remove them all. Maybe you can highlight some regions with highest risks. Border lines between countries look better using white color. I recommend adding a title to each facet, since without the reader has to go to the caption. Finally, a single colorbar as legend would be better, instead of a two row legend. I don't see the need to add a scale. Maybe a graticulate could be useful. A diverging color palette is not recommended if there isn't any midpoint. In this case a sequential palette would be ideal or define a reference midpoint. You must also report here death by population, if not, it is a population map. For instance, in Spain Madrid and Barcelon both have high death numbers because they are the most populated regions.

Response: Thank you for your detailed suggestions on improving the map's presentation. Based on your recommendations, we have made the following revisions in Fig 3.

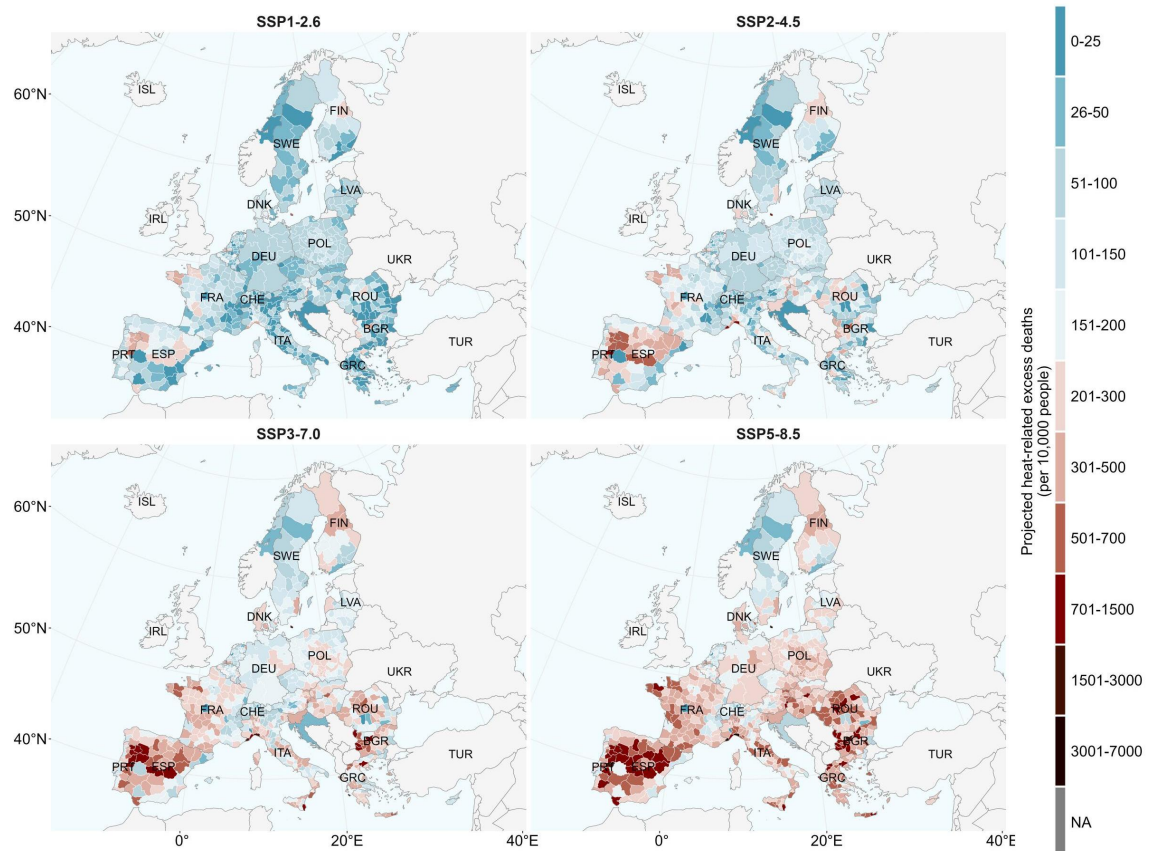


Fig 3. Geographic distributions of expected cumulative heat-related excess deaths per 10,000 people. The projected heat-related excess deaths per 10,000 people at the NUTS3 level from 2024 to 2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The regions with missing data are shaded in grey.

4. From my point of view the use of line-area chart is not really helping to understand the difference between both (dashed and solid line). The meaning of both lines should be included in the graph.

Response: Following your suggestion, we have added the meaning of both lines in the graph.

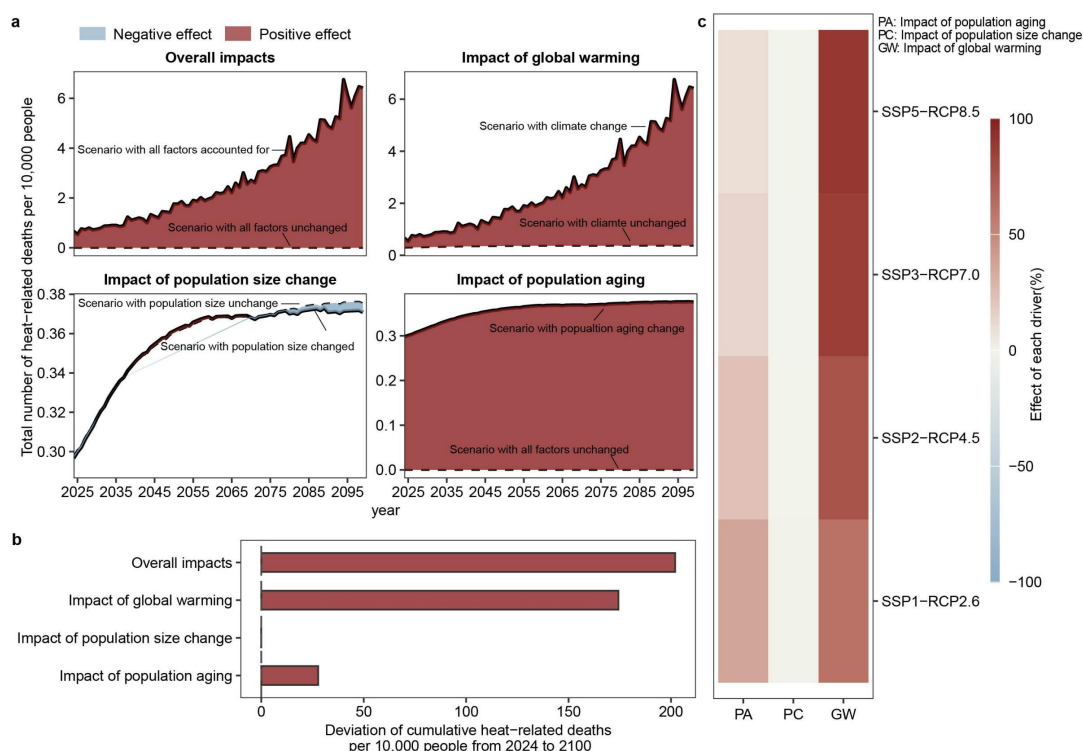


Fig. 4. The relative contributions of climate change, population size change, and population aging to future heat-related excess mortality per 10,000 people in Europe. (a) The temporal variations of individual effects of global warming, population size change, population aging, and their total effects (overall impacts) on future heat-related excess deaths in Europe during 2024-2100 under SSP3-7.0. The solid line displays the projected heat-related excess mortality with all factors or a specific factor accounted for. The dashed line denotes the projections with all factors remaining unaltered. (b) The cumulative number of heat-related excess deaths due to the changes in climate, population size, and age structure from 2024 to 2100. Additional projection results for alternative scenarios are available in Supplementary Figs. 9-11. (c) Heat map showing the relative contributions of global warming, population size change, and population aging under several scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The relative contribution of each driver is measured by comparing the cumulative number of heat-related facilities per 10,000 people caused by that driver to the total number of heat-related deaths per 10,000 people caused by all factors.

Reviewer #2 (Remarks to the Author):

This is potentially an interesting and important study that tries to unpick the role of demographic and climate change on the evolving mortality burden from extreme humid heat. However, there are a number of significant issues with the paper. I highlight the ‘major’ concerns below; more minor comments are included as PDF annotations (attached with my review).

On the basis of these, recommend rejection and resubmission at this stage – due to the significant issues related to model validation and the deployment of the climate scenarios. These aspects require modifications to the analysis, and I cannot anticipate how substantially this will affect the results/conclusions (e.g., it might be that integrating humidity via the Humidex does not lead to more skilful predictions after all, and hence the key results/significance would change).

Encouraging resubmission would enable the authors to take their time to revisit the key issues, whilst leaving the door open for publication if their findings (which are of interest) remain robust.

Thank you for your thorough review and for highlighting both major and minor concerns. We appreciate the opportunity to address these issues and resubmit our manuscript. We have focused on the two core issues you mentioned: model validation and the deployment of climate scenarios. Additionally, we have made a concerted effort to address concerns related to the use of Humidex and other pertinent points raised in your review.

Major comments

1. Model calibration and validation

The authors present in the calibration the results of their cross-validation procedure in Supplementary Fig. 5, which shows a comparison between predicted and observed mortality in the 954 regions. However, so far as I understand, this shows total mortality, which is highly dependent on the baseline population. The comparison should be between observed and predicted excess (heat) mortality. For example, I imagine one could get quite close to the observed mortality in any one year for a particular region by simply using the long-term (all, non-pandemic years) mean mortality?

Response: Thank you for the comments and insights. We acknowledge the widely recognized challenge in validating models for attributing mortality to extreme heat/cold due to the difficulty in obtaining precise mortality data attributed to temperature extremes. To enhance the validation of our model, following your

suggestion and the references below provided by reviewer 3, we have revised and improved our methodology.

A) Rodrigues, M., Santana, P. & Rocha, A., 2019. Bootstrap approach to validate the performance of models for predicting mortality risk temperature in Portuguese Metropolitan Areas. *Environ Health* 18, 25. <https://doi.org/10.1186/s12940-019-0462-x>

B) Rodrigues, M., Santana, P. & Rocha, A., 2019. Effects of extreme temperatures on cerebrovascular mortality in Lisbon: a distributed lag non-linear model. *Int J Biometeorol* 63, 549–559.

First, following the validation method in reference A, to validate the estimates of the risk contributions at varying temperature exposure intensity and lags without resampling, we split the data into training data (2010-2014) and test data (2015-2019) to estimate the parameter based on different exposure period. The root mean square error (RMSE) and mean absolute deviation (MAD) were derived as follows:

$$RMSE = \frac{\sqrt{\frac{1}{n} \sum (\hat{\beta}_i - \beta_i)^2}}{\beta_i/n}$$

$$MAD = \frac{\left| \sum (\hat{\beta}_i - \beta_i) / n \right|}{\beta_i/n}$$

Where $\hat{\beta}_i$ is estimated from the training data and β_i is estimated from the test data. Here, we used either Humidex or air temperature as inputs to compare their respective performances in modeling the relationship between heat and mortality. The results are shown in Supplementary Table 4. For the age groups 0-15 and 16-65, models using Humidex demonstrated slightly better stability across different periods compared to air temperature.

Supplementary Table 4. Comparison of model performance using Humidex and air temperature. The RMSE and MAD values reported for each group represent the differences in model parameters when models were trained using Humidex and air temperature with data from different periods. The p-value test is based on the Wald test, with $p < 0.05$ indicating a significant difference, $p < 0.01$ indicating a substantial difference, and $p < 0.001$ indicating an extremely significant difference.

Age group	Metric	RMSE	MADs	P-value
0-14	Humidex	0.43	0.06	0.99
	Air temperature	0.47	0.13	
15-64	Humidex	0.13	0.01	0.89

	Air temperature	0.15	0.01	
65+	Humidex	0.15	0.03	<0.001***
	Air temperature	0.15	0.04	

Second, we employed the bootstrapping approach recommended by reviewer 3 to validate the performance of our models. This method creates resamples of the same size from the validation data with replacement and then predicts the values for the original data using the model. Unlike cross-validation, which focuses on assessing model stability on different fixed subsets, bootstrapping evaluates the model's sensitivity to data variability through repeated sampling. We repeated this step 30 times. The final model accuracy was reported as the average RMSE and the average coefficient of determination (R^2) of these 30 iterations. The root mean squared error and R^2 between the predicted number of deaths from the random sample and the observed value were computed as follows:

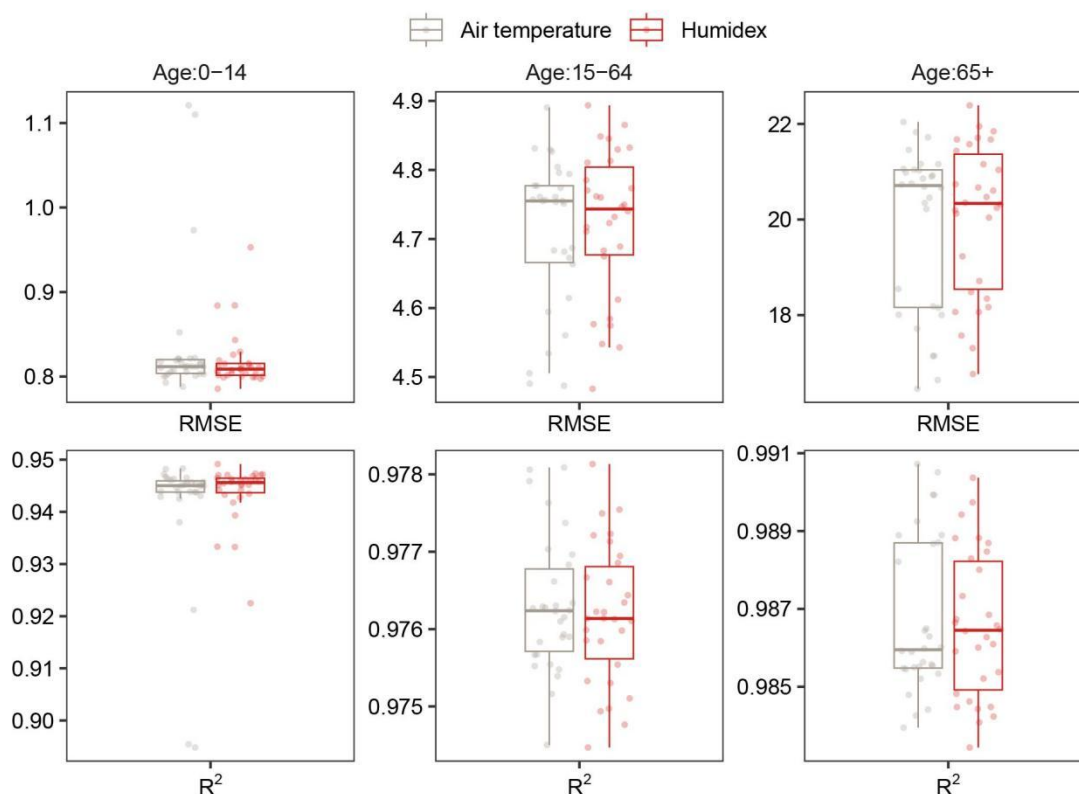
$$RMSE = \sqrt{\frac{1}{n} \sum (Y_{obs,i} - Y_{pred,i})^2}$$

$$R^2 = 1 - \frac{\sum_i (Y_{obs,i} - Y_{pred,i})^2}{\sum_i (Y_{obs,i} - \frac{1}{n} \sum_{i=1}^n Y_{obs,i})^2}$$

Table 5. Comparison of bootstrapping validation using Humidex and air temperature.

Age group	Metric	Humidex	Air temperature
0-14	RMSE	0.81	0.84
	R^2	0.94	0.94
15-64	RMSE	4.72	4.71
	R^2	0.98	0.98
65+	RMSE	20.00	20.00
	R^2	0.99	0.99

As shown in Table 5, the results indicate low sensitivity to data variability and high model robustness. Here, Humidex and air temperature did not show significant differences in performance (see Supplementary Fig 8).



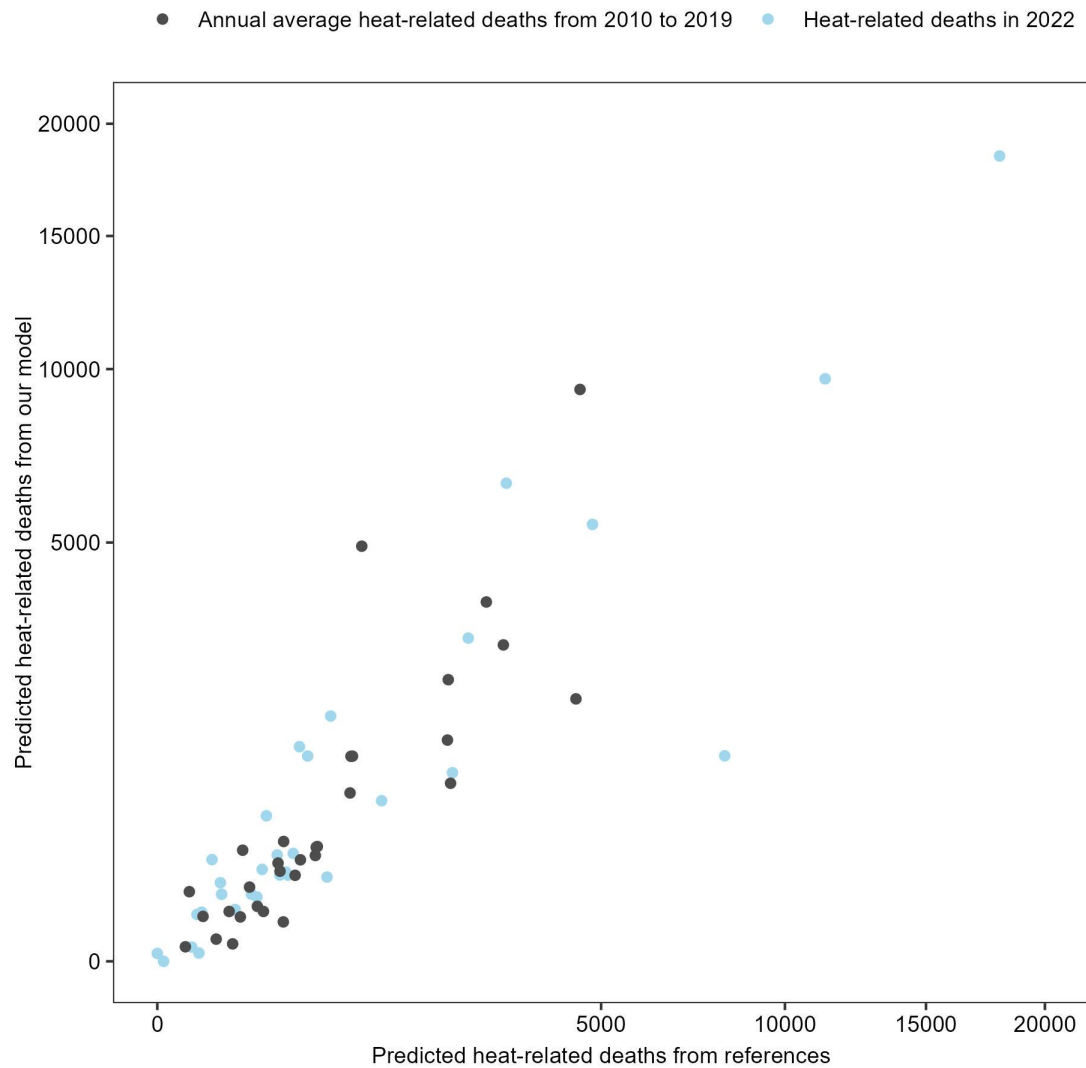
Supplementary Fig 9. Boxplot of the accuracy comparison. The comparison was performed between model using Humidex (in red) and air temperature (in grey).

Last, we cross-validated the predicted heat-related mortality from our model with results from existing studies, yielding an R^2 of 0.78. Compared to the results using dry-bulb surface air temperature ($R^2 = 0.63$), the model using humidex showed higher accuracy. While inherent differences in model construction details naturally lead to some variation between our results and those of other studies, this cross-validation suggests that our model results are credible and highlight the critical role of ambient humidity in modulating heat-related excess mortality.

Refs for predicted heat-related mortality:

2022: Heat-related mortality in Europe during the summer of 2022

The mean value from 2010 to 2019 : Global, regional, and national burden of heatwave-related mortality from 1990 to 2019: A three-stage modelling



Supplementary Fig 4. Comparison between predicted heat-related deaths from our model using Humidex and other studies. The predicted results were extracted as the annual average from 2010 to 2019 and the total value in 2022 to match the available data from the references. The R-squared is equal to 0.78.

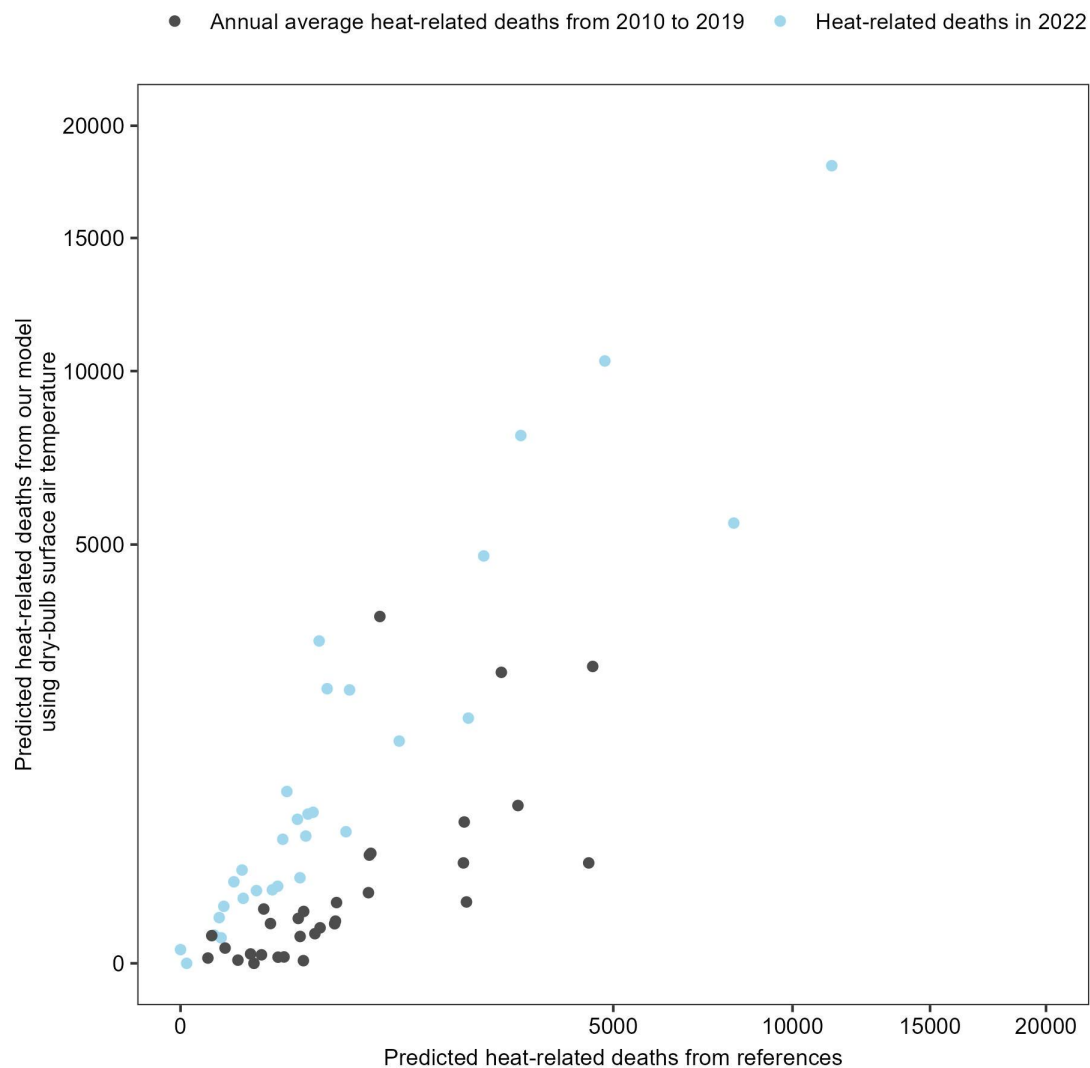


Fig 5. Comparison between predicted heat-related deaths from our model using dry-bulb surface air temperature and other studies. The predicted results were extracted as the annual average from 2010 to 2019 and the total value in 2022 to match the available data from the references. The R-squared is equal to 0.63.

The significant issue above is highlighted quite clearly when the authors ‘test’ their model when forced with 2023 projections of climate change (from RCP4.5 and RCP8.5) against observed mortality. Unfortunately this is nonsensical: the weather *which actually occurred in 2023* will of course be different from the random ensemble generated by the climate model simulations for that year. Agreement between your projected mortality and observed mortality therefore mostly represents everything *but* the impact from the heat/humidity that prevailed during that year. This issue seems to represent a misunderstanding of what the climate model simulations represent (explained in point #2) – it goes beyond an inappropriate method of validation.

Response: Sorry for the confusion. Following your suggestion, we modified the validation method. It was based on historical data, specifically data from 2022, as we have done above. In this revision, we have revised the relevant sections to clarify our purpose in the methods, as “ **A three-step validation procedure was created to validate the model’s robustness and ability for generalization. First, the data was divided into training (2010-2014) and test (2015-2019) sets to verify the estimates of the risk contributions at different temperature exposure intensities. Second, we employed a bootstrapping technique to validate the sensitivity of our models to data variability. Third, we cross-validated our model’s prediction of heat-related mortality with findings from previous research. More details can be found in Supplementary Note 2.**”

To summarise, then, the model validation needs to be rethought. First, *excess* deaths should be compared between simulations and observations. Second, rather than 2023, a far more convincing test would be to assess to what extent your calibrated models could capture the excess mortality in 2022 – an extreme year more similar (in temperature and humidity distributions) to the future, warmer climates that you’re investigating. And please note that you can’t validate using the RCPs as they’re storylines – not predictions.

Response: Thank you for raising this question. We agree that validating the model using excess deaths rather than total mortality would provide a more robust assessment. Specifically, we acknowledge the suggestion to assess the extent to which our calibrated models can capture excess mortality in 2022, a year characterized by extreme conditions more akin to future warmer climates. As we mentioned earlier, we have strengthened our model validation by emphasizing the evaluation of heat-related excess mortality.

2. The ‘humid’ heat component

The authors contend that their analysis moves beyond earlier work by asserting that inclusion of humidity (through the humidex) improves the modelling of heat related mortality. However:

The statistical significance of this very small reduction in the RMSE is not commented on (unless I missed it)?

Response: Thank you for your detailed feedback on our manuscript. In fact, the inclusion of humidity indeed enhances model accuracy and robustness. As the findings in model validation above, we found models incorporating the Humidex demonstrated slightly better stability across different periods compared to air temperature for the age groups 0-15 and 16-65. Cross-validation between our results and other studies further supports that models using Humidex ($R^2 = 0.78$) provide more accurate estimates of heat-related mortality than using dry-bulb surface air temperature ($R^2 = 0.63$). To address the statistical significance of the RMSE reduction,

we have added a detailed discussion of this in the revised validation section of the supplementary information (SI). We used statistical tests to evaluate whether the observed reduction in RMSE was significant. Our results indicate that the reduction, while small, was statistically significant, supporting the utility of including Humidex in improving model performance. In summary, our findings suggest that incorporating Humidex enhances the precision of heat-related mortality estimates. We have re-organized the validation section to provide a clearer presentation of these results and their statistical significance. The revised details can now be found in the SI.

B.2 Three-step validation of DLNM model

The DLNM model was constructed using data from 955 NUTS3-level regions during 2010-2019. To validate the model, we employed a three-step validation approach. First, following the validation method in a previous study, to validate the estimates of the risk contributions at varying temperature exposure intensity and lags without resampling, we split the data into training data (2010-2014) and test data (2015-2019) to estimate the parameter based on different exposure period. The root mean square error (RMSE) and mean absolute deviation (MAD) were derived as Eqs.E1 and E2:

$$\text{RMSE} = \frac{\sqrt{\frac{1}{n} \sum (\hat{\beta}_i - \beta_i)^2}}{\beta_i/n} \quad (\text{E1})$$

$$\text{MAD} = \frac{|\sum (\hat{\beta}_i - \beta_i)/n|}{\beta_i/n} \quad (\text{E2})$$

Where $\hat{\beta}_i$ is estimated from the training data and β_i is estimated from the test data. As shown in Supplementary Table 1, the model performance more robust when character the relationship between heat exposure and mortality among the working-aged adults.

Supplementary Table 1. Robustness validation of the estimated parameters based on different exposure periods.

Age group	RMSE	MADs
0-14	0.43	0.06
15-65	0.13	0.01
65+	0.15	0.04

Secondly, we employed the bootstrapping approach to validate the performance

of our models. This method evaluates the model's sensitivity to data variability through repeated sampling. We repeated this step 30 times. The final model accuracy was reported as the average RMSE and the average coefficient of determination (R^2) of these 30 iterations. As shown in Supplementary Table 2, the results indicate low sensitivity to data variability and high model robustness. The root mean squared error and R^2 between the predicted number of deaths from the random sample and the observed value were computed as Eqs. E3 and E4:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (Y_{\text{obs},i} - Y_{\text{pred},i})^2}$$

(E3)

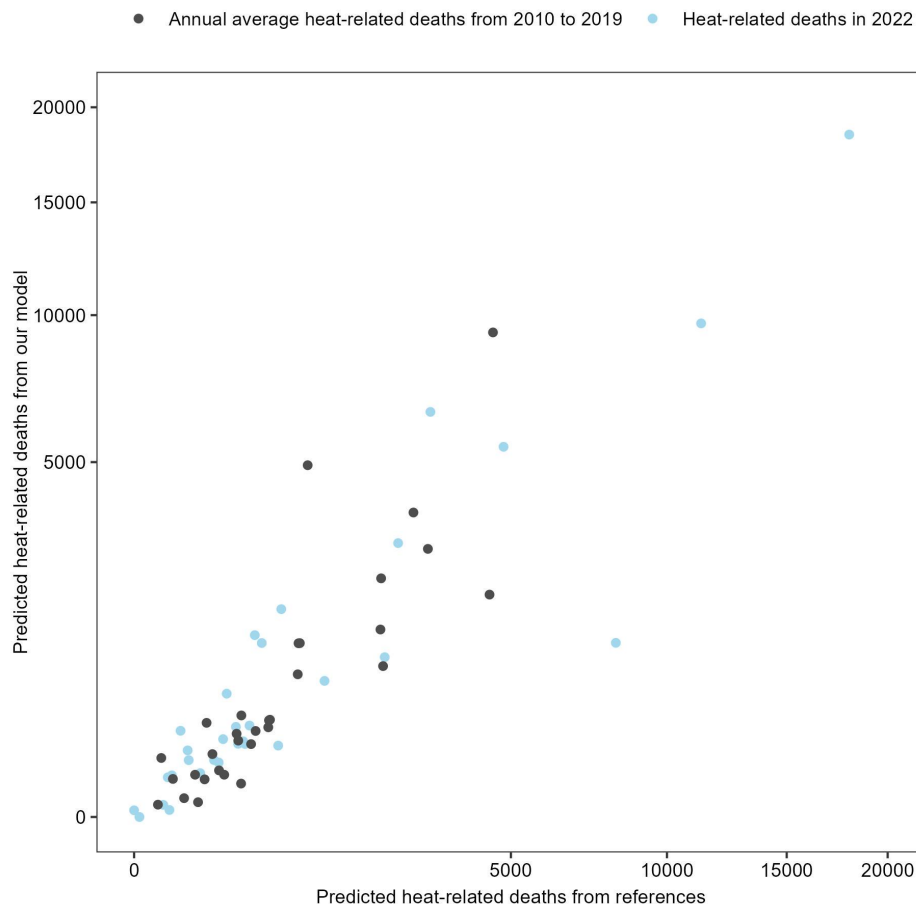
$$R^2 = 1 - \frac{\sum_i (Y_{\text{obs},i} - Y_{\text{pred},i})^2}{\sum_i (Y_{\text{obs},i} - \frac{1}{n} \sum_{i=1}^n Y_{\text{obs},i})^2}$$

(E4)

Supplementary Table 2. Summaries of root mean square error (RMSE) and coefficient of determination (R^2) of bootstrapping validation of the model among different age groups.

Age group	RMSE	R2
0-14	0.81	0.94
15-65	4.72	0.98
65+	20.00	0.99

Finally, we cross-validated the predicted heat-related mortality from our model with results from existing studies, yielding an R^2 of 0.78 (see Supplementary Fig 4). While inherent differences in model construction details naturally lead to some variation between our results and those of other studies, this cross-validation suggests that our model results are credible and highlight the critical role of ambient humidity in modulating heat-related excess mortality.



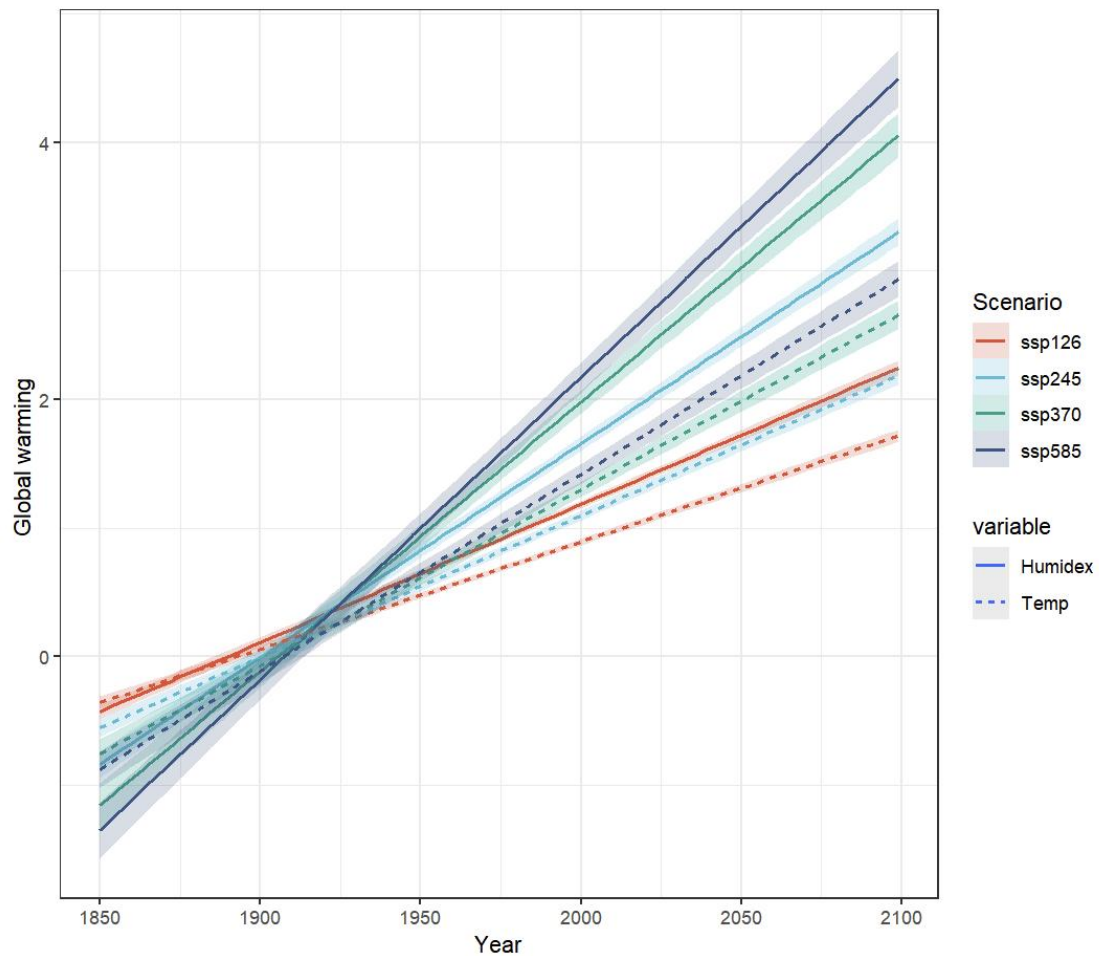
Supplementary Fig 4. Comparison between predicted heat-related deaths from our model using Humidex and other studies. The predicted results were extracted as the annual average from 2010 to 2019 and the total value in 2022 to match the available data from the references. The R-squared is equal to 0.78.

The authors seem to neglect the very substantial body of work that has probed this topic at length (and which concludes that, in general, adding a humidity term does not improve model skill). Please see: Baldwin, J.W., Benmarhnia, T., Ebi, K.L., Jay, O., Lutsko, N.J. and Vanos, J.K., 2023. Humidity's role in heat-related health outcomes: a heated debate. *Environmental health perspectives*, 131(5), p.055001 for a recent overview. At the very least, the authors need to interpret their results in the context of such work.

Response: We are concerned that the debate regarding the role of humidity in assessing health effects has indeed been longstanding, with the academic community divided on this issue. Some studies argue that moisture does not significantly impact the evaluation of health effects, while others emphasize its importance. We have added a discussion in our manuscript to address this debate and present our perspective. First, as shown in Supplementary Fig 12, it is evident that the world is transitioning from dry heat to humid heat. The increase in humid heat is notably faster than that of dry heat under all scenarios we focused on in this study. Past observations

might have suggested that including humidity is not crucial, as these observations were conducted under predominantly dry heat conditions. However, we must acknowledge that the world is transitioning towards more humid heat. Consequently, the effects of humidity may become increasingly significant in the future. As more data becomes available, we plan to conduct further research to determine if the impact of humidity is indeed becoming more pronounced over time.

In our discussion, we have referenced the work by Baldwin et al. (2023) and acknowledge the substantial body of research on this topic. We also interpret our results within the context of this existing literature and provide a balanced view of the ongoing debate, as **“To the best of our knowledge, our study may be the first to use a weather indicator that combines dry-bulb air temperature and humidity to model the Europe-wide mortality responses to day-night compound, daytime-only, and nighttime-only hot extremes across various age groups. A related study³⁴ that examined the relation between hot nights and mortality in four countries in Southern Europe reported an excess mortality risk related to compound heat ranging from 12% to 37%, which aligns with our findings (over 30%). Recent research also highlights the importance of considering humidity when assessing heat stress³⁵. Our findings indicate that persistently extreme humid heat during the day and night is associated with a higher mortality rate among the elderly. Sweating is a crucial cooling mechanism for the human body^{36,37}. As a result, a decreased sweating rate due to high ambient humidity may raise body temperature and increase the risk of heat-related illnesses. Nevertheless, a few studies suggested that adding humidity to air temperature does not considerably improve the prediction accuracy of the heat exposure-mortality response model^{37–39}. We note that most of these studies were conducted in predominantly dry conditions, with the possibility of a global shift towards more humid heat unnoticed (Supplementary Fig 12.). In this regard, our results provide a contrasting emphasis on the humid heat burden. Specifically, the validation demonstrates that Humidex gives a more reliable representation of heat-mortality association throughout different periods when compared to dry-bulb air temperature alone. The models that account for humidity show higher accuracy than those using dry-bulb air temperature alone in estimating heat-related mortality ($R^2 = 0.78$ vs. 0.63). Despite this, the role of humidity in modeling heat-related mortality may depend on many other factors, such as local climate conditions and data characteristics. Our study contributes to the ongoing discussion by stressing that humidity should be considered in health effect assessments in the future when humid heat is more prevalent. It also highlights the importance of paying more attention to the potential health impacts of humidity during extreme heat events. Further study is required to determine whether the impacts of humidity are getting more pronounced with time and how they interact with other factors like air temperature and population vulnerability.”**



Supplementary Fig 12. Global trends in Humidex and air temperature over time under four scenarios, including SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, SSP5-RCP8.5.

Related to the above: why did the authors choose the Humidex versus any one of the other many combined temperature-humidity measures (e.g., wet-bulb temperature, simplified wet-bulb globe temperature, wet-bulb globe temperature, heat index, equivalent temperature, universal thermal climate index)?

Response: Thank you for raising this important question. Notably, there is a wide range of combined temperature-humidity measures that can be chosen. Here, we selected Humidex for two main reasons. First, the Humidex provides a unit that combines temperature and humidity into a single measure, making it easier to compare with temperature directly. Second, Humidex has been widely used in climate and health research, particularly in North America and parts of Europe, which aligns with our study region. Its established use and historical data availability made it a practical choice for our analysis. While other indices like the Wet-Bulb Globe Temperature (WBGT) or Heat Index are also valuable, the Humidex was chosen due to its straightforward application and existing references in related studies. We acknowledge that the effectiveness of various indices can vary based on location,

climate, and health outcomes. Thus, comparing different indices remains a worthwhile area of future research. For our study, Humidex was selected based on its practicality and the context of our research objectives.

3. Deployment of the climate scenarios

The RCPs and SSPs are combined inappropriately. For example, RCP8.5 is incompatible with SSP1. Please read the relevant literature and either justify the approach taken here, or reconsider the scenarios considered. A readable overview of this issue is available courtesy of the Carbon Brief: <https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/>

Response: Thank you for pointing out this issue regarding the inappropriate combination of RCPs and SSPs. Following your suggestion and based on the guidance from Reviewer 1, we have updated our future climate model simulation data to the CMIP6 version, which considers the compatibility and matching of scenarios during simulation. In this revision, we have focused on four scenarios, including SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, and SSP5-RCP8.5. And the corresponding manuscript has been revised as **“We integrated population estimates that align with four shared socioeconomic pathways (SSP1, SSP2, SSP4, and SSP5) with single-model large-ensemble simulations under four future emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) (Methods)...**

In addition, the monthly relative humidity and surface air temperature derived from the new Max Planck Institute (MPI) grand ensemble with CMIP6 was used. The MPI grand ensemble simulations were performed with combined natural and anthropogenic forcing, including historical runs up to 2014 and future projections under various Shared Socioeconomic Pathways (SSPs), such as SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.”

4. Headline findings

The headline messages need reconsideration, regardless of the other concerns raised above. Concluding that declining total population can ‘offset’ the climate induced rise in heat mortality is, I contend, an unhelpful framing. ‘Impact’ will surely be felt by the change in heat mortality per capita rather than the total? That is, if global population declined by a factor of 10, and the likelihood of dying from extreme heat increased by a factor of 10, would we really regard that as no change in the heat mortality burden? To avoid any such interpretation, I suggest that the authors reconsider their framing throughout.

Response: Thank you for the suggestion. We agree that framing the findings in terms of per capita heat mortality rather than total heat mortality provides a more accurate representation of the impact of climate change. As a result, we have revised our analysis and conclusions to focus on changes in heat mortality per capita.

In the Methods section, we now describe our approach as follows: **“We calculated the changes in future mortality per capita ($\Delta\mu_{y,c}$) relative to the baseline of 2022 ($\mu_{2022,c}$) in each region as Eq.8:**

$$\Delta\mu_{y,c} = (\mu_{y,c} - \mu_{2022,c})/\mu_{2022,c} \quad (8)$$

where $\mu_{y,c}$ represents the heat-related excess mortality per capita in year y and region c .”. All conclusions and headline findings have been updated accordingly to reflect this change in focus.

Future burden of heat-related mortality

The exposure-response functions of heat-related mortality by three age groups were utilized to project future changes in heat-related excess mortality per capita in Europe from 2024 to 2100 (Methods). We integrated population estimates that align with four shared socioeconomic pathways (SSP1, SSP2, SSP4, and SSP5) with single-model large-ensemble simulations under four future emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) (Methods). We found that as global warming intensifies, the per capita heat-related mortality rate increases faster (Fig. 2). Specifically, the rates are projected to rise by 109.8% (95% confidence interval: 38.0 – 145.7%) for SSP1-2.6, 126.4% (61.5 – 169.9%) for SSP2-4.5, 211.9% (121.7 – 270.0%) for SSP3-7.0, and 273.3% (165.0 – 344.7%) for SSP5-8.5 with every degree of global warming.

We compared the growth rates of heat-related deaths per capita before and after the middle of the twenty-first century (Fig. 2a). The difference between 2045 – 2050 and 2025 – 2030 (between 2095 – 2100 and 2045 – 2050) was used to represent the growth rate before (after) the middle of the twenty-first century. Under the high-emission scenarios (SSP3-7.0 and SSP5-8.5), the growth rate of heat-related deaths per capita in the post-mid-century is 2.2 – 2.8 times higher than that in the pre-mid-century. Heat-related deaths are projected to increase by about 1 per 10,000 people per degree of global warming under SSP1-2.6 and SSP2-4.5, compared to about 2 per 10,000 people under SSP3-7.0 and about 3 per 10,000 people under SSP5-8.5 (Fig. 2b). Specifically, more than 77.0% of heat-related deaths are experienced by individuals aged 65 years or above. The growth rates of heat-related mortality with each degree of global warming show a strong spatial diversity in response to climate change and population dynamics (Fig. 2c). The most significant increase in heat-related mortality per capita is found in Western Europe and Northern Europe, with an increase of rate of 266.2

- 600.1% and 327.3 - 573.2% per degree of global warming, respectively. For an additional 1 ° C of global warming, Southern Europe shows the lowest growth rates at 57.1 - 163.3%.

To better understand the spatial distribution of future health burdens, the cumulative number of heat-related deaths per 10,000 people is illustrated in Fig. 3. For various population-emission combinations, the cumulative number of heat-related summer deaths per 10,000 inhabitants in Europe might surpass 56.2 - 119.5 if the global warming exceeds 2.5 ° C. Summer heat might lead to more than 244.3 per 10,000 individuals in Europe if global warming keeps rising and surpasses 4 ° C. Until the end of the twenty-first century, a disproportionate increase in the negative effects of heat on health is predicted for the nations with fast-aging populations, such as Germany, Italy, Spain, France, and Slovenia. With rising global carbon emissions, new hotspots with high cumulative heat-related mortality per 10,000 persons will emerge, which include Spain (85.7 - 372.6), Denmark (127.0 - 313.1), Finland (73.5 - 161.2), Romania (52.9 - 396.1), and Bulgaria (81.4 - 535.4).

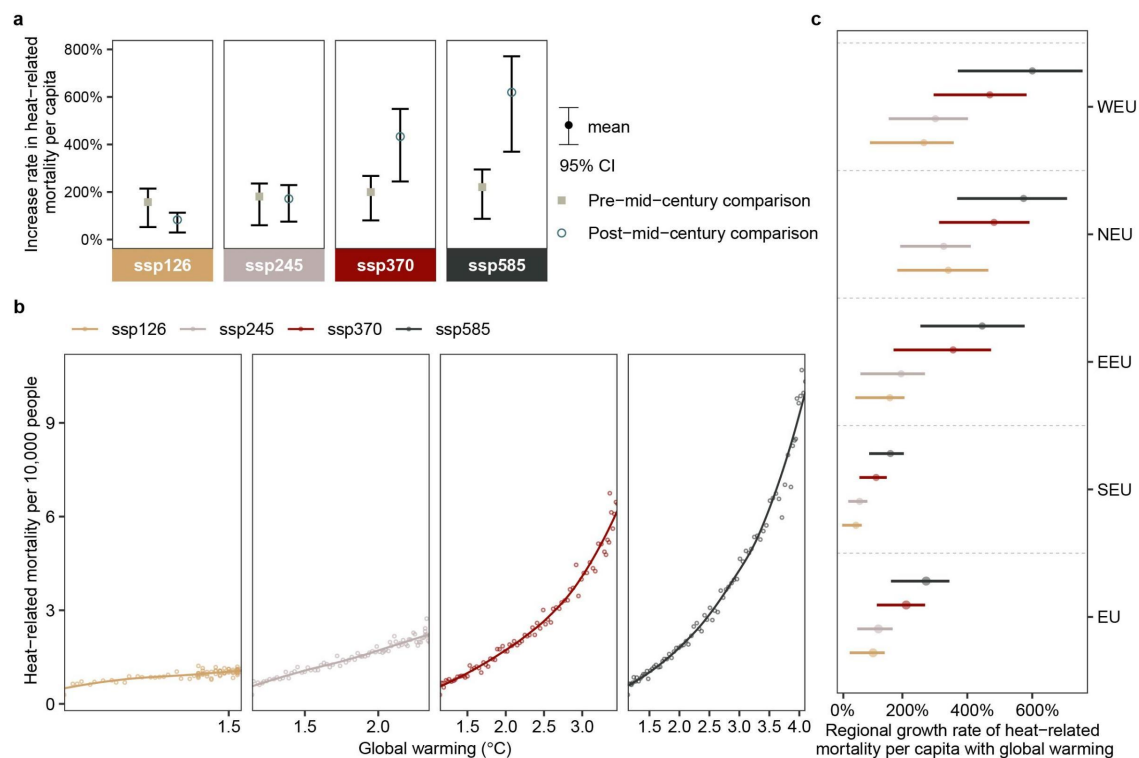


Fig. 2. Projected changes in heat-related mortality in Europe. (a) The growth rate of heat-related excess mortality per capita under different climate-population scenarios. Squares and circles indicate the comparison for near-mid-century and mid-end-century, respectively. The pre-mid-century growth rate is calculated by comparing the mean mortality per capita between 2045 - 2055 and 2025 - 2030. The post-mid-century growth rate is calculated by comparing the mean mortality per capita between 2095 - 2100 and 2045 - 2055. The black bars represent the 95% confidence interval of the projected growth

rate of heat-related mortality per capita. (b) The variation of heat-related deaths per 10,000 people with global warming. The global warming levels are determined by the years in which the 20-year moving average global mean surface temperature anomaly (relative to the pre-industrial period 1850 – 1900) exceeds specific warming levels. (c) Regional growth rates of heat-related excess mortality per capita with global warming. The growth rate is represented by the linear slope of heat-related mortality against the levels of projected global warming, i.e., the percentage change in added heat-related mortality per capita with each degree of global warming. The percentage changes are estimated relative to the 2022 baseline of 1.07 heat-related deaths per 10,000 capitals. Europe (EU) is divided into four regions: Northern (NEU), Western (WEU), Eastern (EEU), and Southern Europe (SEU), with baseline heat-related excess deaths of 0.25, 0.38, 0.74, and 2.59 per 10,000 capitals, respectively. Note that the baselines reported in 2022 differ from the previous section due to excluding regions with missing data in the projections.

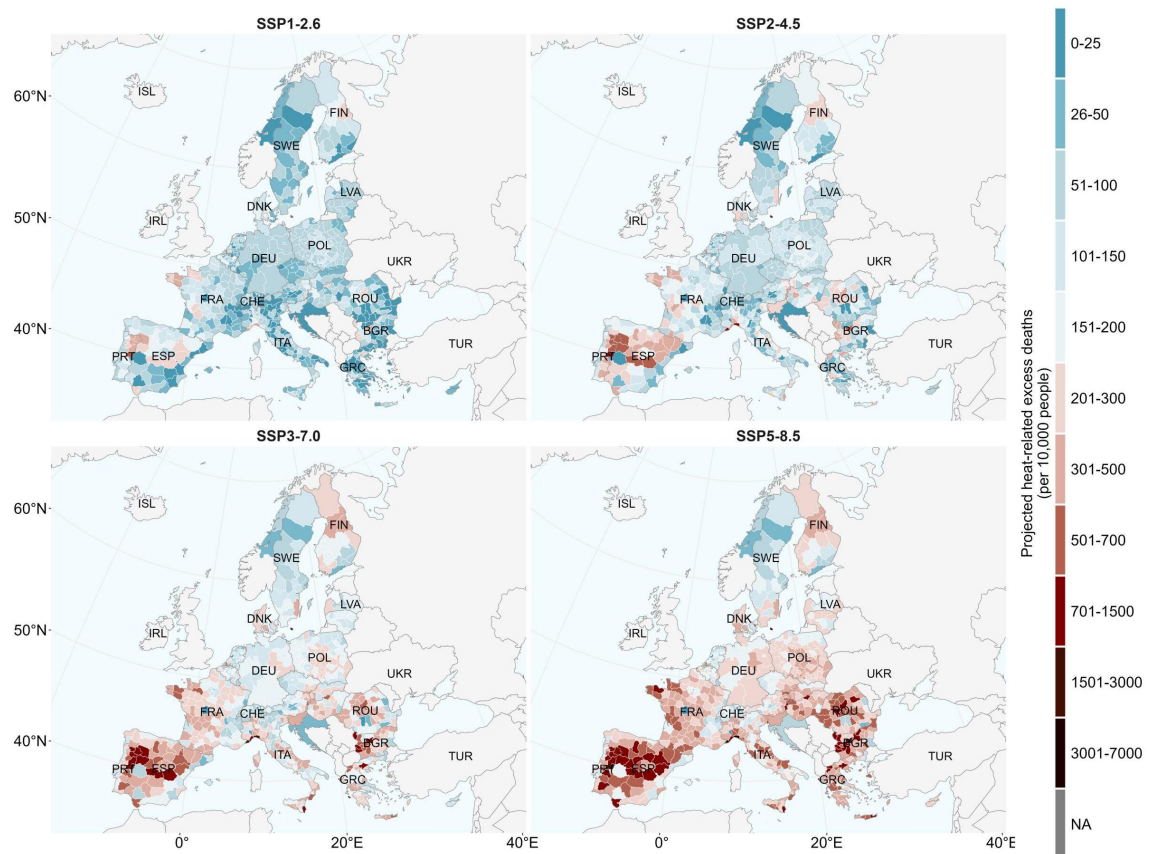


Fig. 3. Geographic distributions of expected cumulative heat-related excess deaths per 10,000 people. The projected heat-related excess deaths per 10,000 people at the NUTS3 level from 2024 to 2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The regions with missing data are shaded in grey.

Roles of climate change, population growth, and aging

Assuming no future improvements in thermal acclimation and adaptive capacity,

future changes in heat-related mortality burden will be shaped by the changes in climate, population size, and composition. To better understand the drivers of future heat-related mortality in Europe, we developed a decomposition method to analyze the individual roles of climate change, population growth, and aging in heat-related deaths at the country level (Methods). Until the end of the century, the cumulative heat-related mortality burden across a range of warming scenarios is largely determined by climate change (28.3 – 285.2 deaths per 10,000 people), followed by population size change (28.2 – 28.5 deaths per 10,000 people) and population aging (27.8 deaths per 10,000 people). By the end of the twenty-first century, almost 62% of the cumulative heat-related deaths can be attributed to climate change. Under SSP3-7.0, population decline mitigates a limited number of heat-related mortality burden induced by climate change (<0.03%) (Fig. 4). The percentage change in future heat-related mortality due to the change in population structure was relatively stable (35 – 50%) before global warming reaching 2° C. The contribution of population age structure change to the increase in heat-related deaths per capita decreases from about 50% to 10% once global warming surpasses this level. However, if global warming hits 4° C or more, future climate change will contribute to nearly 96% of the rise in heat-related deaths in Europe, substantially increasing the burden of heat-related mortality.

Comparing the cumulative number of heat-related deaths per 10,000 people caused by each factor (Fig 4c), it can be found that global warming (accounting for 61.7 – 90.0% of the increase in heat-related deaths) and population aging (accounting for 9.7 – 37.5% of the increase in heat-related deaths) contribute the most growth of heat-related mortality under all population-emission scenarios, with global warming being the dominant driver. Under a high-emission scenario, namely SSP5-8.5, the relative contribution of global warming is more pronounced (90.0%) compared to the moderate-emission scenario SSP2-4.5 (76.4%). Population decline plays a limited role in the future change of heat-related mortality per capita (-0.02% – 0.07%).

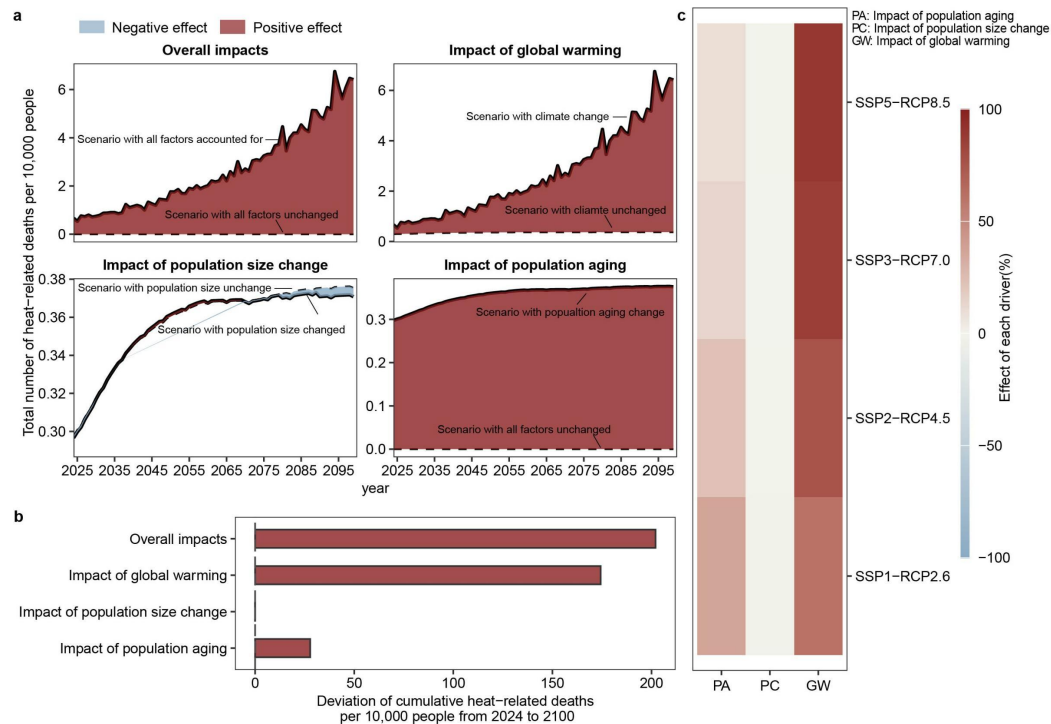


Fig. 4. The relative contributions of climate change, population size change, and population aging to future heat-related excess mortality per 10,000 people in Europe. (a) The temporal variations of individual effects of global warming, population size change, population aging, and their total effects (overall impacts) on future heat-related excess deaths in Europe during 2024 - 2100 under SSP3-7.0. The solid line displays the projected heat-related excess mortality with all factors or a specific factor accounted for. The dashed line denotes the projections with all factors remaining unaltered. (b) The cumulative number of heat-related excess deaths due to the changes in climate, population size, and age structure from 2024 to 2100. Additional projection results for alternative scenarios are available in Supplementary Figs. 9-11. (c) Heat map showing the relative contributions of global warming, population size change, and population aging under several scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The relative contribution of each driver is measured by comparing the cumulative number of heat-related facilities per 10,000 people caused by that driver to the total number of heat-related deaths per 10,000 people caused by all factors.

Reviewer #2 (Remarks on code availability):

I have looked at the database, but have not reviewed the code in detail. What I can see, though, is that there is a README that describes (albeit very briefly) what the different scripts do. However, there is insufficient integration with the datasets (or explanation about which data should be fed into which script) to make the work reproducible.

Response: Thank you for pointing out the need for better integration and explanation of our datasets and scripts to enhance reproducibility. We will add more detailed documentation to ensure that others can replicate our work effectively.

In the context of the above, I do wonder how authors are supposed to satisfy such requirements -- given that often datasets will be far too large to be managed locally. In such cases, some code may be run on a remote server to cut out/manage data there, and other code would be used to process derived data locally. Really, everything would be required for reproducibility, but so too would the access to the remote server!

Response: Sorry for any confusion. To address these concerns, we checked the upload of code and data, ensuring all the code was available.

Reviewer #3 (Remarks to the Author):

I was kindly asked to review the manuscript: Future burden of humid-heat related mortality in Europe aggravated by compound day-night warming and aging. This is a well written and well detailed manuscript. Such study is highly relevant as it could add to the scientific body of knowledge and address a pressing public health issue, but I would encourage them to consider the following:

Response: Thank you for your positive feedback on our revision. Your suggestions and comments have significantly enriched our research's content and presentation.

The introduction section should be reorganized, provide additional information related to the methods followed in previous studies and highlight the gap of knowledge that this study seeks to fill.

Please, provide a statement of why this research is particularly novel aside from the study area.

Response: Thank you for pointing out this issue. We have restructured the introduction to provide additional information related to the methods followed in previous studies and to highlight the knowledge gap that this study seeks to fill. We have revised the manuscript accordingly in lines 60-109, as “**The occurrence of extreme heat events has increased in recent decades, with a notable rise in the intensity, frequency, and duration of these episode. This trend has significant implications for human health. Climate models consistently predict that as the world warms, more land will be exposed to humid heat and compound hot extremes, which may exacerbate the effects of heat stress on human health. In recent decades, Europe has experienced a warming trend that is nearly twice as large as the global average, making it a ‘hotspot’ of heat stress⁹. Meanwhile, the continent is experiencing a notable shift in its population age structure, with an increasing proportion of vulnerable older adults resulting from a declining birth rate, rising life expectancy, and an immigration pattern characterized by a net inflow of retirees. Although Europe’s developed economy allows for better adaptation to extreme heat, nearly 21.4% of the population lived in dwellings that were not comfortably cool during summers until 2020. The continent’s most vulnerable groups are susceptible to heat stress due to amplified warming, an aging population structure, and low adaptability to summer heat. Therefore, accurately predicting the European future burden of heat-related mortality and understanding the underlying drivers are of the utmost importance.**

Previous efforts have demonstrated the amplified health risks associated with compound hot extremes, which encompass both daytime and nighttime heat, compared to daytime-only heat. However, the discourse on heat-related health burdens in Europe remains largely anchored in daily mean temperature and mortality records. There is a dearth of research exploring the additional health

impacts of prolonged and compound hot extremes, and few studies assessing the adverse health effects of compound extreme heat events on age-specific populations in Europe. This may lead to an underestimation of the overall societal vulnerability to extreme heat. The majority of previous studies have estimated the change in heat-related mortality risk as a function of changes in ambient dry-bulb temperature, thereby emphasizing that the estimation of heat-related mortality in empirical models is not affected by humidity. However, the body's sweating rate is significantly affected by specific humidity, which, in turn, significantly impacts mortality responses to heat stress. Ignoring the interaction between temperature and humidity is insufficient for meaningful projections, given the anticipated expansion of humid regions in Europe at high levels of global warming⁴. Additionally, research on heat-related mortality is geographically limited, focusing on specific cities or countries and lacks cross-nation comparisons for the entire continent of Europe.

In addition to a precise quantitative relationship between heat and mortality, robust projections of heat-related risks also necessitate an understanding of the uncertainties inherent in climate change and variability, as well as changes in population size and age structure. The traditional use of climate models in Coupled Model Intercomparison Project (CMIP) phases 5 and 6 with a limited size of ensemble members may underestimate the uncertain range of future heat-related mortality burdens, as it fails to fully sample the internal variability in the climate system. The emerging single-model large-ensemble simulations are beneficial for sampling internal climate variability and its potential roles in future changes in heat-related excess mortality. Besides, our capability to consider the evolving vulnerability of individuals to future heat exposure is impeded by the conventional omission of population age structure transformation, which may cause an overly conservative lower-bound projection of the heat-related health burden.

To address these challenges, we developed a comprehensive, Europe-wide, fine-grained dataset that incorporates an integrated metric of temperature and humidity (i.e., the Humidex) and a range of extreme heat categories. Using data aggregated from hourly to weekly intervals, a Quasi-Poisson generalized regression combined with a distributed lag non-linear model was employed to estimate location-age specific associations between weekly mortality and Humidex, consecutive and inconsecutive daytime, nighttime and diurnal compound hot extremes across 955 NUTS3-level (the most detailed level of the Nomenclature of territorial units for statistics classification) regions in 34 European countries. After validating the robustness and prediction accuracy of the model, we projected future heat-related mortality per capita at different levels of global warming from 2024 to 2100, by combining single-model large-ensemble simulations with projections of population size and age-structure. Finally, a decomposition approach was used to identify the roles of climate

change, population growth, and aging in the future burden of heat-related mortality in Europe.”

Methods:

Could the authors provide more information on the control the validity of the results?

A)Rodrigues, M., Santana, P. & Rocha, A., 2019. Bootstrap approach to validate the performance of models for predicting mortality risk temperature in Portuguese Metropolitan Areas. Environ Health 18, 25. <https://doi.org/10.1186/s12940-019-0462-x>

B)Rodrigues, M., Santana, P. & Rocha, A., 2019. Effects of extreme temperatures on cerebrovascular mortality in Lisbon: a distributed lag non-linear model. Int J Biometeorol 63, 549–559.

Response: Thanks for the comments. We acknowledge the widely recognized challenge in validating models for attributing mortality to extreme heat/cold due to the difficulty in obtaining precise mortality data attributed to temperature extremes. Following your suggestion and the references provided by reviewer 2, to enhance the validation of our model, we have revised and improved our methodology.

A)Rodrigues, M., Santana, P. & Rocha, A., 2019. Bootstrap approach to validate the performance of models for predicting mortality risk temperature in Portuguese Metropolitan Areas. Environ Health 18, 25. <https://doi.org/10.1186/s12940-019-0462-x>

B)Rodrigues, M., Santana, P. & Rocha, A., 2019. Effects of extreme temperatures on cerebrovascular mortality in Lisbon: a distributed lag non-linear model. Int J Biometeorol 63, 549–559.

Supplementary Table 4. Comparison of model performance using Humidex and air temperature. The RMSE and MAD values reported for each group represent the differences in model parameters when models were trained using Humidex and air temperature with data from different time periods. The p-value test is based on the Wald test, with $p < 0.05$ indicating a significant difference, $p < 0.01$ indicating a very significant difference, and $p < 0.001$ indicating an extremely significant difference.

Age group	Metric	RMSE	MADs	P-value
0-15	Humidex	0.43	0.06	0.99
	Air temperature	0.47	0.13	
16-65	Humidex	0.13	0.01	0.89
	Air temperature	0.15	0.01	
65+	Humidex	0.15	0.03	<0.001***

	Air temperature	0.15	0.04	
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Second, we employed the bootstrapping approaching recommended by reviewer 3 to validated the performance of our models. This method creates resamples of the same size from the validation data with replacement and then predicting the values for the original data using the model. Unlike cross-validation, which focuses on assessing model stability on different fixed subsets, bootstrapping evaluates the model's sensitivity to data variability through repeated sampling. We repeated this step for 30 times. The final model accuracy was reported as the average RMSE and the average coefficient of determination (R^2) of these 30 iterations. The root mean squared error and R^2 between the predicted number of deaths from the random sample and the observed value were computed as follow:

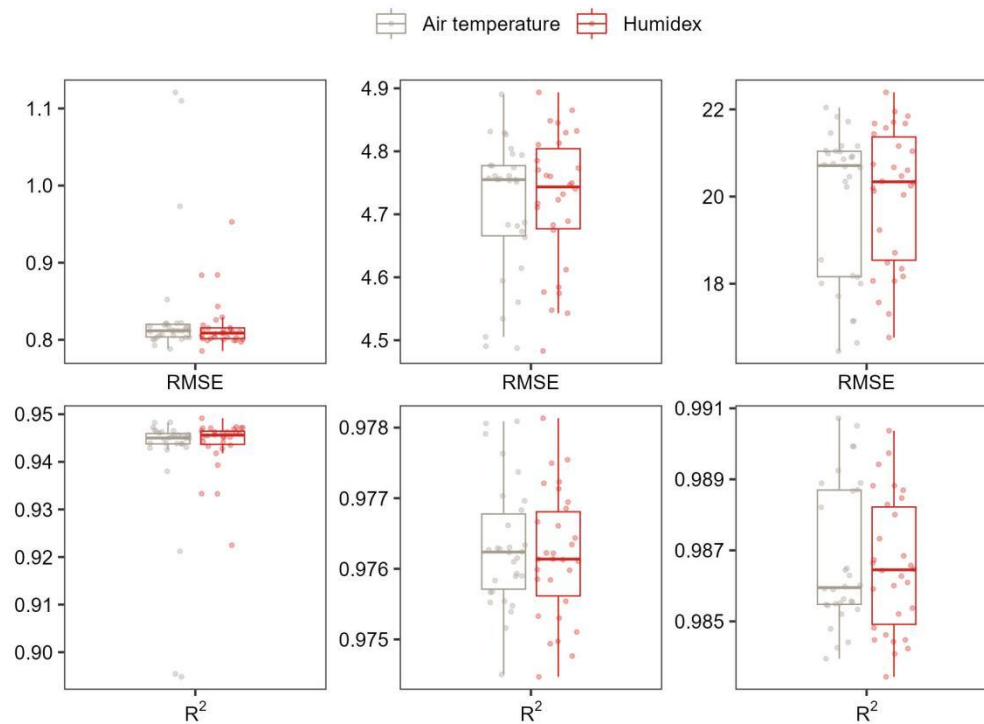
$$RMSE = \sqrt{\frac{1}{n} \sum (Y_{obs,i} - Y_{pred,i})^2}$$

$$R^2 = 1 - \frac{\sum_i (Y_{obs,i} - Y_{pred,i})^2}{\sum_i (Y_{obs,i} - \frac{1}{n} \sum_{i=1}^n Y_{obs,i})^2}$$

Table 5. Comparison of bootstrapping validation using Humidex and air temperature.

Age group	Metric	Humidex	Air temperature
0-14	RMSE	0.81	0.84
	R^2	0.94	0.94
15-65	RMSE	4.72	4.71
	R^2	0.98	0.98
65+	RMSE	20.00	20.00
	R^2	0.99	0.99

As shown in Table 5, the results indicate low sensitivity to data variability and high model robustness. Here, Humidex and air temperature did not show significant differences in performance (see Supplementary Fig 8).



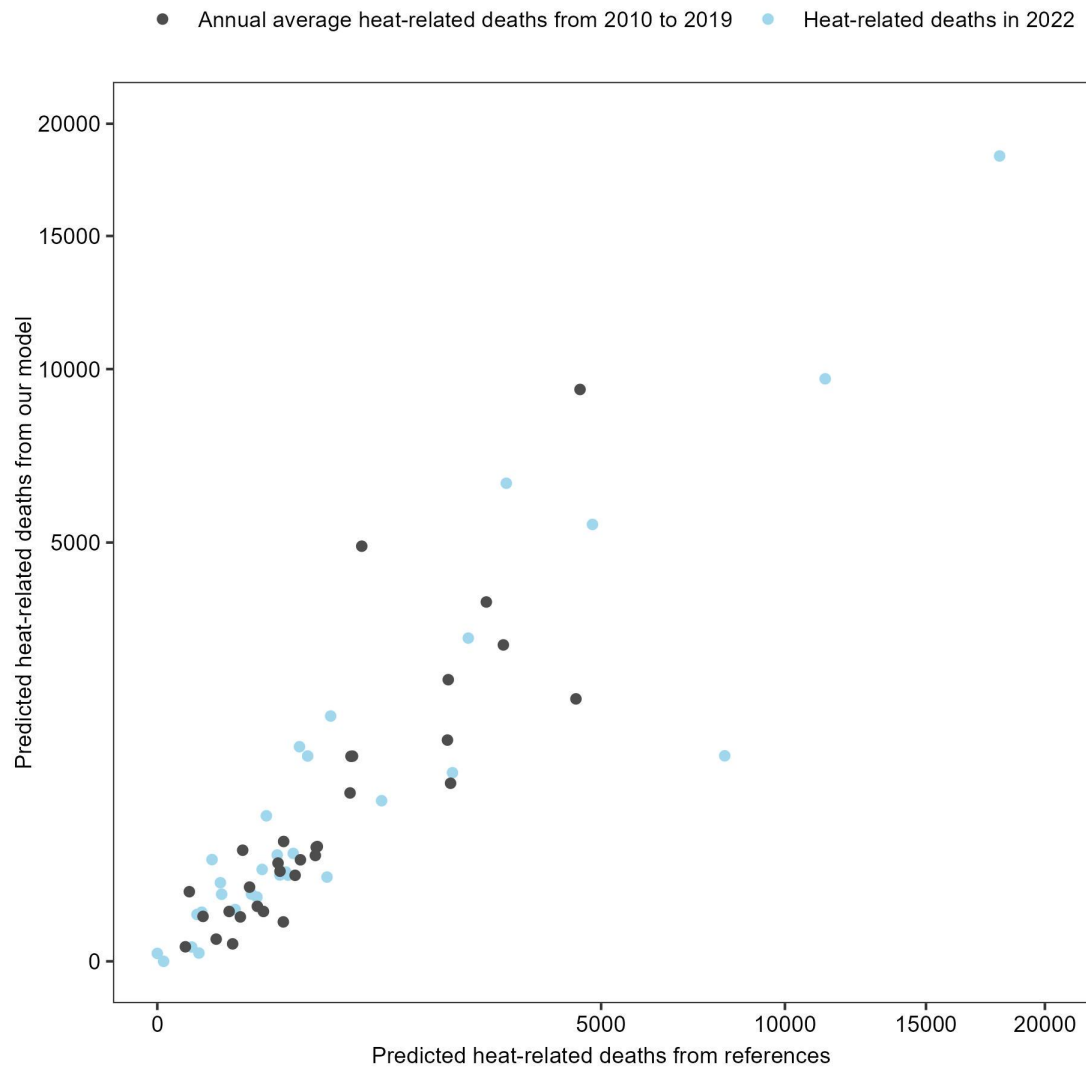
Supplementary Fig 9. Boxplot of the accuracy comparison. The comparison was performed between model using Humidex (in red) and air temperature (in grey).

Last, we cross-validated the predicted heat-related mortality from our model with results from existing studies, yielding an R^2 of 0.78. Compared to the results using dry-bulb surface air temperature ($R^2 = 0.63$), the model using humidex showed a higher accuracy. While inherent differences in model construction details naturally lead to some variation between our results and those of other studies, this cross-validation suggests that our model results are credible and highlight the critical role of ambient humidity in modulating heat-related excess mortality.

Refs for predicted heat-related mortality:

2022: Heat-related mortality in Europe during the summer of 2022

The mean value from 2010 to 2019 : Global, regional, and national burden of heatwave-related mortality from 1990 to 2019: A three-stage modelling



Supplementary Fig 4. Comparison between predicted heat-related deaths from our model using Humidex and other studies. The predicted results were extracted as the annual average value from 2010 to 2019 and the total value in 2022 to match the available data from the references. The R-squared is equal to 0.78.

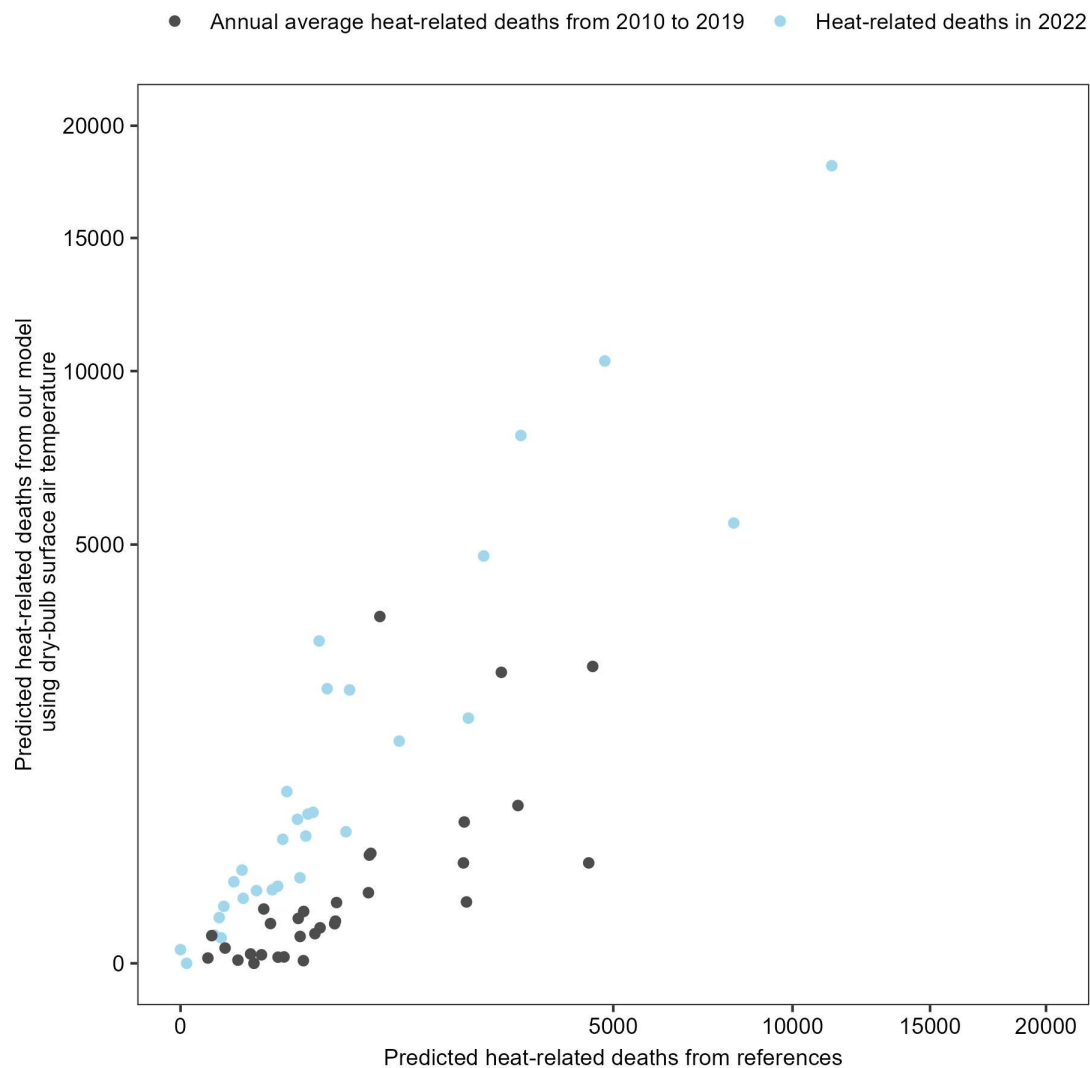


Fig 5. Comparison between predicted heat-related deaths from our model using dry-bulb surface air temperature and other studies. The predicted results were extracted as the annual average value from 2010 to 2019 and the total value in 2022 to match the available data from the references. The R-squared is equal to 0.63.

Discussion

Overall, the discussion of findings is complete and concise. The results are adequately compared with previous work, explanations are proposed for the results observed and limitations are well discussed.

Response: Thank you for your positive feedback on our discussion of the findings. Again, we appreciate your recognition of our efforts. Following the suggestions from you and other reviewers, we have further refined and modified the discussion to enhance its clarity. We hope these revisions have strengthened our manuscript, **“We investigated the health impact of compound day-night humid heat on three age**

groups and projected future heat-related mortality in Europe from 2024 to 2100. When exposure lasts more than three days, compound day-night heat has a much greater impact on older adults than single daytime heat, with about a 2.9-fold increase in risk. In line with previous studies³¹⁻³³. The projection shows a notable hot future on the assumption of no adaptation, the number of heat-related deaths in summer (weeks 22-35) is projected to increase at varying rates with each additional degree of global warming under various climate and socio-economic scenarios: 109.8% (38.0 – 145.7%) for SSP1-2.6, 126.4% (61.5 – 169.9%) for SSP2-4.5, 211.9% (121.7 – 270.0%) for SSP3-7.0, and 273.3% (165.0 – 344.7%) for SSP5-8.5. In particular, it was projected that the largest rate of increase in heat-related deaths would be in Western Europe (266.2 – 600.1%), followed by Northern Europe (327.3 – 573.2%). We also noticed divergent change patterns of climate change and aging, two major factors that will increase the burden of heat-related mortality in the future. With global warming, the contribution of climate change to future heat-related mortality burden is estimated to increase from 54.6% to 96.2%. However, the contribution of aging shows a different change pattern compared to climate change, which peaks at about 45%.

To the best of our knowledge, our study may be the first to use a weather indicator that combines dry-bulb air temperature and humidity to model the Europe-wide mortality responses to day-night compound, daytime-only, and nighttime-only hot extremes across various age groups. A related study³⁴ that examined the relation between hot nights and mortality in four countries in Southern Europe reported an excess mortality risk related to compound heat ranging from 12% to 37%, which aligns to our findings (over 30%). Recent research also highlights the importance of considering humidity when assessing heat stress³⁵. Our findings indicate that persistently extreme humid heat during the day and night are associated with a higher mortality rate among the elderly. Sweating is a crucial cooling mechanism for human body^{36,37}. As a result, a decreased sweating rate due to high ambient humidity may raise body temperature and increase the risk of heat-related illnesses. Nevertheless, a few studies suggested that the addition of humidity to air temperature does not considerably improve the prediction accuracy of the heat exposure-mortality response model³⁷⁻³⁹. We note that most of these studies were conducted in predominantly dry conditions, with the possibility of a global shift towards more humid heat unnoticed (Supplementary Fig 12.). In this regard, our results provide a contrasting emphasis on the humid heat burden. Specifically, the validation demonstrates that the Humidex gives a more reliable representation of heat-mortality association throughout different time periods when compared to dry-bulb air temperature alone. The models that account for humidity show higher accuracy than those using dry-bulb air temperature alone in estimating heat-related mortality ($R^2 = 0.78$ vs. 0.63). Despite this, the role of humidity in modelling heat-related mortality may depend on many other factors, such as

local climate conditions and data characteristics. Our study contributes to the ongoing discussion by stressing that humidity should be taken into consideration in health effect assessments in the future when humid heat is more prevalent. It also highlights the importance for the European Union to pay more attention to the potential health impacts of humidity during extreme heat events. Further study is required to determine whether the impacts of humidity are getting more pronounced with time and how they interact with other factors like air temperature and population vulnerability.

In light of numerous previous studies^{40,41}, we assumed that both the shape of the heat-mortality curve and the human capacity to cope with climate change would remain constant at a fixed level between 2010 and 2019. Therefore, our estimates should be viewed as potential impacts of future extreme heat under specific scenarios considered, rather than as exact predictions of excess heat-related mortality. An individual's ability to adapt may be greatly impacted by various factors, including social support, health services and education^{31,38,42}. The uncertainties surrounding population adaptability and demographic change require further research. Assuming no changes in adaptation, our analysis reveal an unexpected increase in heat-related mortality in Northern Europe, an area that has been largely overlooked in other studies^{27,44,45}. Though the total number of heat-related deaths in Northern Europe is currently less than a tenth of that in Southern Europe, poor adaptability to hot extremes and lack of air conditioning may leave it unprepared for climate change. In order to resist cold environments, these high-latitude cities prioritize maximizing solar efficiency and minimizing ventilation in architectural designs⁴⁶. According to a recent analysis⁴⁷, the increasing trends in surface air temperatures in Lithuania, Finland, and Latvia were found to be substantially higher than the European average. This might support the reasoning behind our results and serve as a reminder to monitor these high latitudes more closely. However, according to statistics from the WHO Regional Office for Europe, except for Sweden, most Northern European countries still lack heat-health action plan (HHAP) and heat-health warning system (HHWS)⁴⁸. An even more urgent challenge than global warming is Europe's rapidly aging society⁴⁹⁻⁵¹. As our study shows, elderly heat-related deaths in Western Europe will account for over 44.3% of all heat-related deaths in Europe when global warming surpasses the crucial 1.5°C threshold. Elderly individuals, being particularly vulnerable to extreme heat, should be a primary focus of Europe's heatwave response strategies^{52,53}. However, most current HHAPs in Europe merely acknowledge vulnerable groups without offering targeted actions for them. Our findings underscore the need for authorities in Europe to develop more coordinated and adaptive solutions to address the rising threat of extreme heat.

Some caveats should be acknowledged. First, using weekly data may lead to an underestimation of the number of heat-related deaths due to limitations in

identifying the effect of continuous hot extremes. In the absence of finer-resolution mortality data, we employed weekly Humidex and mortality data in our epidemiological model, categorically aggregating different duration of continuous heat events on a weekly basis. Additionally, our study is lack of distinction between indoor and outdoor exposure, which may lead to an overestimation of predicted mortality rates. Individuals who spend more time indoors may benefit from cooling measures and thus be better adapted to heat-related threats. Future research should incorporate indoor exposure data to provide a more accurate estimation of heat-related health risks and to better understand how different living environments influence vulnerability to extreme heat. Second, the mortality data used in our research lacks precise details regarding the cause of death. To remove measurement errors in mortality ascribed to other causes (e.g., crime, air pollution), we introduced region-specific fixed factors and seasonal variation. It was assumed that these uncertainties have a random distribution, with a mean of zero. Third, we used only one set of single-model large-ensemble simulations in this study, namely the new Max Planck Institute grand ensemble with CMIP6. While it helps assess the uncertainty arising from internal climate variability, it may lead to a limited understanding of the uncertainty arising from model structure. However, we projected heat-related mortality burden changes under specific global warming levels, which could mitigate the effect of the model' s structural uncertainty on future projections.”

Conclusions

Include suggestions for how the analyses could be incorporated into public health programs.

Response: Thank you for your valuable suggestion. In response, we have expanded the conclusions to include more discussion on how our analyses can be integrated into public health programs. We hope that our research offers a meaningful perspective for the planning of European Union integration health policy addressing hot extreme risks.

POINT-BY-POINT RESPONSE TO REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily answered my questions.

Response: Thank you for your valuable feedback in the previous round of review. Your comments and suggestions were really helpful in improving the quality of our study and enhancing the scientific rigor of the model. We greatly appreciate your time and effort in reviewing our work.

Reviewer #4 (Remarks to the Author):

I found the paper interesting and well written.

Question: However, I have here few comments for improvement:

- there is a recent paper at [https://www.thelancet.com/journals/lanpub/article/PLIS2468-2667\(24\)00179-8/fulltext](https://www.thelancet.com/journals/lanpub/article/PLIS2468-2667(24)00179-8/fulltext) on a similar topic. Please reference it, explaining also the differences between the 2 (yours, this one) proposed approaches

Response: Thank you for your valuable suggestion. We agree that the recent paper you mentioned is a valuable contribution to the field. We have now referenced it in our manuscript. We note two key differences. First, our study places a stronger emphasis on the effects of humid heat and the combination of day-night hot extremes during warm season, whereas the referenced paper primarily focuses on air temperature alone, examining the impacts of both cold and hot extremes. Second, the age groups and warming scenarios included were different. These methodological differences may lead to some variations in the results. To address your concern, we have included a brief comparison in the results, as *"The spatial trend of the future heat-related mortality burden is similar to a recent study¹, with our results showing a higher heat burden in the coastal region of Western and Southern Europe. While the previous study projected the human health effects of both cold and hot impacts, the current study investigates a more comprehensive future heat burden by integrating daytime–nighttime compound heat extremes and humid heat rather than focusing solely on dry-bulb air temperature."*

Question: fig 1: the "Italy" case is much higher then the other countries...please explain why, and better describe this behavior

Response: Thank you for your thoughtful comment. We appreciate your attention to the anomalously high values observed for Italy in Fig. 1. This phenomenon has been noted in several studies ¹, and current reports suggested that it might be related to the factors such as severe aging

population and prolonged exposure to heat ^{2,3}. Although Italy introduced heat prevention and mitigation plans in its cities as early as 2004⁴, making it one of the largest air conditioning markets in Europe. However, health concerns about the side effects of air conditioning and environmental awareness⁵ have limited the usage of air conditioning⁶. In addition, the energy-saving law⁷ and high electricity prices⁸ may restrict the use of air conditioning in Italy, potentially amplifying the heat-related health burden. However, we are unable to provide a definitive scientific explanation at this time without dedicated investigation into this issue. To address your concern, we have added some notes in the discussion and have suggested that future research should explore this unusual behavior more thoroughly, see *“Given their heightened vulnerability, elderly individuals should be the primary focus of Europe’s heatwave response strategies^{9,10}. However, most current heat-health action plans in Europe merely acknowledge vulnerable groups without offering targeted actions for them. This may also explain the abnormally high heat-related mortality observed in Italy, which has always been at the forefront of summer heat^{1–3,11}. Italy introduced heat health prevention plans and warning systems as early as 2004⁴, making it one of the largest air-conditioning markets in Europe. However, both health concerns about the side effects of air conditioning and environmental awareness⁵ have limited the use of air conditioning⁶. The energy-saving law⁷ and high electricity prices⁸ in Italy may also potentially amplify the vulnerability of this region. Further investigations on understanding the causes of diverse vulnerability and adaptation to extreme heat are needed to develop coordinated and adaptive solutions for each European country.”*

1. García-León, D. *et al.* Temperature-related mortality burden and projected change in 1368 European regions: a modelling study. *Lancet Public Health* **9**, e644–e653 (2024).
2. Settanta, G., Frascchetti, P., Lena, F., Perconti, W. & Piervitali, E. Recent tendencies of extreme heat events in Italy. *Theor Appl Climatol* **155**, 7335–7348 (2024).
3. Morabito, M. *et al.* Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? *Int J Biometeorol* **56**, 801–810 (2012).
4. Michelozzi, P. *et al.* Temperature and summer mortality: geographical and temporal variations in four Italian cities. *J Epidemiol Community Health* (1978) **60**, 417 (2006).
5. Euronews Green. Europeans reluctantly turn to air conditioning as heatwaves bite | Euronews. *APTN* (2023).
6. Enerdata. *Air Conditioning per Dwelling | ODYSSEE-MURE*. <https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/unit-consumption-air-conditioning.html>.
7. Reuters. The heat is on, Italy plans to turn down air conditioning to save energy | Reuters. *Reuters* (2022).

8. Statista. *Electricity Price by Country 2024*.
<https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/> (2024).
9. WMO. Extreme weather and human health. *ECMWF* (2024).
10. Iacobucci, G. Europe is seeing “devastating” rise in health harms from extreme weather events, experts warn. *BMJ* q934 (2024) doi:10.1136/bmj.q934.
11. Ballester, J. *et al.* Heat-related mortality in Europe during the summer of 2022. *Nat Med* **29**, 1857–1866 (2023).

Question: fig 3: why some countries (i.e. Ireland) are missing from the map?

Response: Thank you for raising this important point. After re-examining the reasons for the missing data in Figure 3, we identified gaps in the historical records and projection data that we used. A detailed explanation of the missing data is provided below.

(1) Missing historical data

The historical data used to construct the heat exposure-mortality relationship were obtained from Eurostat via <https://ec.europa.eu/eurostat/>. These datasets included all-cause mortality records (last accessed: 2023.06.28) and population statistics (last accessed: 2024.05.29) by sex, five-year age group, and region of residence at NUTS3 regions for 34 European countries: Austria, Belgium, Bulgaria, Switzerland, Germany, Estonia, Spain, Finland, Croatia, Hungary, Iceland, Liechtenstein, Luxembourg, Latvia, Norway, Poland, Portugal, Serbia, Sweden, Slovenia, Slovakia, Czech Republic, Montenegro, Denmark, Lithuania, Italy, Malta, France, Albania, Cyprus, Greece, Netherlands, Romania, United Kingdom. However, some regions and countries had missing data:

- **Unavailable or incomplete data:** Data for Norway was marked as unavailable for the period 2014-2019 in our last accessed version (2024.05.29). However, in the updated version on June 11, 2024, data for this region were available. Meanwhile, some regions still stated a “b” (break in time series) in their observation flags after 2019, including Italy, Poland, and the Czech Republic, while still no updated data were available for some regions such as the United Kingdom and Norway after 2019.
- **Recent updates:** To provide a more comprehensive assessment, we rechecked and included the latest data updates in this revision (accessed on 2025.01.19) and filled the missing data after 2019 using the latest population data for these regions.

The details were added in our revised manuscript as “*Meanwhile, we notice*

that some regions show a “b” (break in time series) in their observation flags or have no updated data after 2019, including Italy, Poland, the Czech Republic, Norway and the United Kingdom. We fill these missing data after 2019 using their available latest number of population.”

(2) Missing projection data

The data used to estimate heat-related deaths in 2024-2100 were based on:

- **Gridded population projections** (GPWv4): This dataset, covering global population projections under different Shared Socioeconomic Pathways (SSPs), had no missing data.
- **Population structure projections:** These data, derived from the latest Eurostat population projections by EUROPOP2019, had missing values in **Albania, Montenegro, Serbia, and the United Kingdom.**

For the United Kingdom, where statistic data are relatively comprehensive, we supplemented the missing population structure data using projections from the Office for National Statistics, as stated in the methodology: *“To fill in the missing data for the United Kingdom, we employed national population projections provided by the Office for National Statistics. This dataset provides population sizes for the United Kingdom and its constituent countries for the next 100 years. We tallied the projected age structure at the NUTS1 level and assumed that the population age structure at the NUTS3 level was consistent with its corresponding NUTS1-level statistical unit.”*

However, upon further review and data updates, we still discovered additional gaps caused by **missing baseline mortality data from 2022** for some regions, such as Albania (data available up to 2021), Norway (2021), Estonia (2019), Hungary (2019), Italy (2020), and the United Kingdom (2020). To address these gaps, we used the latest available historical mortality data as the baseline in future heat-related mortality projection. This revision has been added to the ‘methods’ in the revised manuscript as follows: *“We calculated the changes in future mortality per capita ($\Delta\mu_{y,c}$) relative to the baseline of 2022 ($\mu_{2022,c}$) in each region, as in Eq. 8; if data from 2022 were missing, we used the available latest historical mortality data as the baseline.”*

To provide a more comprehensive assessment, we filled the missing historical data, supplemented the projection data, and updated our model accordingly. Thus, the projections for 30 countries were updated using the most complete dataset currently available.

We sincerely apologize for any issues caused by delayed data updates and have now ensured that our results incorporate the latest available data. These updates have been clarified in the revised manuscript.

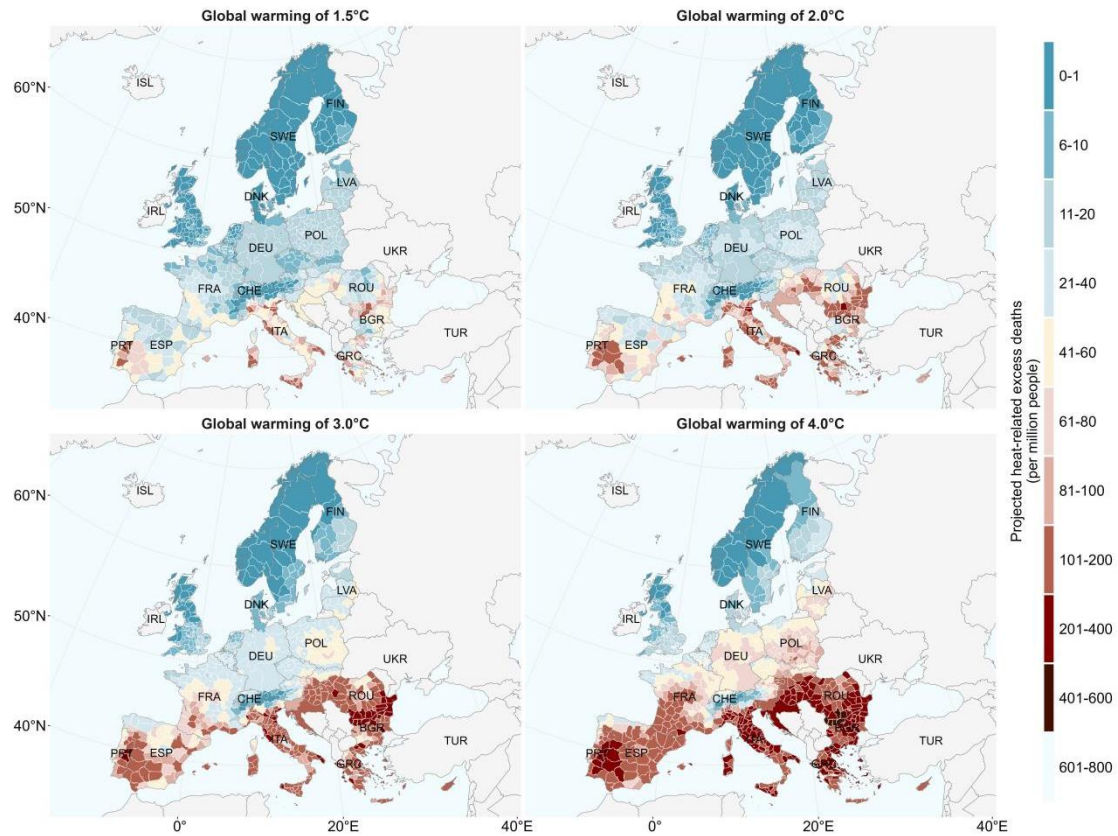
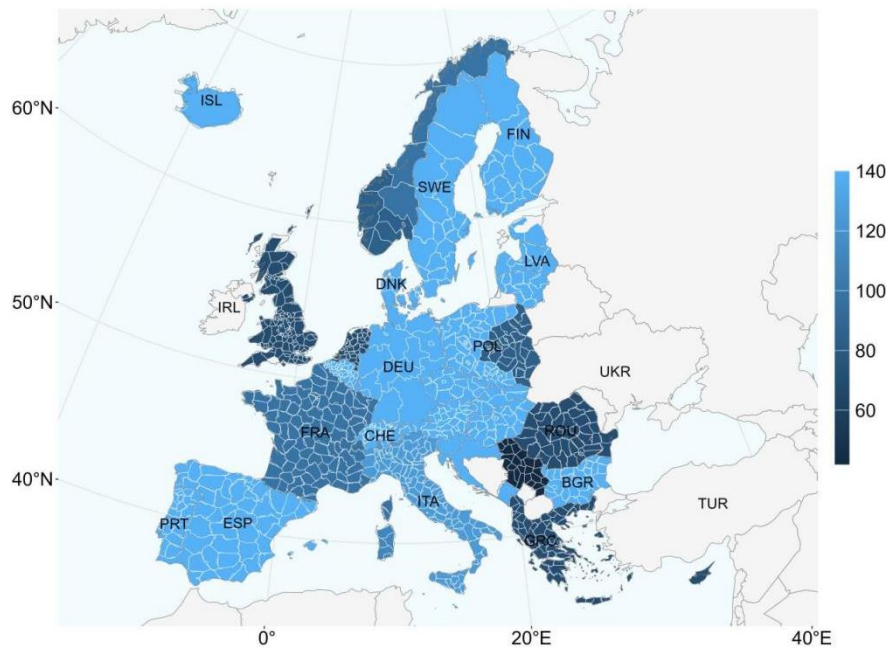


Fig. 3. Geographic distributions of expected annual average heat-related excess deaths per million people under 1.5°C, 2.0°C, 3.0°C, and 4.0°C levels of global warming. The results are based on the population–climate scenario SSP5 – 8.5. Additional projections for alternative scenarios (SSP1 – 2.6, SSP2 – 4.5, SSP3 – 7.0) are available in Supplementary Figs. 10–12. The regions with missing data are shaded in grey.



Supplementary Fig 18. Sample sizes of each region used for model training. Regions with missing data are shaded in grey.

Question: - fig 4: it is not clear how the decomposition approach works...can you elaborate more on this, in the text?

Response: We apologize for any confusion regarding the decomposition approach. While we did provide an initial explanation of this method in the Results section, we recognize that additional clarification is necessary. In response to your comment, we have expanded on the description of the decomposition method to enhance its readability and understanding, as “*The individual contributions of climate change, population size change and population ageing to the future burden of heat-related excess mortality in Europe were analysed using a decomposition method¹². The decomposition method isolates the effect of individual factors by adjusting whether each factor changes or remains constant. In this study, the weekly mean Humidex, the three types of heat extremes and their durations served as indicators of the effects of climate change. Population ageing refers to changes in age composition or population structure. We first projected the burden of heat-related excess mortality by considering changes in all three factors. Subsequently, projections were made in a similar manner, with the exception of maintaining one of the factor constants at its corresponding level in 2022. The differences between these two projections primarily represented the respective impacts of the factors (climate change, population size change and population ageing) on the projected total heat-related excess mortality.*”

12. Chen, M. *et al.* Rising vulnerability of compound risk inequality to ageing and extreme heatwave exposure in global cities. *npj Urban Sustainability* **3**, 38 (2023).

Reviewer #5 (Remarks to the Author):

This is a study in which the authors aim to analyse the "Future heat-related mortality in Europe driven by compound day-night heatwaves and demographic shifts". In my opinion, this study has two major methodological shortcomings that detract from the scientific validity of the results obtained.

Question: Firstly, the authors define a heat wave on the basis of the 95th percentile of the average temperature series for the summer months.

Defining a heat wave with a similar percentile for all European countries means admitting that socio-economic, demographic and adaptation factors do not influence mortality attributable to temperature, which goes against scientific evidence and the WHO itself, which states in chapter 3 of this document on prevention plans in Europe that the health effects of heat waves cannot be based on fixed percentiles but on previous epidemiological studies of temperature-mortality that determine the temperatures above which mortality increases : "Threshold levels in heat waves should be based on health risks and not only on meteorological conditions"

<https://iris.who.int/bitstream/handle/10665/339462/9789289055406-eng.pdf>.

A good example of this is the Spanish Plan de Prevención de Prevención ante altas temperaturas in which up to 182 different regions with different temperatures and percentiles are determined in a single country.

https://www.sanidad.gob.es/areas/sanidadAmbiental/riesgosAmbientales/temperaturasExtremas/planAltasTemperaturas/2024/docs/Plan__Excesos_Temperaturas_2024.pdf

Response: Thank you for raising this important issue. We appreciate the opportunity to address your concerns regarding the definition of heatwaves in our study and its implications for the scientific validity of our results. We fully agree that the health impacts of heat waves should account for socio-economic, demographic, and adaptation factors as well as epidemiological evidence, rather than relying solely on fixed meteorological thresholds.

As you noted, the WHO's guidelines on heat wave prevention emphasize that "threshold levels in **heat waves** should be based on health risks and not only on meteorological conditions," which is a critical point in considering the broader context of temperature-mortality relationships. Similarly, region-specific prevention plans, such as the *Spanish Plan de Prevención ante altas temperaturas*, underscore the importance of tailoring thresholds to local

conditions, incorporating epidemiological evidence and regional variability.

(1) Clarification of heatwave definition in our study

We have carefully reviewed the reference provided. We acknowledge that defining heatwaves using a 95th percentile of summer temperature across all European regions does not fully account for regional diversity in population vulnerabilities or adaptive capacities. However, we would like to clarify that the threshold values identified in our model are not intended to serve as a definitive definition of heat waves. Instead, they are used as an objective meteorological tool to identify extreme heat condition relative to historical average status.

Our primary goal is to examine the health impacts of such extreme condition rather than to establish precise heatwave threshold that directly corresponds to human health risk. To address the limitation of using air temperature alone, we opted to define “extreme” heat condition using the Humidex index, which integrates ambient temperature and humidity. This approach is better suited to capture regional variations in the perceived intensity of heat, which significantly affects health outcomes. This approach represents a step towards accounting for regional variations in the perceived intensity of heat and its effects on health.

(2) Revisions in the manuscript

We recognize that this approach does not incorporate other regional factors, such as socio-economic factors, demographics, and specific population vulnerabilities, although some of the factors have been included in our study to examine the heat-related health impact. We value your suggestion to consider more region-specific thresholds, as seen in the Spanish heatwave prevention plan, to better align our analysis with established epidemiological evidence and localized adaptation strategies. **In response to this valuable feedback, we have added the following clarification to the revised manuscript:**

“It is important to emphasise that the thresholds used in this study were not definitive health-based heatwave definitions but were instead intended to identify extreme weather conditions relative to historical status. These thresholds served as a tool to explore the relationship between extreme heat and health impacts, but we acknowledge the need for localised and health risk-based definitions of heatwaves.”

(3) Plans for future work

Although developing region-specific heatwave threshold is not the focus of the current study, we propose to address the methodological limitation you

highlighted in future work. Specifically, we plan to:

- Develop region-specific thresholds for extreme heat based on local temperature-mortality relationships, incorporating socio-economic and demographic factors.
- Explore the integration of additional meteorological and non-meteorological factors, such as wind speed, sunlight exposure, and urban heat island effects, to refine our understanding of heat-related health risks.
- Apply region-specific prevention strategies, like those implemented in Spain, as a model for tailoring adaptive responses to heatwaves across diverse European regions.

We sincerely apologize for any misunderstandings caused by the unclear phrasing in the original manuscript and thank you for pointing out the need for additional nuance in the interpretation of our findings. We hope that these clarifications strengthen the scientific basis of our study while aligning with the suggestions made by the reviewer.

Question: The second major methodological deficiency is that the authors maintain the RR calculated for the period 2010-2019 constant over time and only allow changes in the population for the calculation of attributable mortality. This goes against the scientific evidence that shows that in Europe and around the world there is a decrease in the risks attributable to high temperatures as a consequence of adaptation processes.

I recommend that the authors read these articles together with others that calculate the impact of heat waves on the 2050-2100 horizon taking into account adaptation processes and how to consider them in impact projections.

Response: We appreciate the reviewer's insightful comments on the role of adaptation processes in future heat-related mortality projection. We acknowledge that neglecting potential changes in relative risk (RR) due to adaptation processes is a methodological limitation, and appreciate the opportunity to further clarify and expand the complex impact of adaptation on heat-mortality relationship.

1. Adaptation and its consideration in projections

As the reviewer notes, scientific evidence suggests that the risks attributable to extreme heat may decrease over time as populations adapt. This is a complex and evolving topic, which has gained considerable attention in recent years. Previous studies suggested that adaptation manifests in several ways, such as:

- Increased minimum mortality temperature (MMT): Populations tend to adapt to higher temperatures, resulting in a shift in the MMT over time.
- Flattened RR curves: The slope of the RR curve tends to decrease, resulting in reduced mortality sensitivity to extreme temperatures.

Several recent studies ^{13,14} have further considered the impact of these adaptation processes by adjusting the RR curves to account for the changes in heat-related mortality risks under future climate scenarios. However, adaptation processes are highly complex, region-specific, and nonlinear, as these and other studies¹⁵ have highlighted. These characteristics make it challenging to apply a uniform adaptation model across regions or populations.

2. Supplementary analysis and key findings

To explore this issue, we conducted a supplementary analysis of historical data (2000–2019) for 19 countries and 362 regions to assess the trends in heat adaptation. Our analysis included:

- **Five-year intervals:** We split the data into five-year intervals to observe changes in the MMT and the slope of the RR curve over time.
- **Ten-year moving windows:** We used a 10-year moving window approach to track cumulative RR curves and MMT variations for different age groups.

Our findings (Supplementary Figs. 19) indicated a general trend of adaptation, with increasing MMTs and flattening RR curves across different age groups. However, we also observed notable variability, including the anomalous result for the 2010-2014 period, where both the MMH and RR slope exhibited patterns contrary to expected adaptation. To further assess whether this anomaly was due to data irregularities, we used the moving window approach with a 10-year interval to train the model with data from the periods of 2000-2009, 2001-2010, ..., and 2010-2019 (Supplementary Figs. 20). Results show that the variation in MMH (Supplementary Figs. 21) and the RR slopes (Supplementary Figs. 22) is not a simple linear process, and thus, cannot be easily extrapolated to the future. This highlights the inherent complexity of adaptation processes. They are affected by numerous factors beyond just the physiological responses to temperature and humidity, such as socioeconomic conditions, healthcare access, government policy, and infrastructure development ¹⁶, which cannot be assumed to evolve at a constant rate.

To quantify the potential impact of adaptation processes on future projection, we recalculated the annual heat-related deaths per million people at different level of global warming using the heat-mortality curves estimated from 10-year moving windows (Supplementary Table 6). Interestingly, we found a significant improvement in heat adaptation after 2003, after which the changes stabilized

with minor fluctuations. This underscores the dynamic and context-specific nature of adaptation processes.

3. Challenges in assuming future adaptation and uncertainty

While our findings confirm historical trends in adaptation, predicting future adaptation remains highly uncertain due to the following factors:

- Nonlinear and region-specific trends: Adaptation rates vary significantly across regions and populations, as shown in our analysis and other studies ^{17–19}.
- Uncertainty in future adaptation capacity: The ability to adapt may be restricted by socio-economic disparities, resource limitations, and physical constraints (e.g. limits to human thermoregulation).
- Incomplete models: Current models often rely on simplified assumptions about adaptation rates (e.g., fixed percentage changes in RR), which may not fully capture the complexity of dynamic adaptation processes. This may lead to an overly optimistic view of population-level heat adaptation and potentially underestimate the health impacts of future heatwaves, particularly under high-emission scenarios.

4. Revisions to address adaptation in our manuscript

In our study, we opted to use the most recent RR curve (2010–2019) as a baseline to project heat-related mortality, assuming that mortality risks are based on the current level of adaptation. This approach underscores the need for further improvements in heat adaptation strategies while acknowledging its limitations in capturing potential future adaptation.

Supplementary Table 6 shows the sensitivity of our mortality projections to the change of RR curve. We observed a reduction in estimated deaths by up to 23.7% when using current RR curves (2010–2009) compared to the earlier 2000–2019 curve. These results highlight two key points: 1) The potential for overestimating future heat-related deaths if adaptation is not accounted for. 2) The significant impact and benefits of having effective adaptation strategies in place, whether based on the benchmark 2010–2019 level or further improvements. Recognizing the importance of addressing adaptation more comprehensively, we have made the following revisions in the manuscript:

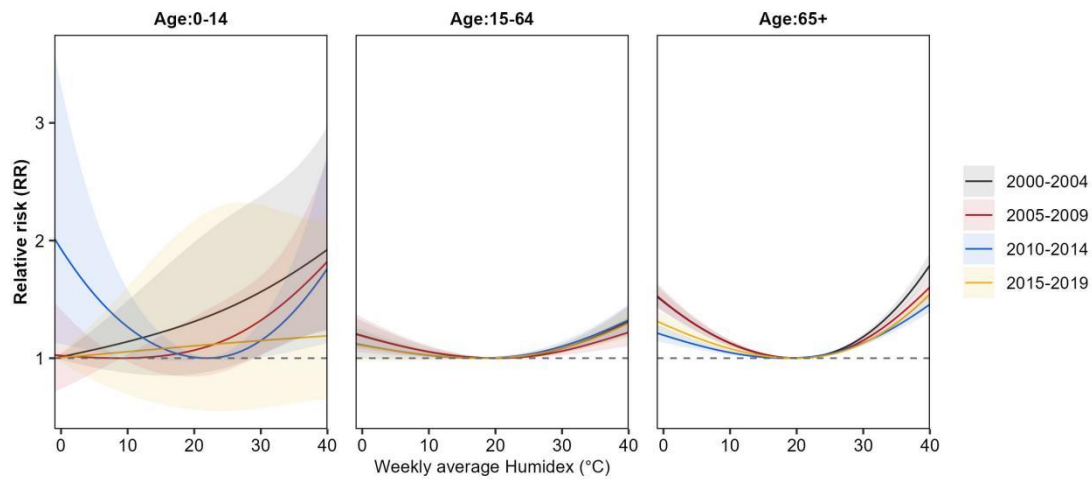
- Expanded discussion: We have emphasized the limitations of assuming a constant RR and highlighted the complexities of heat adaptation processes, including its nonlinearity and region-specific nature.
- Acknowledgment of uncertainty: We have clarified that our estimates

represent a "*2010-2019 adaptation with further improvements*" baseline scenario. This highlights the importance of enhancing adaptation strategies in the future, while also acknowledging that our results may overestimate future heat-related mortality burdens in Europe if heat adaptation continues to improve.

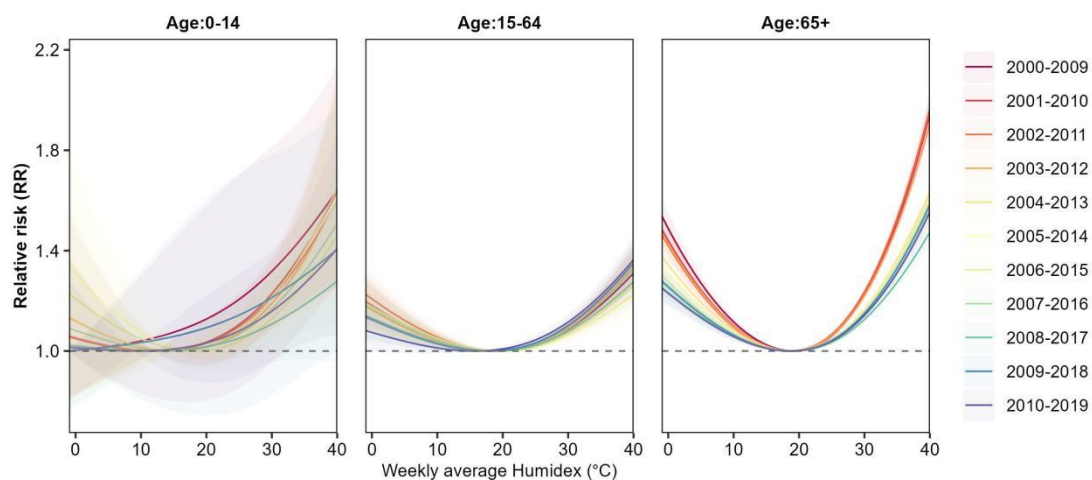
- Inclusion of historical analysis: We have incorporated findings from our supplementary analyses (Figs. 19–22, Table 6) to demonstrate historical adaptation trends and discuss their implications for future projections.

By incorporating these revisions, we provide a more detailed and scientifically robust discussion of heat adaptation and its role in shaping future heat-related mortality. We added the following text to the revised discussion:

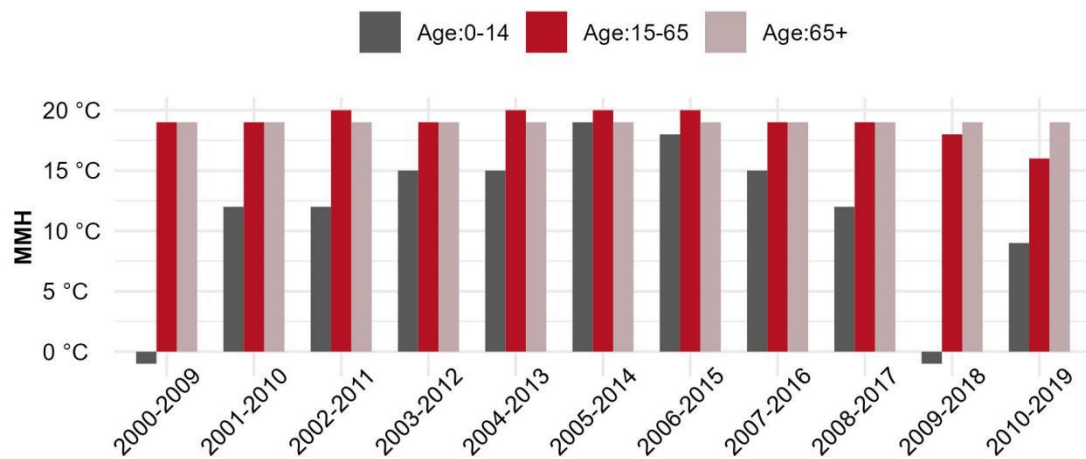
“Similar to numerous previous studies^{20–23}, we assumed that both the shape of the heat–mortality curve and the human capacity to cope with heat stress would remain constant at a fixed level between 2010 and 2019. Recent studies have suggested that the human capacity to adapt to rising temperatures varies with time^{48–50}, which is reflected in increased minimum mortality temperatures and flattened relative risk (RR) curves. We find that the latest RR curve (2010–2019) predicted a reduction in estimated heat-related deaths by 23.7% compared to the early one (2000–2009) (Supplementary Table 6). If the heat-stress adaptation capacity continues to increase in the future, our estimates may have overestimated the future heat-related mortality burden in Europe. However, further investigation revealed the fluctuating rate at which the RR curve flattened, highlighting the complexity of human adaptation processes (see Supplementary Note 5). Recent studies have attempted to simulate future adaptation processes by adjusting the percentage change in excess RR over time, based on specific assumptions^{13,14}. Such assumptions were typically defined based on future changes in socioeconomic factors, such as GDP. However, an individual’s ability to adapt may be greatly impacted by various factors, including social support, health services and education^{24–26}. The assumptions on future adaptation to heat remain incomplete, and more importantly, the upper limit of heat adaptation remains unknown. Future work should prioritise integrating dynamic, region-specific adaptation models into heat-related mortality projections while considering the limits of human adaptation under extreme warming scenarios.”



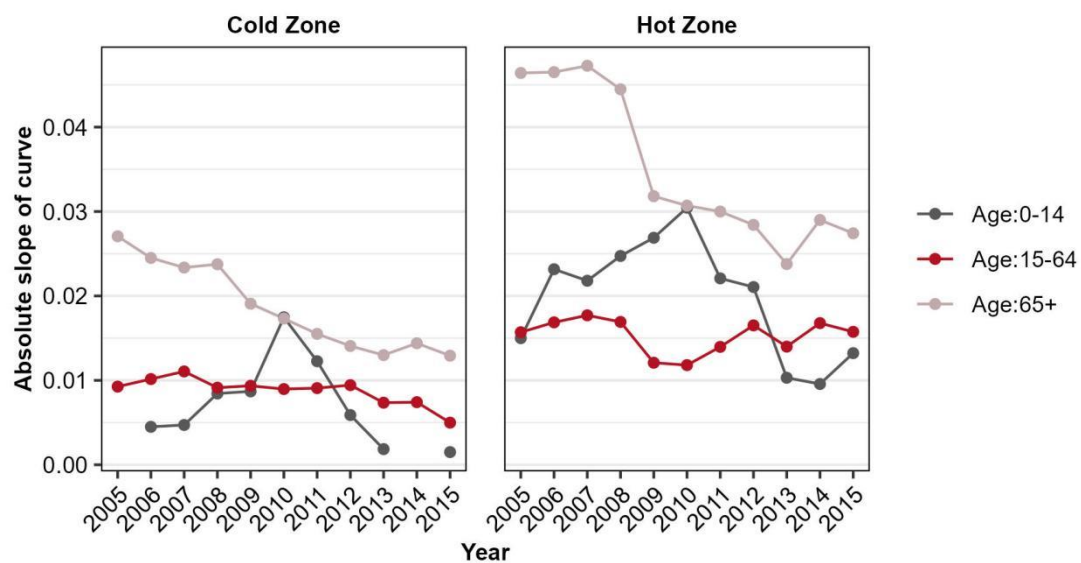
Supplementary Fig 19. Cumulative relative risk-weekly Humidex response curves for three age groups, presented for every 5 years: children (aged 0–14 years), the working-age population (aged 15–64 years), and the elderly (aged 65 years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group.



Supplementary Fig 20. Cumulative relative risk-weekly Humidex response curves for three age groups, presented for a 10-year sliding window: children (aged 0–14 years), the working-age population (aged 15–64 years), and the elderly (aged 65 years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group.



Supplementary Fig 21. Variation in minimum mortality Humidex (MMH) across three age groups. The data are analyzed using a sliding 10-year window.



Supplementary Fig 22. Variation of the absolute slope of the cumulative relative risk-weekly Humidex response curves for three age groups. The input data slides in a 10-year window. The data are analyzed using a sliding 10-year window, where the horizontal axis represents the midpoint of each 10-year window. The 'cool zone' reflects the slope changes to the left of the minimum mortality Humidex (MMH), while the 'heat zone' reflects the slope changes to the right of the MMH.

Supplementary Table 6. Annual average heat-related excess deaths per million people under 1.5°, 2.0°, 3.0°, and 4.0° level of global warming based on heat-mortality relative risk curve estimated from 10-year window sliding. The projected heat-related excess deaths per million people are reported as the mean value across all population-climate scenarios that result in the corresponding warming level. Please note that the estimates focus on 19 countries with 362 regions, where data are available from 2000 to 2019.

War ming level	Region	Annual average heat-related excess deaths from 2024 to 2100 per million people (19 countries)										
		Model: 2000-200	Model: 2001-201	Model: 2002-201	Model: 2003-201	Model: 2004-201	Model: 2005-201	Model: 2006-201	Model: 2007-201	Model: 2008-201	Model: 2009-201	Model: 2010-201
		9	0	1	2	3	4	5	6	7	8	9
1.5°C	Eastern Europe	67.1 (40.5-86.0)	69.3 (42.0-88.7)	69.9 (42.4-89.5)	67.9 (41.3-86.9)	37.4 (19.3-49.9)	37.9 (20.2-50.3)	49.6 (30.3-63.4)	51.2 (31.4-65.5)	43.0 (26.4-55.0)	52.7 (32.5-67.4)	52.7 (33.0-67.1)
	Northern Europe	20.0 (14.3-23.9)	19.9 (14.0-23.9)	19.9 (13.9-24.0)	19.1 (13.4-23.0)	8.7 (5.2-11.0)	9.0 (5.4-11.3)	14.0 (9.9-16.9)	14.0 (9.8-16.8)	12.0 (8.5-14.4)	13.9 (9.6-16.8)	13.3 (9.0-16.3)
	Southern Europe	94.2 (66.2-116.9)	97.2 (68.6-120.4)	99.4 (70.3-123.0)	95.0 (67.2-117.7)	58.7 (39.0-74.5)	59.4 (40.1-75.1)	69.7 (49.7-86.2)	69.9 (49.9-86.4)	59.0 (42.1-73.0)	72.0 (51.4-89.0)	70.3 (50.5-86.7)
	Western Europe	36.6 (22.8-46.7)	37.9 (23.6-48.3)	38.8 (24.2-49.5)	37.0 (23.1-47.2)	19.2 (9.8-25.8)	20.0 (10.6-26.7)	27.7 (17.3-35.5)	27.7 (17.4-35.4)	23.4 (14.6-29.8)	28.7 (18.0-36.6)	28.6 (18.1-36.4)
	Europe	56.2 (36.9-70.7)	57.9 (38.1-72.9)	59.0 (38.9-74.3)	56.5 (37.3-71.2)	32.2 (18.9-41.9)	32.9 (19.7-42.6)	41.7 (27.7-52.5)	42.1 (23.0-53.0)	35.5 (23.6-44.7)	43.4 (28.8-54.6)	c (28.7-53.8)
	Eastern Europe	101.7 (66.1-129.8)	104.9 (68.4-133.6)	106.1 (69.2-125.1)	102.3 (66.9-130.2)	60.6 (36.0-79.7)	61.0 (37.0-79.8)	74.5 (49.1-94.7)	75.9 (50.2-96.5)	63.7 (42.0-81.0)	77.8 (51.5-98.9)	76.8 (51.4-97.3)
2.0°C	Northern Europe	23.9 (16.8-28.7)	24.1 (16.7-29.1)	24.2 (16.8-29.3)	23.2 (16.1-28.0)	11.1 (6.7-13.9)	11.5 (7.00-14.4)	17.0 (11.8-20.6)	17.0 (11.8-20.5)	14.4 (10.1-17.4)	17.0 (11.7-20.7)	16.4 (11.2-20.1)

3.0°C	Southern Europe	135.1 (100.5-163.3)	139.0 (103.8-167.8)	142.1 (106.3-171.5)	135.6 (101.4-163.7)	86.9 (62.8-106.8)	87.3 (63.7-106.8)	99.0 (74.7-119.1)	98.5 (74.4-118.6)	83.2 (62.8-100.2)	101.4 (76.5-122.0)	98.4 (74.5-118.2)
	Western Europe	49.2 (31.6-62.5)	50.8 (32.8-64.5)	52.0 (33.6-66.0)	49.6 (23.0-62.9)	27.8 (15.4-36.7)	28.6 (16.3-37.6)	37.0 (24.0-46.9)	37.0 (24.1-47.0)	31.2 (20.2-39.6)	38.3 (24.9-48.6)	38.0 (25.0-48.0)
	Europe	79.7 (55.2-99.0)	82.1 (57.0-101.9)	83.7 (58.2-103.8)	80.1 (55.7-99.3)	48.2 (31.2-61.5)	48.9 (32.1-61.9)	58.8 (41.2-72.8)	59.0 (41.4-73.0)	49.7 (34.8-61.5)	60.7 (42.5-75.1)	59.5 (41.9-73.5)
	Eastern Europe	178.0 (125.2-220.3)	182.9 (129.0-226.0)	184.9 (130.6-228.6)	177.7 (125.8-219.5)	112.4 (76.4-141.4)	111.7 (76.8-140.0)	128.1 (91.7-157.7)	129.9 (93.2-159.8)	108.9 (78.2-134.0)	133.1 (95.4-163.8)	130.2 (93.9-159.8)
	Northern Europe	36.3 (25.1-44.2)	37.0 (25.5-45.2)	37.5 (25.8-45.9)	35.7 (24.6-43.7)	18.8 (11.5-23.9)	19.5 (12.1-24.6)	26.2 (18.1-32.0)	26.1 (18.1-32.0)	22.0 (15.2-26.8)	26.4 (18.2-32.3)	25.7 (17.8-31.5)
	Southern Europe	203.4 (159.1-237.6)	208.5 (163.5-243.3)	212.8 (167.1-248.2)	203.0 (159.5-236.9)	133.7 (103.8-157.3)	133.0 (103.8-156.0)	146.1 (116.1-169.8)	145.3 (115.5-168.8)	122.7 (97.6-142.6)	150.0 (118.9-174.4)	145.1 (115.2-168.6)
	Western Europe	81.7 (57.1-99.8)	84.2 (59.1-102.7)	86.0 (60.5-104.8)	82.0 (57.5-100.0)	50.2 (32.8-62.9)	50.9 (33.8-63.4)	60.7 (43.1-73.9)	60.6 (43.1-73.8)	51.1 (36.2-62.3)	62.7 (44.5-76.3)	61.7 (44.1-74.9)
	Europe	127.1 (93.6-152.8)	130.5 (96.4-156.8)	83.7 (58.2-103.8)	127.0 (94.0-152.5)	80.6 (57.6-98.4)	80.7 (58.2-98.1)	92.3 (69.0-110.4)	92.3 (69.1-110.5)	77.8 (58.2-93.1)	95.1 (71.0-113.9)	92.8 (69.5-110.9)
	Eastern Europe	304.5 (230.5-366.5)	311.7 (236.4-375.0)	315.2 (239.1-379.0)	302.1 (229.6-363.1)	196.7 (148.6-238.6)	193.4 (147.0-234.1)	213.9 (165.0-256.3)	216.3 (167.1-259.1)	131.0 (140.1-216.7)	222.6 (171.3-266.6)	216.8 (167.0-259.1)
	Northern Europe	52.6 (37.2-64.3)	53.9 (38.2-65.9)	54.8 (38.8-67.0)	52.0 (36.0-63.5)	29.6 (19.3-37.2)	30.4 (20.1-38.0)	38.1 (27.1-46.4)	37.9 (27.0-46.2)	31.7 (22.6-38.7)	38.4 (27.3-46.8)	37.2 (26.7-45.4)
	Southern Europe	314.8 (258.8-364.2)	321.7 (264.9-371.9)	327.8 (270.1-378.7)	312.4 (257.6-360.8)	206.9 (171.0-239.5)	204.0 (169.2-235.7)	219.9 (183.6-252.8)	218.2 (182.3-250.8)	184.0 (154.0-211.4)	226.8 (188.9-261.0)	219.4 (182.6-252.4)

Western	150.3	154.1	157.1	149.7	97.5	97.4	109.1	108.6	91.7	112.6	109.9
Europe	(108.0-181.7)	(111.0-186.1)	(113.4-189.6)	(108.1-180.8)	(68.5-119.7)	(69.0-119.2)	(79.7-131.6)	(79.5-131.0)	(67.1-110.6)	(82.2-135.8)	(80.5-132.3)
Europe	20.7.5	212.4	216.1	206.2	134.7	133.5	147.2	146.9	123.6	152.1	147.8
	(159.7-246.3)	(163.7-251.9)	(166.7-256.1)	(159.2-244.3)	(103.0-161.1)	(102.6-159.3)	(115.0-174.0)	(114.9-173.6)	(96.8-146.1)	(118.6-179.8)	(115.4-174.5)

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Reviewer #5 (Remarks to the Author):

I thank the authors for their responses to my comments on the original manuscript.

However, the two substantive issues raised (the first regarding the choice of a fixed percentile and the second regarding the assumption of constant RRs over time) have not been resolved.

These are not mere limitations of the study as the authors would have us believe by including some paragraphs in the revised version of the manuscript.

‘It is important to emphasise that the thresholds used in this study were not definitive health-based heatwave definitions but were instead intended to identify extreme weather conditions relative to historical status. These thresholds served as a tool to explore the relationship between extreme heat and health impacts, but we acknowledge the need for localised and health risk-based definitions of heatwaves.

Reply: We are sincerely grateful for your continued engagement with our manuscript and for your thoughtful comments. We appreciate this opportunity to further address the two important methodological issues that our prior revision did not fully resolve. In direct response to your concerns referenced from Montero et al (2010), Carleton et al (2022) and Rai et al (2022), we have made the following substantive changes in the manuscript:

1. Adoption of a health risk-based heatwave definition

We have replaced the original percentile-based heatwave definition with a health risk-based approach, drawing on established methodologies (e.g., Montero et al (2010)). This revised definition enhances the statistical significance of extreme heat identification from a physiological perspective, thereby augmenting the reliability of our estimates.

2. Integration of time-dependent exposure-response functions for adaptation strategies

To address the assumption of constant RRs, we have developed a scenario matrix that explicitly accounts for potential adaptation trajectories through time-dependent exposure-response functions. This framework, guided by recent literature (e.g., Carleton et al (2022) and Rai et al (2022)), reflects potential trajectories of adaptation and contributes to a more intuitive understanding of the effects of adaptation strategies in extreme heat responses. This approach allows us to model changes in population sensitivity to extreme heat over time, providing a scientific reference for the implementation of integrated European heat adaptation policies.

These methodological refinements are detailed in revised Sections ‘Method’ and ‘Implications for integrated

European heat adaptation policy’, and are also visually supported by Fig. 5 and Supplementary Figs. 4 and 23-27. While the central findings of the study remain broadly consistent with our earlier results, these updates have significantly enhanced the scientific rigor, interpretability, and policy relevance of our study.

We acknowledge that these revisions do not fully resolve all complexities inherent in modelling climate adaptation processes. Nevertheless, we believe they represent a meaningful step toward addressing these long-standing methodological challenges in climate-health research, as emphasised in seminal works by Xu et al. (2016), Vicedo-Cabrera et al. (2021) and others. We hope that these revisions adequately address your concerns and clarify the intent and limitations of our methodological framework. We warmly welcome your suggestions to strengthen our approach further and are prepared to conduct supplementary analyses as needed.

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- Carleton, T., Jina, A., Delgado, M. et al. Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits. *Q. J. Econ.* **137**, 2037–2105 (2022).
- Rai, M., Breitner, S., Wolf, K., Peters, A., Schneider, A., Chen, K. Future temperature-related mortality considering physiological and socioeconomic adaptation: a modelling framework. *Lancet Planet. Health.* **6**, e784-e792 (2022).
- Vicedo-Cabrera, A.M., Scovronick, N., Sera, F. et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Chang.* **11**, 492–500 (2021).
- Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., Tong, S. Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environ. Int.* **89-90**, 193–203 (2016).

The detailed revisions are also presented below:

1. Replacement of percentile-based heatwave definition with a health risk-based approach

To directly address the reviewer’s concern regarding the fixed percentile approach, we have implemented a localized, health risk-based method for defining heat thresholds. This method builds upon the framework proposed by *Montero et al.* (2010) and is designed to capture region-specific physiological vulnerability to heat by leveraging historical mortality data.

The process started with the Autoregressive Integrated Moving Average (ARIMA) modelling using Box-Jenkins stochastic procedures to extract three low-frequency components from the mortality time series: seasonal variations, periodic fluctuations, and long-term trends. This decomposition, implemented through the 'tseries' package in R4.1.1. The resulting detrended mortality residuals are interpreted as proxies for heat-related excess mortality signals, accounting for potential confounding temporal patterns.

Following this temporal decomposition, we established a correlation framework between mortality residuals and binned Humidex values (grouped in 2°C increments) across all the 112 NUTS-1 regions. As shown in Supplementary Fig. 3 (using Albania as an example), the mortality impact of each Humidex bin was quantified through the distributions of the mortality residuals. We first conducted one-sample Student's t-tests for each region, comparing each Humidex bin's mean residual mortality against the population-mean baseline. Daytime and nighttime thresholds were derived based on weekly maximum and minimum Humidex, respectively. We initially set the significance level threshold α to 0.05 for all the NUTS-1 regions. For 18 regions where this threshold yielded no statistically significant differences, we relaxed α to 0.10 to accommodate the reduced statistical power in areas due to data sparsity. In 37 regions where the residual mortality showed non-monotonic Humidex relationships, the 98th percentile of Humidex distribution was adopted as an objective heat threshold. This adjustment was necessary to address limitations in aggregating weekly mortality data, which may obscure acute, short-term mortality spikes.

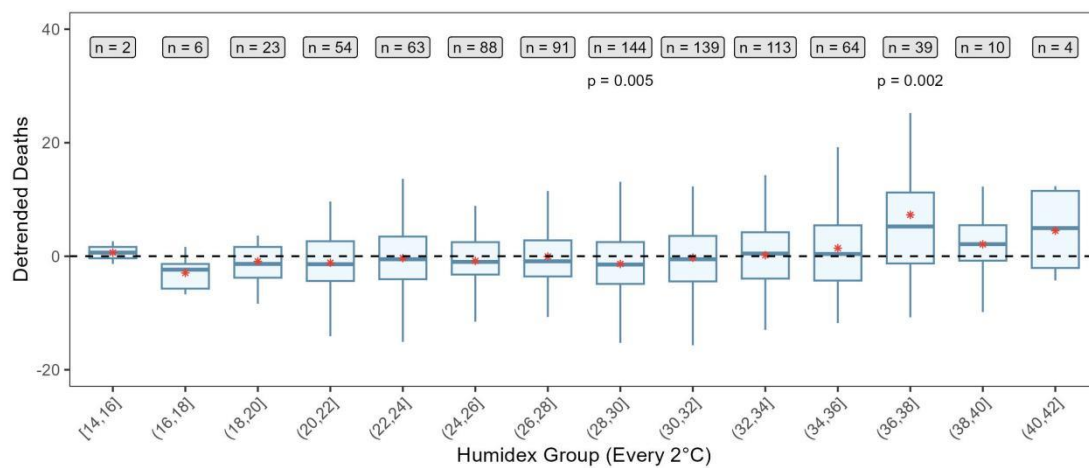
This approach captures population-specific heat sensitivity through residual analysis and methodological robustness through predefined significance level criteria. Supplementary Note 1 details the algorithm of health risk-based heatwave definition, including the logic for significance level threshold adjustment. Additionally, we show the heat thresholds for each NUTS-1 region in Supplementary Fig. 4 and present the results of the significance tests in Supplementary Table 1.

We have integrated the details of this method into our manuscript in the revised Methods section as follows:

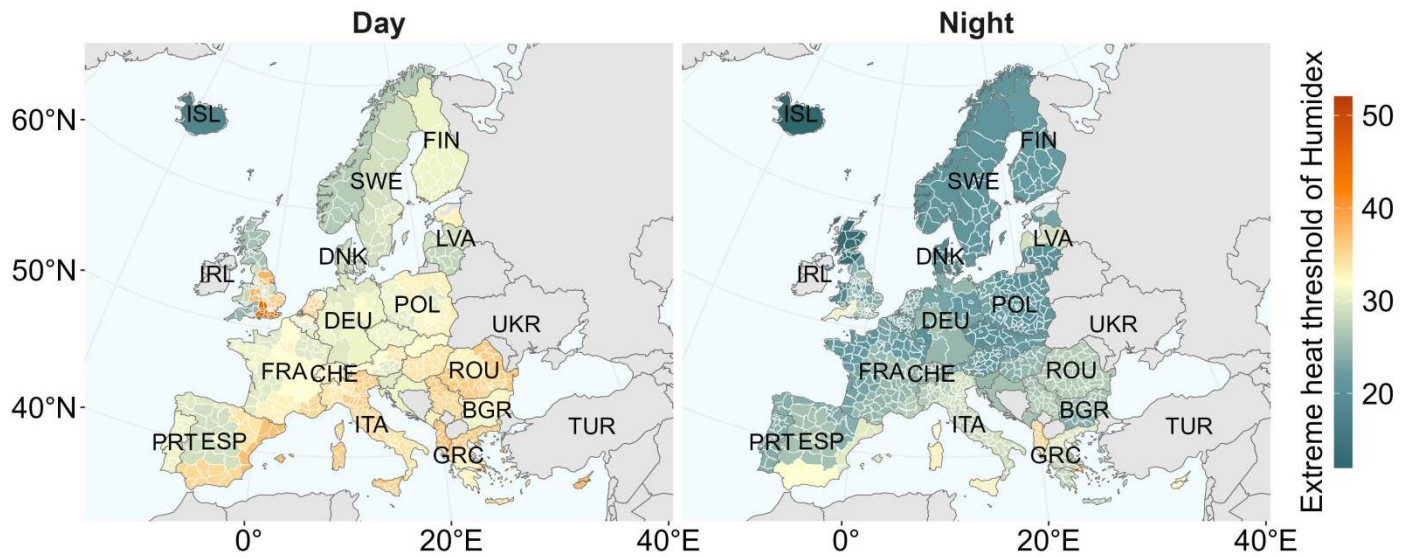
“Based on the method proposed by Montero et al. (2010), we determined localised health risk-based heat thresholds based on the relationship between Humidex and mortality. First, we removed the seasonality, periodicities, and long-term trends of the mortality time series using the Box-Jenkins stochastic procedures (ARIMA). We then established a correlation framework between mortality residuals and binned Humidex values (grouped in 2°C increments) across all the NUTS-1 regions. We identified the daytime/nighttime heat threshold as the mid-point of the Humidex interval within which the residual mortality values show a statistically significant increase compared to the population-mean baseline. We calculated the population-

mean baseline as the mean value of the 10-year residual weekly mortality data from 2010 to 2019. We employed the one-sample Student's *t*-test to assess the statistical significance and set the significance level threshold to 0.05. For regions where no statistically significant differences at the 0.05 level were observed, we relaxed the threshold to 0.1 to accommodate the reduced statistical power due to data sparsity. If statistical significance was still not achieved, we defined the extreme daytime/nighttime heat threshold as the 98th percentile of its local maximum/minimum weekly mean Humidex values. All parameters of the detrend modelling were optimized using an automated function from the 'tseries' package in R4.1.1. The heat thresholds of each region can be found in Supplementary Note 1."

We trust this detailed revision adequately addresses your concerns regarding threshold selection and provides a more physiologically grounded basis for our subsequent analysis.



Supplementary Fig 3. Boxplot showing the distributions of detrended mortality residuals for each bin of weekly maximum Humidex in Albania. *n* indicates the sample size of each group. The *p*-value was estimated based on the one-sample Student's *t*-tests.



Supplementary Fig. 4. Spatial patterns of localized health risk-based heat thresholds for NUTS-1 regions.

Supplementary Table 1. The heat thresholds for NUTS-1 regions. The ‘Percentile’ indicates the percentile of the day/night-time heat threshold in weekly maximum/minimum Humidex series in each NUTS-1 region during the summers (weeks 22-35) from 2010 to 2019.

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Albania	AL0	Day	37	97	0.002
		Night	35	100	0.071
Austria	AT1	Day	34	95	<0.001
		Night	21	77	<0.001
	AT2	Day	30	92	0.002
		Night	21	90	0.007
	AT3	Day	32	97	0.097
		Night	23	98	0.003
Belgium	BE1	Day	32	91	0.046
		Night	22	94	0.012
	BE2	Day	33	95	<0.001
		Night	21	90	0.034
	BE3	Day	30	90	<0.001
		Night	22	97	<0.001
Bulgaria	BG3	Day	33	75	0.001
		Night	26	88	0.017

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Switzerland	BG4	Day	31	84	0.003
		Night	24	90	0.009
	CH0	Day	33	92	0.003
		Night	25	96	<0.001
Cyprus	CY0	Day	37	98	NA
		Night	32	98	NA
Czech Republic	CZ0	Day	31	86	<0.001
		Night	20	82	<0.001
Germany	DE1	Day	30	81	0.002
		Night	25	96	0.002
	DE2	Day	31	91	<0.001
		Night	25	98	NA
	DE3	Day	32	90	0.005
		Night	24	96	0.026
	DE4	Day	31	91	<0.001
		Night	22	87	0.019
	DE5	Day	32	86	0.082
		Night	26	97	0.028
	DE6	Day	32	98	NA
		Night	25	99	0.071
	DE7	Day	30	79	0.009
		Night	26	98	NA
	DE8	Day	30	90	0.006
		Night	25	99	0.003
	DE9	Day	30	89	0.007
		Night	23	96	0.013
	DEA	Day	31	89	0.005
		Night	25	98	NA
	DEB	Day	31	85	0.017
		Night	20	79	0.059
	DEC	Day	30	89	0.041

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Denmark	DED	Night	23	96	0.086
		Day	31	91	0.015
	DEE	Night	23	94	0.051
		Day	32	93	0.005
	DEF	Night	22	84	0.045
		Day	30	91	0.078
	DEG	Night	24	98	NA
		Day	30	93	0.028
	DK0	Night	24	98	0.001
		Day	29	99	<0.001
Estonia	EE0	Night	19	95	0.018
		Day	33	98	NA
Greece	EL3	Night	23	97	0.039
		Day	52	92	0.019
	EL4	Night	45	97	0.005
		Day	35	98	NA
	EL5	Night	28	88	0.009
		Day	36	95	<0.001
	EL6	Night	30	97	<0.001
		Day	33	75	0.044
	ES1	Night	28	87	0.018
		Day	30	94	0.003
Spain	ES2	Night	24	99	0.006
		Day	34	98	<0.001
	ES3	Night	24	91	0.019
		Day	32	87	0.032
	ES4	Night	29	98	NA
		Day	29	75	0.038
	ES5	Night	26	91	0.001
		Day	37	98	NA
		Night	30	93	0.009

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Finland	ES6	Day	35	92	0.012
		Night	32	99	0.012
	ES7	Day	31	98	NA
		Night	28	98	NA
	FI1	Day	31	97	0.004
		Night	22	96	0.009
	FI2	Day	29	98	NA
		Night	21	94	0.06
	FR1	Day	33	85	0.018
		Night	23	86	0.014
	FRB	Day	32	90	0.044
		Night	25	97	0.004
	FRC	Day	32	90	0.001
		Night	26	98	0
	FRD	Day	30	92	0.011
		Night	21	94	0.006
	FRE	Day	32	93	<0.001
		Night	23	96	0.006
	FRF	Day	30	73	0.025
		Night	22	83	0.001
France	FRG	Day	31	87	0.012
		Night	22	90	0.057
	FRH	Day	31	98	NA
		Night	22	99	0.026
	FRI	Day	30	73	0.048
		Night	23	86	0.016
	FRJ	Day	33	89	0.015
		Night	25	89	0.003
	FRK	Day	32	94	0.049
		Night	25	96	<0.001
	FRL	Day	35	97	0.017

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Croatia	FRM	Night	27	93	0.034
		Day	35	98	NA
		Night	32	99	0.083
		Day	39	98	NA
	FRY	Night	36	98	NA
		Day	31	93	0.001
	HR0	Night	26	93	0.001
		Day	34	82	0.011
	HU1	Night	24	81	<0.001
		Day	34	81	<0.001
Hungary	HU2	Night	24	79	0.003
		Day	34	77	0.002
	HU3	Night	25	81	0.034
		Day	23	98	NA
Ireland	IE0	Night	18	96	0.082
		Day	18	98	NA
Iceland	IS0	Night	12	98	NA
		Day	34	91	0.001
	ITC	Night	27	89	<0.001
		Day	34	84	0.006
Italy	ITF	Night	29	91	0.006
		Day	36	96	<0.001
	ITG	Night	33	100	0.005
		Day	36	92	<0.001
	ITH	Night	29	92	0.002
		Day	35	92	<0.001
	ITI	Night	28	87	0.043
		Day	27	98	NA
	LI0	Night	19	98	NA
		Day	28	71	0.008
Liechtenstein	LT0	Night	20	85	<0.001
Lithuania		Day	28	71	0.008

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
Luxembourg	LU0	Day	33	98	NA
		Night	23	98	NA
Latvia	LV0	Day	29	81	0.043
		Night	29	100	0.019
Montenegro	ME0	Day	33	97	0.029
		Night	26	91	0.015
Malta	MT0	Day	41	98	NA
		Night	37	98	NA
Netherlands	NL1	Day	31	94	0.026
		Night	23	98	NA
	NL2	Day	35	99	0.005
		Night	24	100	0.003
	NL3	Day	36	99	0.027
		Night	24	97	0.099
	NL4	Day	36	100	0.069
		Night	24	98	NA
	NO0	Day	27	99	0.082
		Night	21	99	0.017
Norway	PL2	Day	33	91	<0.001
		Night	20	80	<0.001
	PL4	Day	31	81	0.001
		Night	23	92	0.01
	PL5	Day	30	73	0.032
		Night	22	89	0.005
	PL6	Day	33	95	<0.001
		Night	20	86	0.007
	PL7	Day	32	85	0.001
		Night	20	79	0.023
Poland	PL8	Day	33	90	<0.001
		Night	21	81	0.001
	PL9	Day	30	69	0.041
		Night			

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value	
Portugal	PT1	Night	22	87	<0.001	
		Day	31	83	0.001	
		Night	24	86	0.001	
	PT2	Day	17	98	NA	
		Night	15	98	NA	
	PT3	Day	25	84	0.004	
		Night	24	99	0.058	
	RO1	Day	33	94	0.037	
		Night	27	98	<0.001	
RO2		Day	36	95	0.015	
		Night	27	94	<0.001	
Romania	RO3	Day	35	81	0.002	
		Night	27	87	0.001	
	RO4	Day	36	96	0.004	
		Night	27	92	<0.001	
	RS1	Day	36	90	<0.001	
		Night	26	82	0.005	
		RS2	Day	35	93	0.001
			Night	27	95	<0.001
	Serbia	SE1	Day	30	98	NA
Night			22	97	0.033	
SE2		Day	29	98	NA	
		Night	21	98	0.048	
SE3		Day	29	98	NA	
		Night	21	98	NA	
SI0		Day	30	87	0.03	
		Night	25	96	0.062	
Slovenia		SK0	Day	32	80	0.002
	Night		22	82	<0.001	
Slovakia	UKC	Day	26	90	0.038	
		Night	21	98	0.026	
United Kingdom						

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	<i>p</i> -value
UKD		Day	29	98	NA
		Night	24	100	0.028
UKE		Day	38	98	NA
		Night	26	98	NA
UKF		Day	29	93	0.04
		Night	22	100	0.071
UKG		Day	38	98	NA
		Night	25	98	NA
UKH		Day	36	98	NA
		Night	24	98	NA
UKI		Day	35	98	NA
		Night	21	91	0.098
UKJ		Day	45	100	0.065
		Night	26	98	NA
UKK		Day	25	72	0.034
		Night	31	98	NA
UKL		Day	28	98	NA
		Night	19	98	NA
UKM		Day	26	98	NA
		Night	13	71	0.098
UKN		Day	24	98	NA
		Night	18	98	NA

2. Incorporation of time-dependent exposure-response functions to capture adaptation dynamics

We appreciate your insightful and valuable comments regarding the assumption of constant relative risks (RRs) in our initial analysis. In response, we have substantially revised our methodological framework to address the temporal dynamics of adaptation capacities. Inspired by your suggestion and previous studies on heat-related mortality projections (Carleton et al., 2022; Rai et al., 2022), we have developed a multidimensional adaptation modelling approach that integrates: (1) physiological acclimatisation modelled across a range of scenarios; (2) socioeconomic adaptation represented by a GDP-based risk modification factor.

We have added the details of this approach in the revised manuscript as:

“In addition to the baseline no-adaptation projections, our study incorporated a methodological framework to evaluate heat-related mortality under different combinations of adaptation scenarios, which features two components: (1) Physiological adaptation scenarios: Five distinct physiological acclimatisation trajectories were parameterized with the percentage change in excess relative risk (RR) over time, such as zero adaptation (a reduction in the excess RR by 0%), low adaptation (a decrease in the excess RR by 5%), moderate adaptation (a decrease in the excess RR by 10%), medium adaptation (a decrease in the excess RR by 25%), and high adaptation (a decrease in the excess RR by 50%); (2) Socioeconomic adaptation pathways: Based upon established health economics literature (Carleton et al., 2022; Rai et al., 2022), we used the GDP per capita under the respective shared socioeconomic pathways (SSPs) to represent future socioeconomic adaptive capacity. Specifically, based on the log-linear association between RR and GDP per capita, the ratio of the logarithm of future GDP per capita and the logarithm of current GDP per capita under each SSP is used to simulate future socioeconomic adaptation.

For a given adaptation scenario, future heat-RR was calculated as:

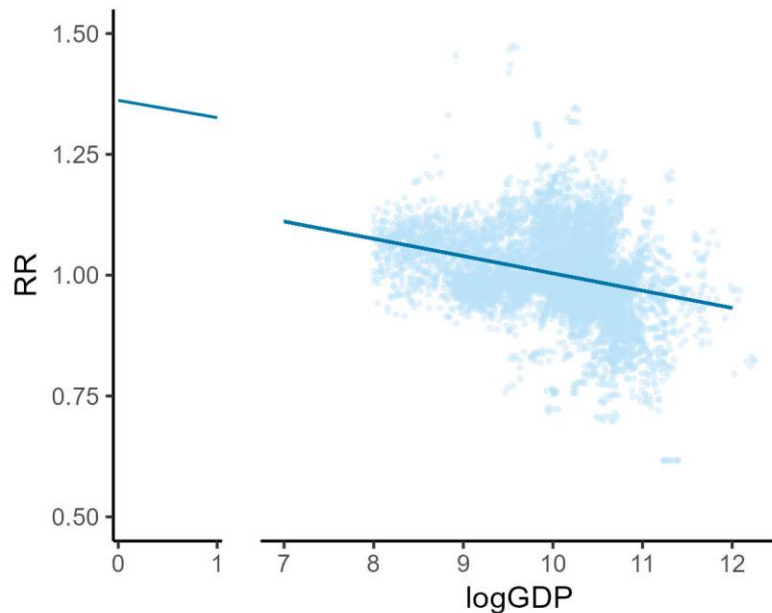
$$RRa_i' = [(\tau * (RRa_i - 1) + 1) * ((RRa_i - b) * x + b)]^{1/2}$$

where RRa_i is the heat-RR under baseline no-adaptation scenario. τ represents the attenuation rate associated with five physiological adaptation scenarios. x denotes the ratio of the logarithm of future GDP per capita and the logarithm of current GDP per capita. b is the intercept of the heat-RR and the logarithm of GDP per capita.”

Additionally, the identification of the association between heat-RR and the logarithm of GDP per capita is detailed in Supplementary Note 6 as below:

“Supplementary Note 6: Association between heat-RR and the logarithm of GDP per capita

The linear relationship between heat-relative risk (heat-RR) and the logarithm of GDP per capita was estimated from the data in 989 NUTS-3 level regions from 2010 to 2019. We derived heat-RR from the annual heat-mortality association. The intercept of the relationship between heat-RR and the logarithm of GDP per capita was calculated to be 1.37, as shown in Supplementary Fig. 19.”



Supplementary Fig. 19. Log-linear association between relative risk (RR) and the logarithm of GDP per capita.

We have also added a section to the revised manuscript to compare the projections of heat-related mortality in Europe under different physiological and socioeconomic adaptation scenarios:

“Implications for integrated European heat adaptation policy

To guide the formulation of integrated heat adaptation policy to reduce future heat-related mortality in Europe, we projected future heat-related mortality under five physiological-socioeconomic adaptation scenarios (see Methods). The zero-adaptation (0%) scenario depicts a future lacking physiological heat adaptation. In this case, the increase in future heat adaptation capacity is solely driven by socioeconomic development under different shared socioeconomic pathways (SSPs). The other four scenarios incorporate varying degrees of physiological adaptation: low (5%), moderate (10%), medium (25%), and high (50%) adaptations.

As illustrated in Fig. 5, the estimated percentage reductions in future heat-related mortality attributed to socioeconomic adaptation alone are 0.8–14.5% under SSP1-2.6, 3.0–11.9% under SSP2-4.5, 1.4–3.3% under SSP3-7.0, and 2.0–10.8% under SSP5-8.5. Low and moderate levels of physiological adaptation have a modest impact on future heat-related mortality. Even a 50% attenuation of the excess relative risk through

physiological adaptation is insufficient to counterbalance the effect of increased population exposure to heat on mortality in a warming world. Notwithstanding, the implementation of high-level adaptation under SSP2-4.5 at 2°C of warming (resulting in 106.5 annual heat-related deaths per million people, 95% CI: 68.3–154.2) reduced heat-related mortality to a level comparable to that with no adaptation at 1.5°C of warming under SSP1-2.6 (112.7, 95% CI: 69.6–169.9). By the end of the 21st century, if a 50% reduction in the excess relative risk can be achieved through physiological adaptation, heat-related deaths in Europe would be reduced by approximately 27.3% (95% CI: 26.9–27.8%) and 32.5% (95% CI: 30.8–34.5%) under SSP3-7.0 and SSP5-8.5, respectively. Our results also highlight the spatial heterogeneity of the impacts of physiological and socioeconomic adaptations on future heat-related mortality (Supplementary Figs. 24–27). Southern European countries exhibit relatively limited effectiveness in heat adaptation. In contrast, countries such as Germany, Finland, Sweden, and the United Kingdom have the greatest potential for heat adaptation to prevent an increase in heat-related mortality.”

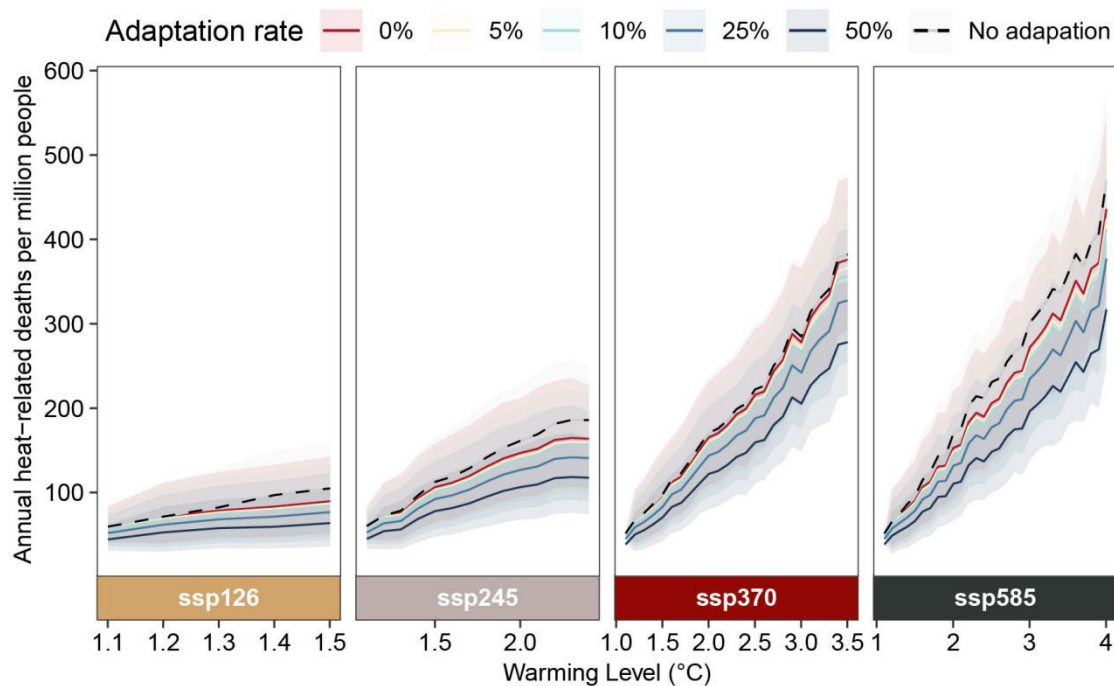
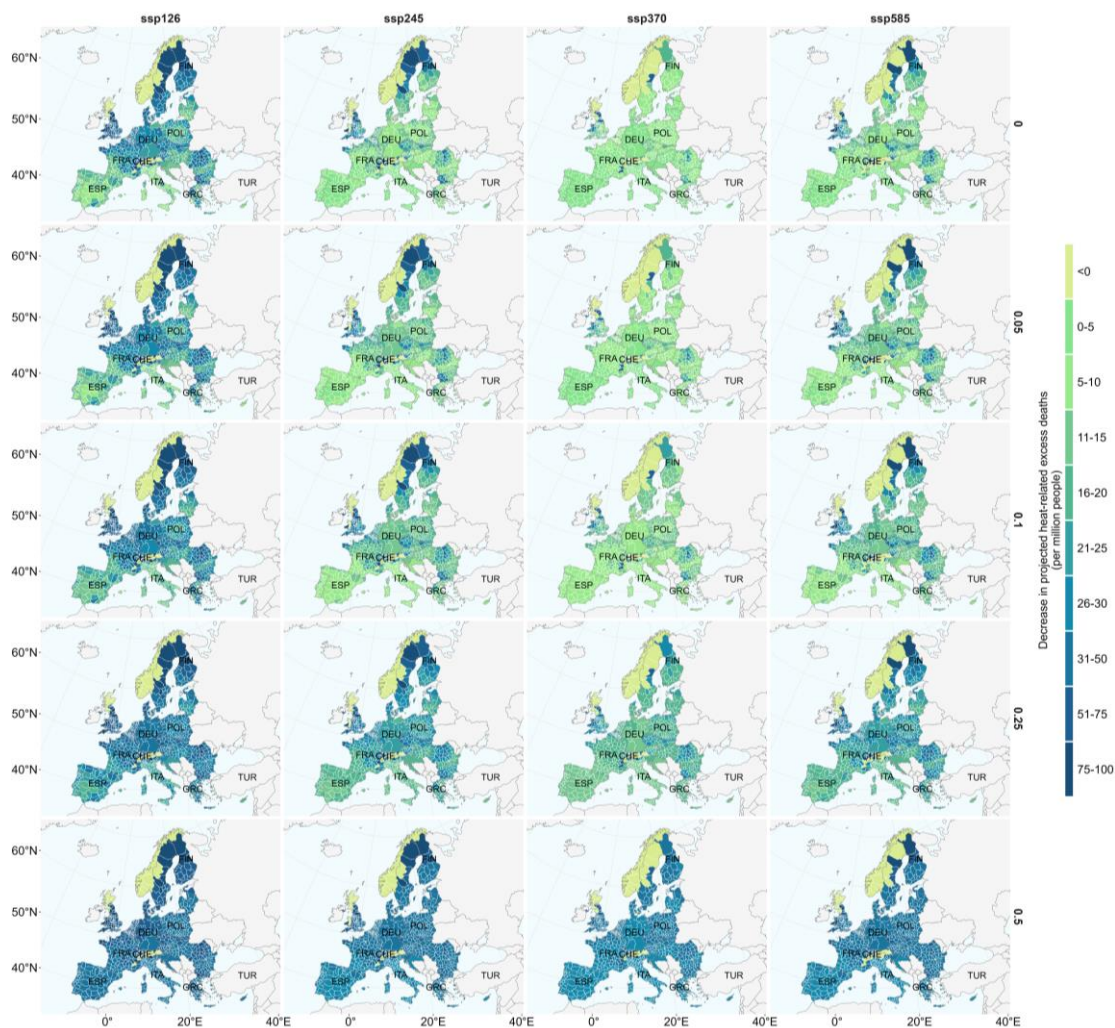


Fig. 5. Projections of annual heat-related deaths per million people in Europe. The dashed line indicates the projection for the baseline no-adaptation scenario. The solid lines represent projections for zero adaptation scenario (characterized by a 0% reduction in excess relative risk), low adaptation scenario (a 5% reduction in excess relative risk), moderate adaptation scenario (a 10% reduction in excess relative risk), medium adaptation scenario (a 25% reduction in excess relative risk), and high adaptation scenario (a 50% reduction in excess relative risk). Note that the baseline no-adaptation and zero-adaptation scenarios depict two different future states. The zero-adaptation scenario assumes no physiological heat adaptation yet incorporates socioeconomic heat adaptation. In contrast, the baseline no-adaptation scenario assumes that future relative risk remains at the current level.

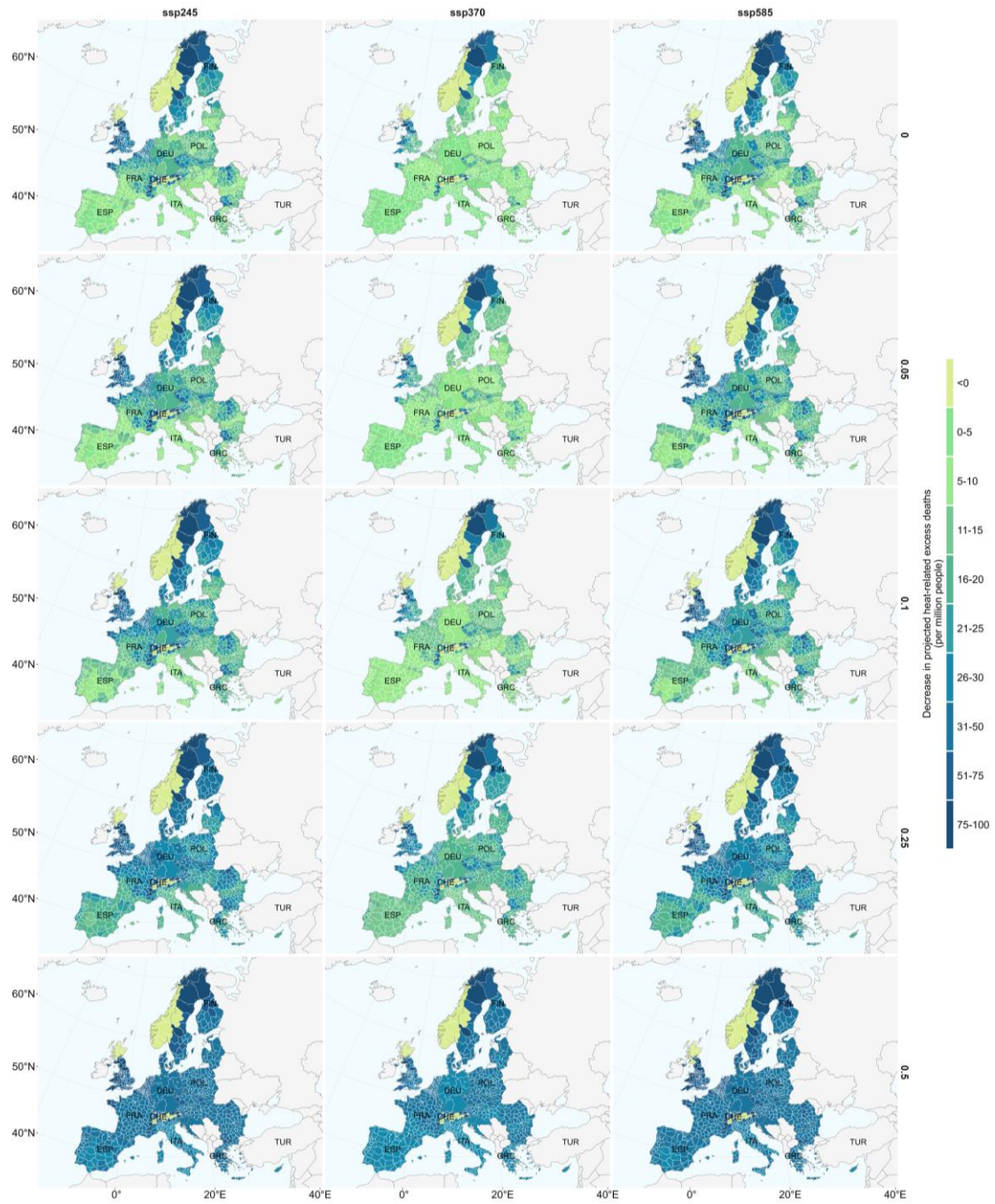
Lastly, heat adaptation constitutes a multifaceted and dynamic process intertwined with socioeconomic dimensions. Our investigation represents a first step to elucidate the effects of physiological and socioeconomic factors on future heat-related mortality trajectories. To contextualize these points, we delineate three critical knowledge gaps in the discussion, demanding prioritized investigations in future research. The first is to develop the methodology to determine physiological adaptation ceilings under projected climate scenarios. The second is to create standardized metrics for varying heat adaptation capacities across different population groups and regions. The third is to investigate the effect of nonlinear interactions between human acclimatisation and socioeconomic development on heat adaptation, particularly emphasizing educational attainment as a potential modifier of heat adaptive behaviours. In our revised Discussion, we contextualize these findings within the broader challenges of modelling dynamic adaptation:

“Building upon established epidemiological framework^{44–47}, the baseline no-adaptation projections employed a constant shape of the heat–mortality curve and static thermal vulnerability parameters. However, compelling evidence reveals temporally dynamic human heat adaptive capacity^{48–50}, suggesting that conventional projections may overestimate mortality risks given increasing heat awareness and cooling infrastructure. To address this gap, we conducted multi-dimensional scenario analyses integrating physiological and socioeconomic adaptations. We find that even achieving a 50% reduction of heat-related mortality risk through physiological adaptation fails to counterbalance the future warming-induced amplification of mortality risk. This indicates that extraordinary adaptation measures may be required to prevent the health costs associated with climate change. Across all SSP scenarios (SSP1, SSP2, SSP3, SSP5), socioeconomic adaptations demonstrate limited mortality attenuation in heat-related deaths (<15%), particularly for SSP3–7.0 (1.3–3.3%). Compared to socioeconomic adaptation with quantifiable metrics, physiological adaptation mechanisms exhibit multidimensional complexity. Analysis of the latest relative risk (RR) curve (2010–2019) indicates a 36.8% reduction in projected heat-related mortality compared to the baseline period (2000–2009) (Supplementary Table 7). This nonlinear progression reveals temporal non-stationarity in adaptation rates (Supplementary Note 5). Such patterns underscore the dynamic nature of human heat adaptive capacity, which is associated with social infrastructure support networks, accessibility of healthcare services, and health education^{50–52}. Current modelling frameworks oversimplify adaptation trajectories by neglecting two critical aspects: the upper limits of physiological adaptation under projected climate scenarios and the varying heat adaptation capacities across different population groups and regions. In addition to these aspects, the effects of nonlinear interactions between physiological and socioeconomic adaptations may shape future heat-related mortality. Therefore, future research is needed to develop new methodologies to determine physiological adaptation ceilings, to create standardised metrics for varying heat

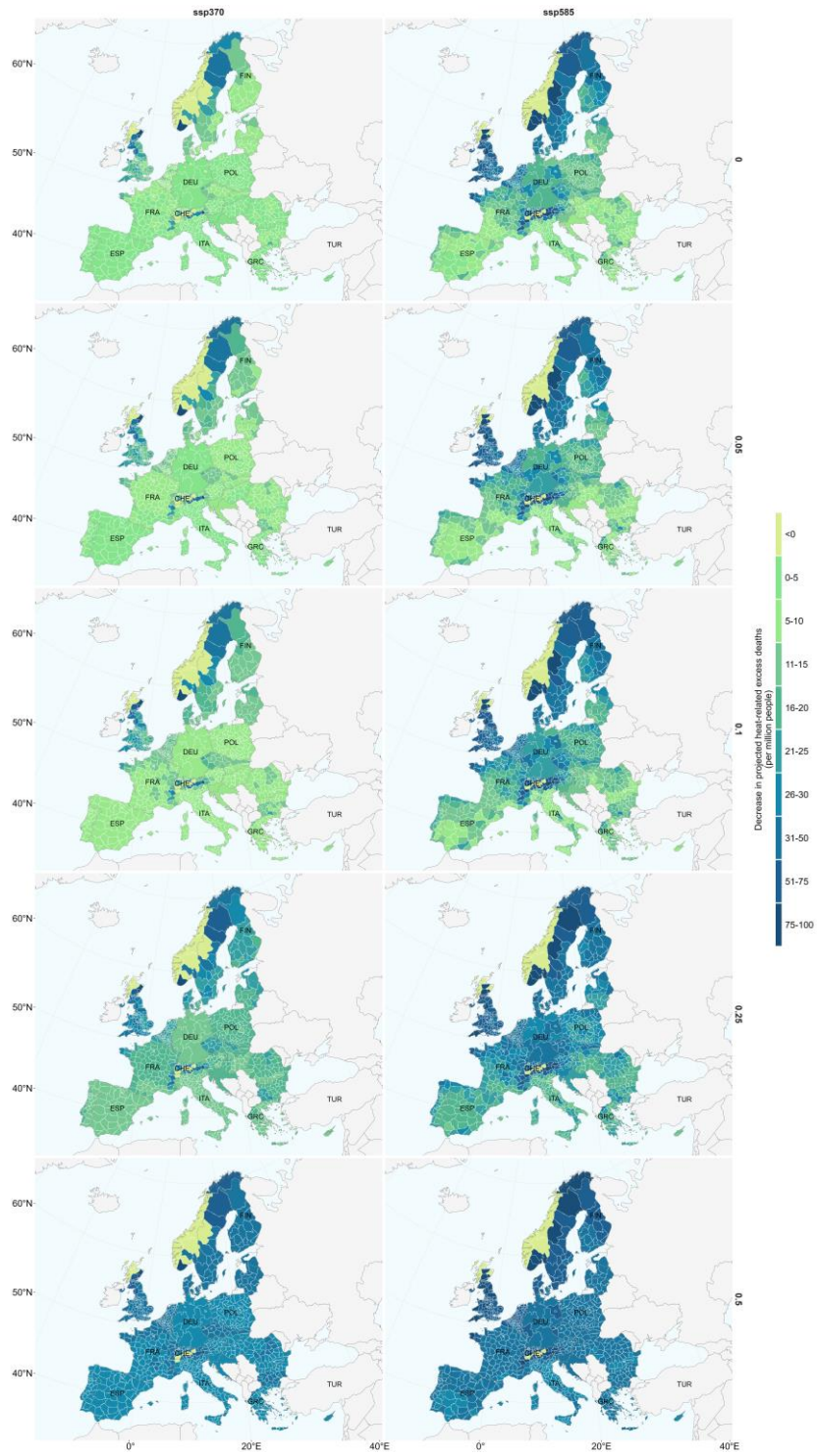
adaptation capacities across different population groups and regions, and to investigate the effect of nonlinear interactions between human acclimatisation and socioeconomic development on heat adaptation, particularly emphasising educational attainment as a potential modifier of heat adaptive behaviours.”



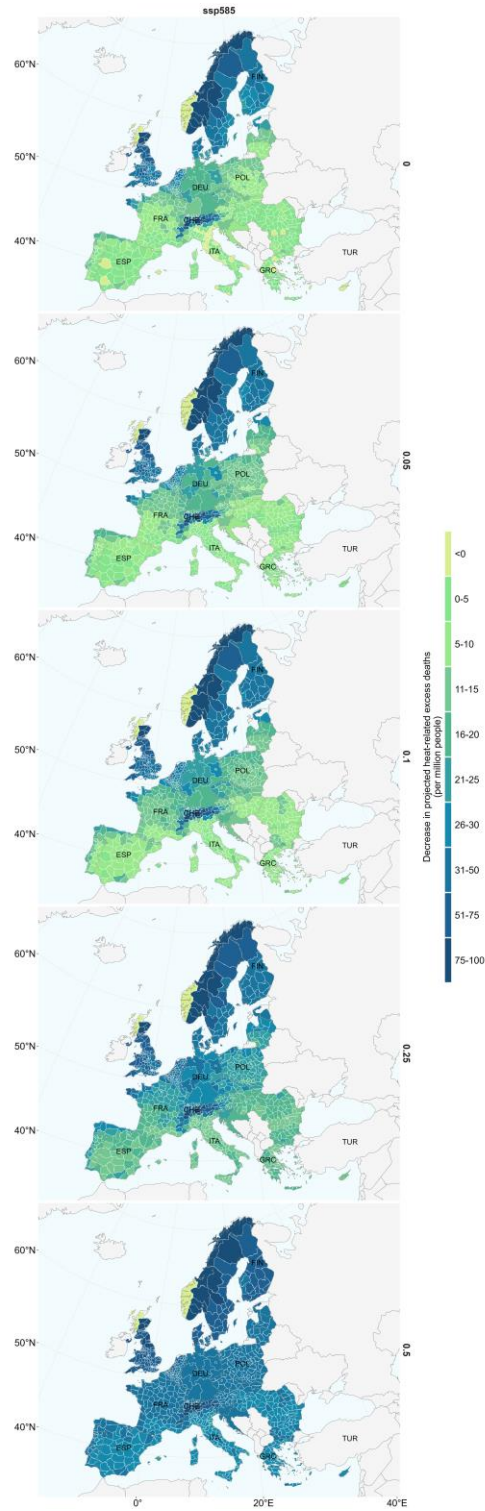
Supplementary Fig. 24. Spatial patterns of the decrease in projected heat-related excess deaths at 1.5°C of global warming under five physiological-socioeconomic adaptation scenarios.



Supplementary Fig. 25. Spatial patterns of the decrease in projected heat-related excess deaths at 2°C of global warming under five physiological-socioeconomic adaptation scenarios.



Supplementary Fig. 26. Spatial patterns of the decrease in projected heat-related excess deaths at 3°C of global warming under five physiological-socioeconomic adaptation scenarios.



Supplementary Fig. 27. Spatial patterns of the decrease in projected heat-related excess deaths at 4°C of global warming under five physiological-socioeconomic adaptation scenarios.