

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

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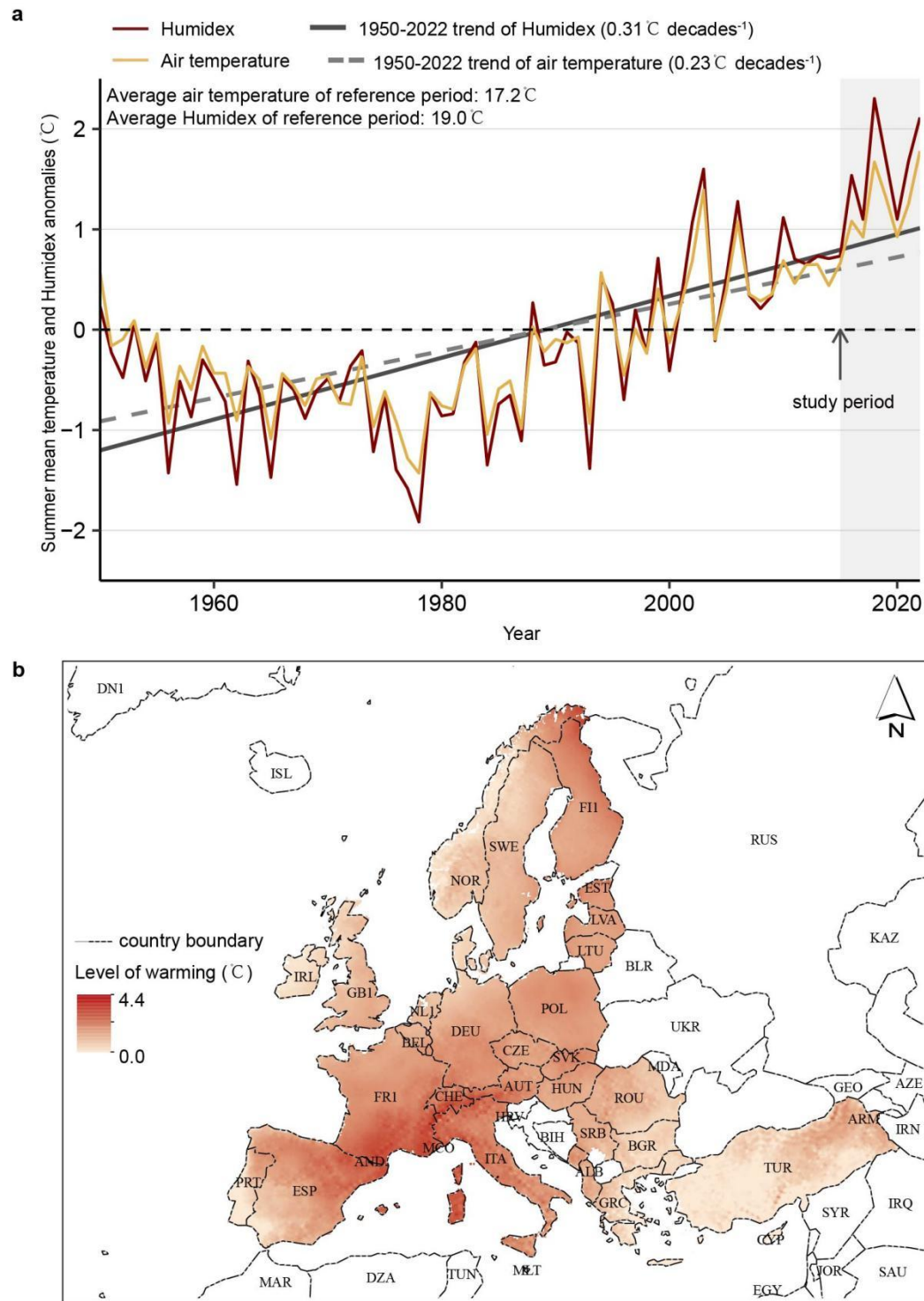
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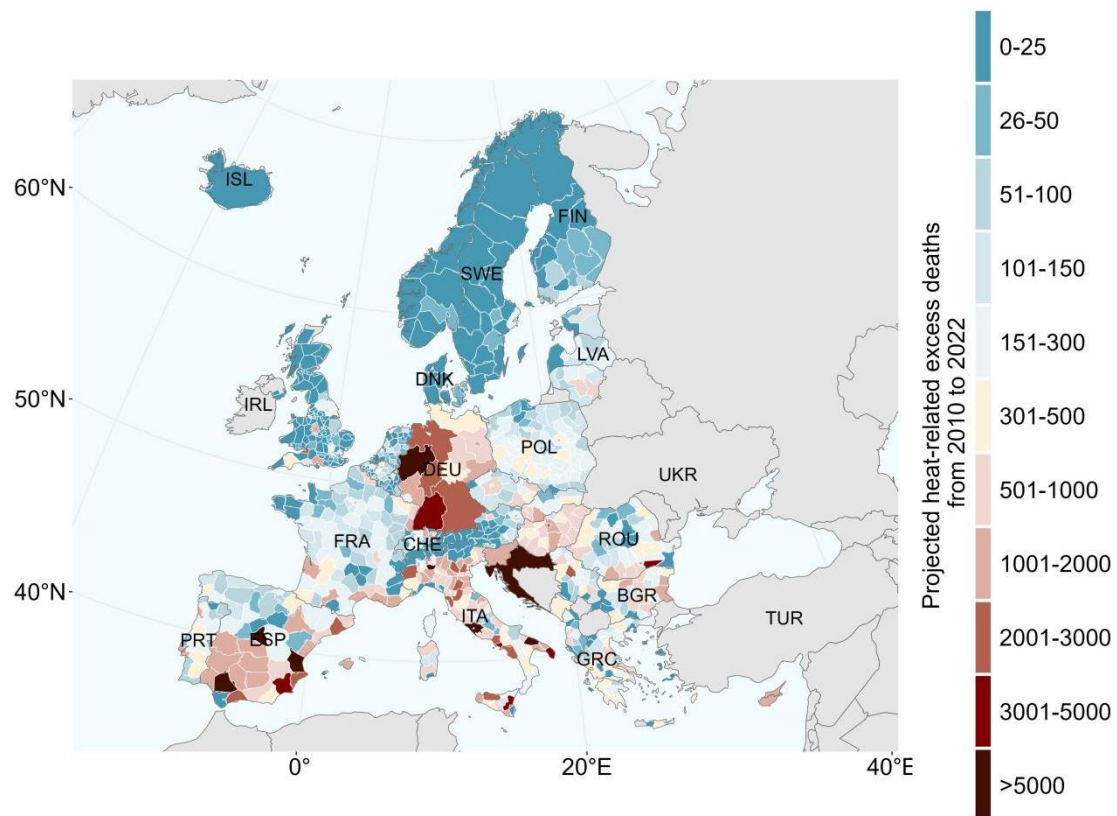
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Supplementary Fig 1. Summertime warming in Europe. (a) Regional area-weighted mean anomalies (relative to 1986–2005) of Humidex (red) and surface air temperature (orange) during summer (weeks 22–35) over 1950–2022. (b) The geographic pattern of summertime mean Humidex anomalies (relative to 1986–2005)

in 2022. The abbreviations for European countries are as follows: Finland (FLI), Sweden (SWE), Norway (NOR), Estonia (EST), Latvia (LVA), Lithuania (LTU), United Kingdom (GB1), Ireland (IRL), Netherlands (NL1), Germany (DEU), Belgium (BEL), France (FR1), Poland (POL), Czechia (CZE), Slovakia (SVK), Hungary (HUN), Austria (AUT), Liechtenstein (LIE), Switzerland (CHE), Monaco (MCO), Italy (ITA), Spain (ESP), Portugal (PRT), Romania (ROU), Bulgaria (BGR), Republic of Serbia (SRB), Greece (GRC), Albania (ALB), Turkey (TUR), Cyprus (CYP), and Malta (MLT).



Supplementary Fig 2. Cumulative heat-related deaths in summer (weeks 22-35) from 2010 to 2022. The abbreviations for the European countries are as follows: Finland (FLI), Sweden (SWE), Norway (NOR), Estonia (EST), Latvia (LVA), Lithuania (LTU), United Kingdom (GB1), Ireland (IRL), Netherlands (NL1),

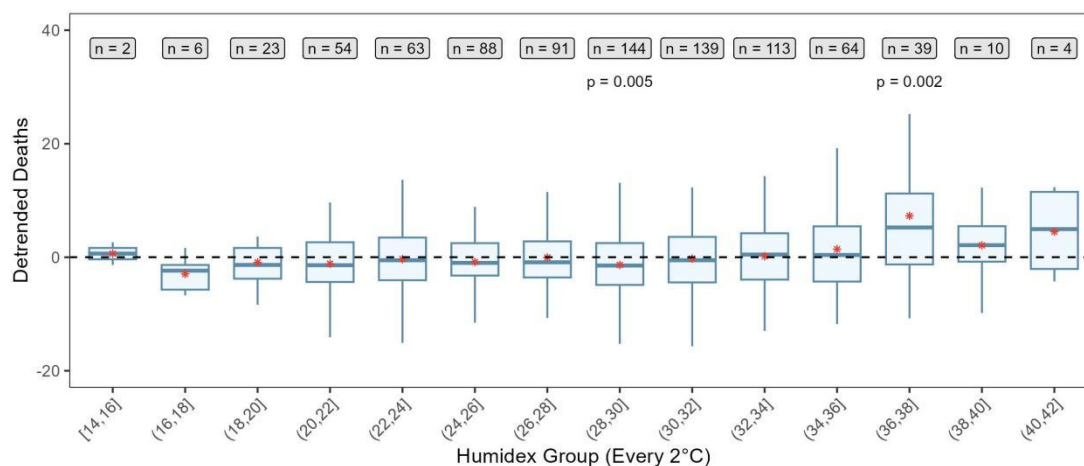
Germany (DEU), Belgium (BEL), France (FRA), Poland (POL), Czechia (CZE), Slovakia (SVK), Hungary (HUN), Austria (AUT), Liechtenstein (LIE), Switzerland (CHE), Monaco (MCO), Italy (ITA), Spain (ESP), Portugal (PRT), Romania (ROU), Bulgaria (BGR), Republic of Serbia (SRB), Greece (GRC), Albania (ALB), Turkey (TUR), Cyprus (CYP), Malta (MLT), Denmark (DNK), Croatia (HRV), Montenegro (MNE), and Luxembourg (LUX).

Supplementary Note 1: Health risk-based extreme heat threshold definition

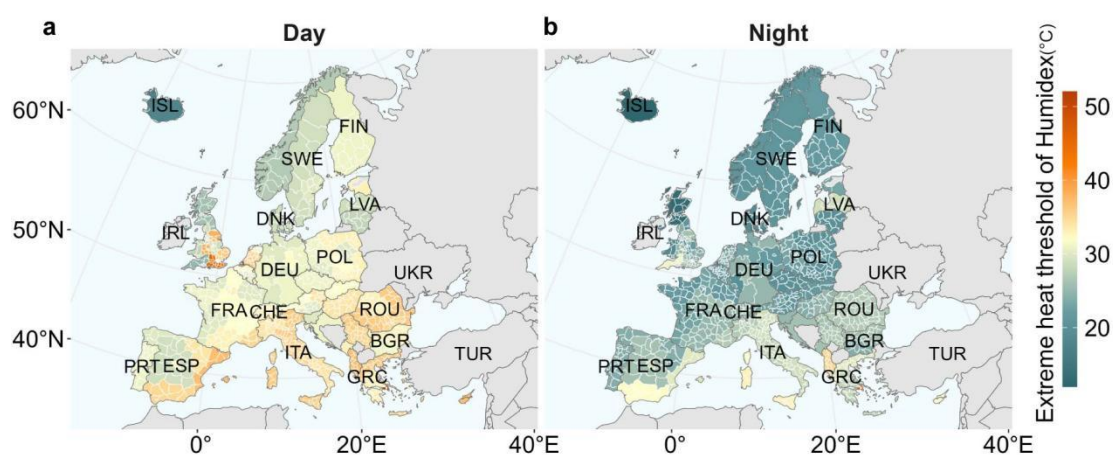
We used a novel method proposed by Montero et al. (2010)¹ to determine localized health risk-based heat thresholds. This method assumes that the detrended mortality residuals represent heat-related excess mortality. The process started with the Autoregressive Integrated Moving Average (ARIMA) modeling 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, yielded the detrended mortality residuals that isolate heat-related mortality signals from 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 a representative case), 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. We initially set the significance level threshold to 0.05 for all the NUTS-1 regions. Initial $\alpha=0.05$ criteria were relaxed to $\alpha=0.1$ in the areas where no significant differences at the 0.05 level were observed (18 regions), acknowledging that the reduced statistical power in areas

with less mortality data. In 37 regions where residual mortality showed non-monotonic Humidex relationships, we implemented the 98th percentile of the Humidex distribution as an objective heat threshold, circumventing the limitations of weekly mortality aggregation in capturing acute heat-health responses. 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.



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 pattern of extreme heat threshold for NUTS-1 level regions during the day (a), and night (b). The abbreviations for the European countries

are as follows: Finland (FLI), Sweden (SWE), Norway (NOR), Estonia (EST), Latvia (LVA), Lithuania (LTU), United Kingdom (GB1), Ireland (IRL), Netherlands (NL1), Germany (DEU), Belgium (BEL), France (FRA), Poland (POL), Czechia (CZE), Slovakia (SVK), Hungary (HUN), Austria (AUT), Liechtenstein (LIE), Switzerland (CHE), Monaco (MCO), Italy (ITA), Spain (ESP), Portugal (PRT), Romania (ROU), Bulgaria (BGR), Republic of Serbia (SRB), Greece (GRC), Albania (ALB), Turkey (TUR), Cyprus (CYP), Malta (MLT), Denmark (DNK), Croatia (HRV), Montenegro (MNE), and Luxembourg (LUX). The specific extreme heat threshold in each region can be found in Supplementary Table 1.

Supplementary Table 1. The heat threshold for NUTS-1 regions. The 'Percentile' indicates the percentile of the day/night-time heat threshold in weekly maximum/minimum Humidex series in NUTS-1 region during the summers (weeks 22-35) from 2010 to 2019. P-values are produced by one-sample t-test.

Country	NUTS-1 Level	Time	Heat threshold (°C)	Percentile (%)	P-value
Albania	AL0	Day	37	97	0.002
		Night	35	100	0.071
	AT1	Day	34	95	<0.001
		Night	21	77	<0.001
Austria	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
	BG4	Day	31	84	0.003

		Night	24	90	0.009
Switzerland	CH0	Day	33	92	0.003
		Night	25	96	<0.001
		Day	37	98	NA
Cyprus	CY0	Night	32	98	NA
		Day	31	86	<0.001
Czech Republic	CZ0	Night	20	82	<0.001
		Day	30	81	0.002
Germany	DE1	Night	25	96	0.002
		Day	31	91	<0.001
	DE2	Night	25	98	NA
		Day	32	90	0.005
	DE3	Night	24	96	0.026
		Day	31	91	<0.001
	DE4	Night	22	87	0.019
		Day	32	86	0.082
	DE5	Night	26	97	0.028
		Day	32	98	NA
	DE6	Night	25	99	0.071
		Day	30	79	0.009
	DE7	Night	26	98	NA
		Day	30	90	0.006
	DE8	Night	25	99	0.003
		Day	30	89	0.007
	DE9	Night	23	96	0.013
		Day	31	89	0.005
	DEA	Night	25	98	NA
		Day	31	85	0.017
	DEB	Night	20	79	0.059
		Day	30	89	0.041
	DEC	Night	23	96	0.086
		Day	31	91	0.015
	DED	Night	23	94	0.051
		Day	32	93	0.005
	DEE	Night	22	84	0.045
		Day	30	91	0.078
	DEF	Night	24	98	NA
		Day	30	93	0.028
	DEG	Night	24	98	0.001
		Day	29	99	<0.001
Denmark	DK0	Night	19	95	0.018
		Day	33	98	NA
Estonia	EE0	Night	23	97	0.039
		Day	52	92	0.019
Greece	EL3	Day	52	92	0.019

Spain	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
	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
	ES6	Night	30	93	0.009
		Day	35	92	0.012
	ES7	Night	32	99	0.012
		Day	31	98	NA
Finland	FI1	Night	28	98	NA
		Day	31	97	0.004
	FI2	Night	22	96	0.009
		Day	29	98	NA
	FR1	Night	21	94	0.06
		Day	33	85	0.018
	FRB	Night	23	86	0.014
		Day	32	90	0.044
	FRC	Night	25	97	0.004
		Day	32	90	0.001
France	FRD	Night	26	98	0
		Day	30	92	0.011
	FRE	Night	21	94	0.006
		Day	32	93	<0.001
	FRF	Night	23	96	0.006
		Day	30	73	0.025
	FRG	Night	22	83	0.001
		Day	31	87	0.012
	FRH	Night	22	90	0.057
		Day	31	98	NA
	FRI	Night	22	99	0.026
		Day	30	73	0.048
	FRJ	Night	23	86	0.016
		Day	33	89	0.015

		Night	25	89	0.003
		Day	32	94	0.049
	FRK	Night	25	96	<0.001
		Day	35	97	0.017
	FRL	Night	27	93	0.034
		Day	35	98	NA
	FRM	Night	32	99	0.083
		Day	39	98	NA
	FRY	Night	36	98	NA
		Day	31	93	0.001
Croatia	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
	ITF	Night	29	91	0.006
		Day	36	96	<0.001
Italy	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
Liechtenstein	LI0	Night	19	98	NA
		Day	28	71	0.008
Lithuania	LT0	Night	20	85	<0.001
		Day	33	98	NA
Luxembourg	LU0	Night	23	98	NA
		Day	29	81	0.043
Latvia	LV0	Night	29	100	0.019
		Day	33	97	0.029
Montenegro	ME0	Night	26	91	0.015
		Day	41	98	NA
Malta	MT0	Night	37	98	NA
Netherlands	NL1	Day	31	94	0.026

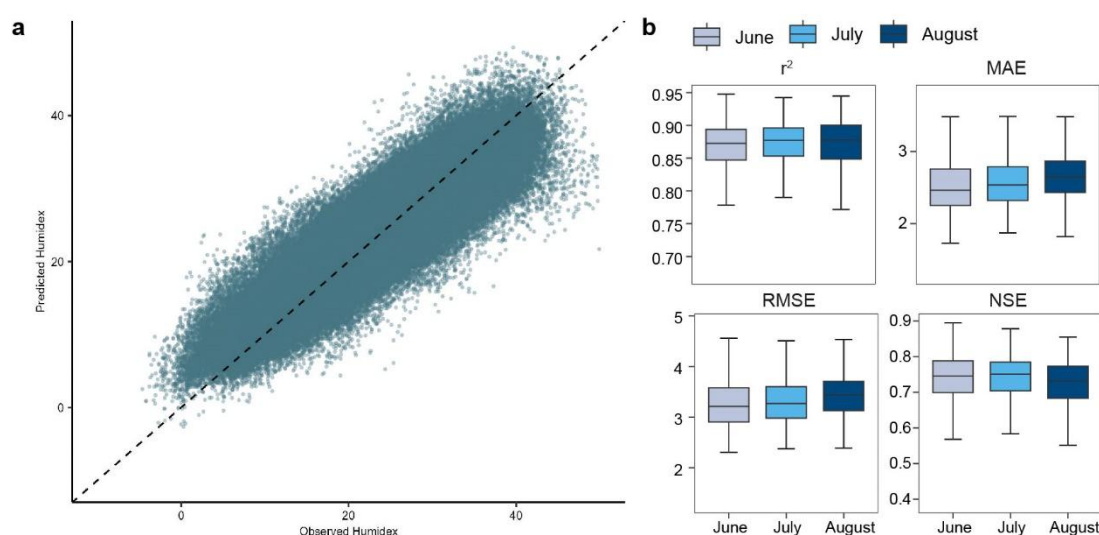
Norway	NL2	Night	23	98	NA
		Day	35	99	0.005
		Night	24	100	0.003
	NL3	Day	36	99	0.027
		Night	24	97	0.099
	NL4	Day	36	100	0.069
		Night	24	98	NA
	NO0	Day	27	99	0.082
		Night	21	99	0.017
	PL2	Day	33	91	<0.001
		Night	20	80	<0.001
	PL4	Day	31	81	0.001
		Night	23	92	0.01
	PL5	Day	30	73	0.032
		Night	22	89	0.005
Poland	PL6	Day	33	95	<0.001
		Night	20	86	0.007
	PL7	Day	32	85	0.001
		Night	20	79	0.023
	PL8	Day	33	90	<0.001
		Night	21	81	0.001
	PL9	Day	30	69	0.041
		Night	22	87	<0.001
	PT1	Day	31	83	0.001
		Night	24	86	0.001
Portugal	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
Romania	RO2	Day	36	95	0.015
		Night	27	94	<0.001
	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
Serbia	RS2	Day	35	93	0.001
		Night	27	95	<0.001
Sweden	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
Slovenia	SI0	Day	30	87	0.03
		Night	25	96	0.062
Slovakia	SK0	Day	32	80	0.002
		Night	22	82	<0.001
	UKC	Day	26	90	0.038
		Night	21	98	0.026
	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
United Kingdom		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

Supplementary Note 2: Humidex data accuracy validation

We validated our results using hourly in-situ data from National Oceanic and Atmospheric Administration (NOAA), accessible at [\[https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00532/html\]](https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00532/html) (last assessed: October 2023). Four statistical metrics, correlation coefficient (r^2), mean absolute error (MAE), root mean square error (RMSE) and

Nash–Sutcliffe efficiency index (NSE), are employed for model performance evaluation. Supplementary Fig. 5 shows the accuracy scatter plot for observed and estimated Humidex, highlighting strong consistency with a population r^2 of 0.90. The population MAE and RMSE were 2.59°C and 3.39°C, respectively. An NSE of 0.81, less than 1, indicates that the prediction errors are significantly lower than the natural variability of hourly Humidex. These results underscore the robustness of our model in accurately estimating Humidex values and provide confidence in the reliability of our findings.



Supplementary Fig 5. Scatter diagrams of the reconstructed Humidex model against observed in-situ data (a). and the accuracy validation across months (b). The R-square between observed Humidex and predicted Humidex is 0.90. The box plots show the accuracy validation results for June (light blue), July (blue) and August (dark blue).

Supplementary Note 3: Three-step validation of DLNM model

The distributed lag nonlinear model (DLNM) is constructed using data from 989 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 ², 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) are derived as Supplementary Equations (1) and (2):

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

$$\text{MAD} = \frac{\left| \sum (\hat{\beta}_i - \beta_i) / n \right|}{\beta_i/n} \quad (2)$$

Where $\hat{\beta}_i$ is estimated from the training data and β_i is estimated from the test data. As shown in Supplementary Table 2, the model performs more robustly when characterizing the relationship between heat exposure and mortality among working-aged adults.

Supplementary Table 2. Robustness validation of the estimated parameters based on different exposure period. The validation results are summarised using root mean square error (RMSE) and mean absolute deviation (MAD).

Age group	RMSE	MAD
0-14	0.24	0.09
15-65	0.04	0.02
65+	0.03	0.02

Secondly, we employed the bootstrapping approach^{2,3} 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 is reported as the average RMSE and the average coefficient of determination (R^2) across these 30 iterations. As shown in Supplementary Table 3, 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 values are computed as Supplementary Equations (3) and (4):

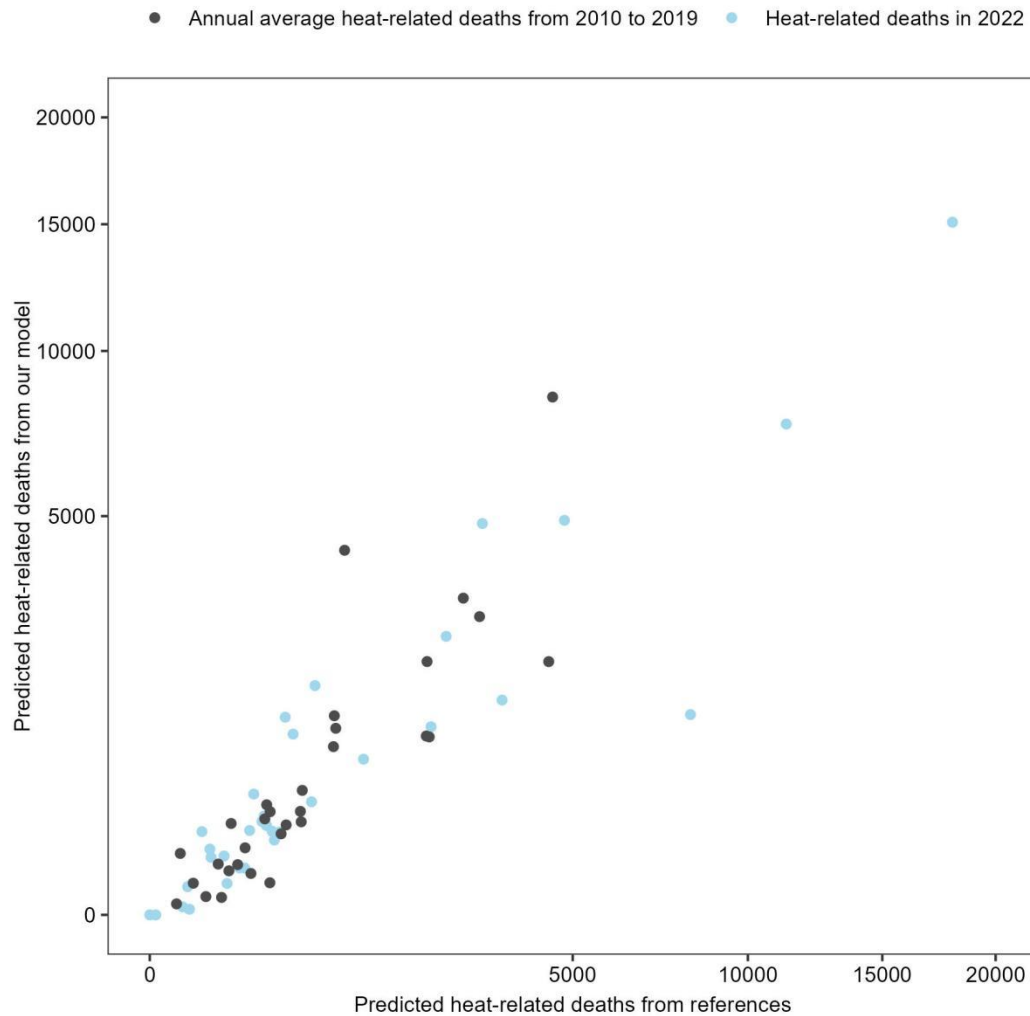
$$RMSE = \sqrt{\frac{1}{n} \sum (Y_{obs,i} - Y_{pred,i})^2} \quad (3)$$

$$R^2 = 1 - \frac{\sum_i (Y_{obs,i} - Y_{pred,i})^2}{\sum_i (Y_{obs,i} - \frac{1}{n} \sum_{i=1}^n Y_{obs,i})^2} \quad (4)$$

Supplementary Table 3. Summary of root mean square error (RMSE) and coefficient of determination (R^2) from bootstrapping validation of the model across different age groups.

Age group	RMSE	R^2
0-14	0.85	0.94
15-65	4.74	0.98
65+	21.30	0.98

Finally, we cross-validated the predicted heat-related mortality from our model with results from existing studies^{4,5}, yielding an R^2 of 0.79 (see Supplementary Fig. 6). 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 underscore the critical role of ambient humidity in modulating heat-related excess mortality.



Supplementary Fig 6. Comparison between predicted heat-related deaths from our model using Humidex and other studies. The predicted results are extracted as the annual average value from 2010 to 2019 and the total value for 2022 to match the available data from the references. The R-squared value is equal to 0.79.

Supplementary Note 4: Sensitivity analysis

To evaluate the robustness of our DLNM model, we designed several sensitivity analyses using various settings. The sensitivity analysis aims to investigate the impact of parameter settings on the relationship between heat exposure and mortality.

Specifically, we devised eight distinct scenarios (S1-S6 and DS) that vary the knots and the degrees of freedom in cross-basis function, as well as the degrees of freedom in natural cubic splines used to control the long-term trends and seasonality. Additionally, we replaced the functional forms of the exposure-response model and time-lag terms to test the responsiveness of the model to variations in the cross-basis function, as shown in scenarios SE1 and SE2.

DS: The cross-basis function f is modeled using a natural spline function with one knot at 80th percentile of weekly Humidex distribution and a time-lag effect function using a natural spline with integer lag values θ of 1, 2, and 4 weeks chosen by the log-knots function. Two natural cubic splines of time with 4 degrees of freedom (df) for the year number and 3 df for the week number are employed to control the long-term trends and seasonality.

SE1: The natural spline function is replaced with a B-spline function.

SE2: The time-lag effect function is replaced by integer lag values up to 2 weeks (with the minimum lag equal to 0 weeks by default).

S1: The knot of B-spline is placed at the 70th percentiles of weekly Humidex distribution.

S2: The knot of B-spline is placed at the 90th percentiles of weekly Humidex distribution.

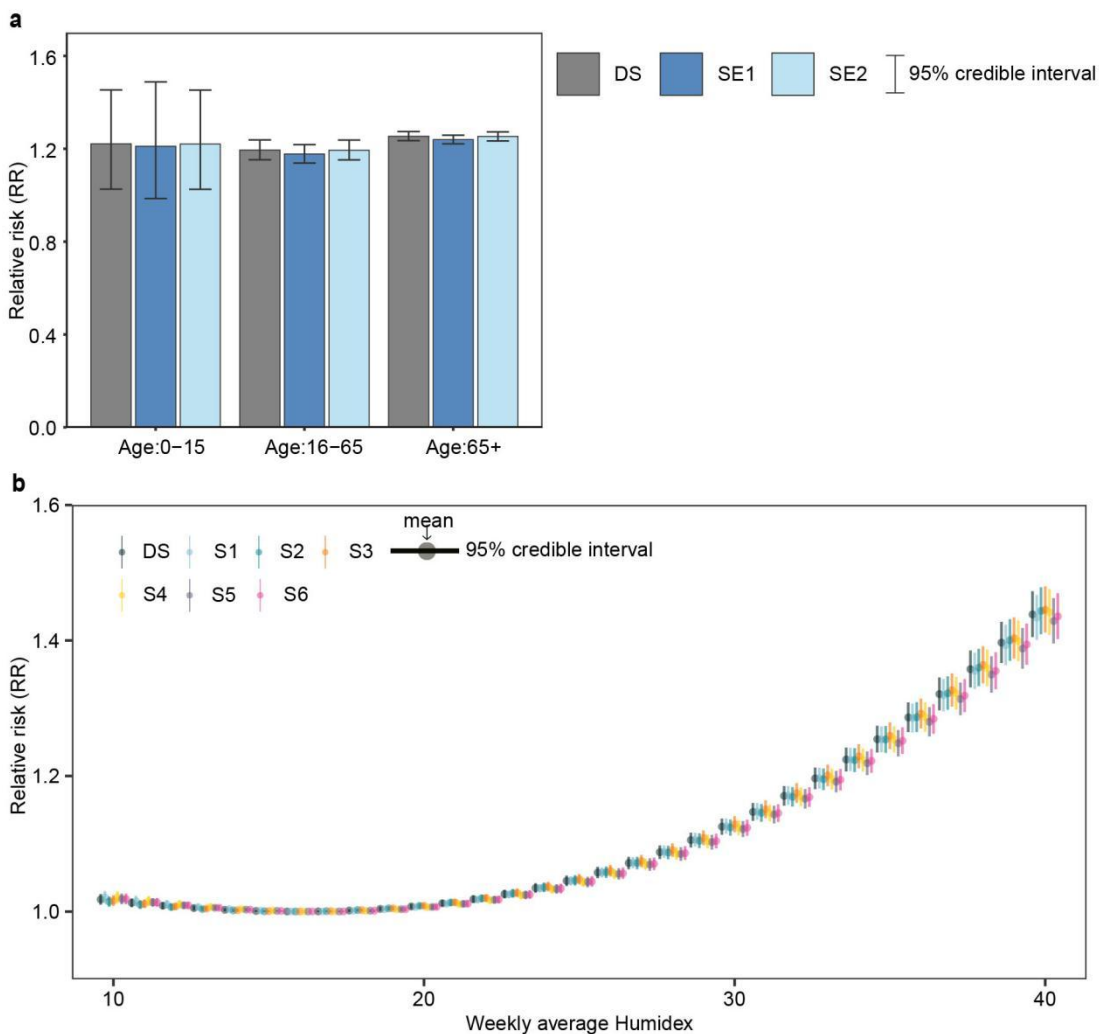
S3: The degree of freedom for the year number is set to 3.

S4: The degree of freedom for the year number is set to 5.

S5: The degree of freedom for the week number is set to 2.

S6: The degree of freedom for the week number is set to 5.

The results of our sensitivity analyses show that the DLNM model is sensitive to the cross-basis functions (Supplementary Fig. 7). Other parameters display a negligible impact on the final results. Given these findings, we decided to set the time-lag effect function using a natural spline in our main analysis, as it yields the narrowest confidence interval.



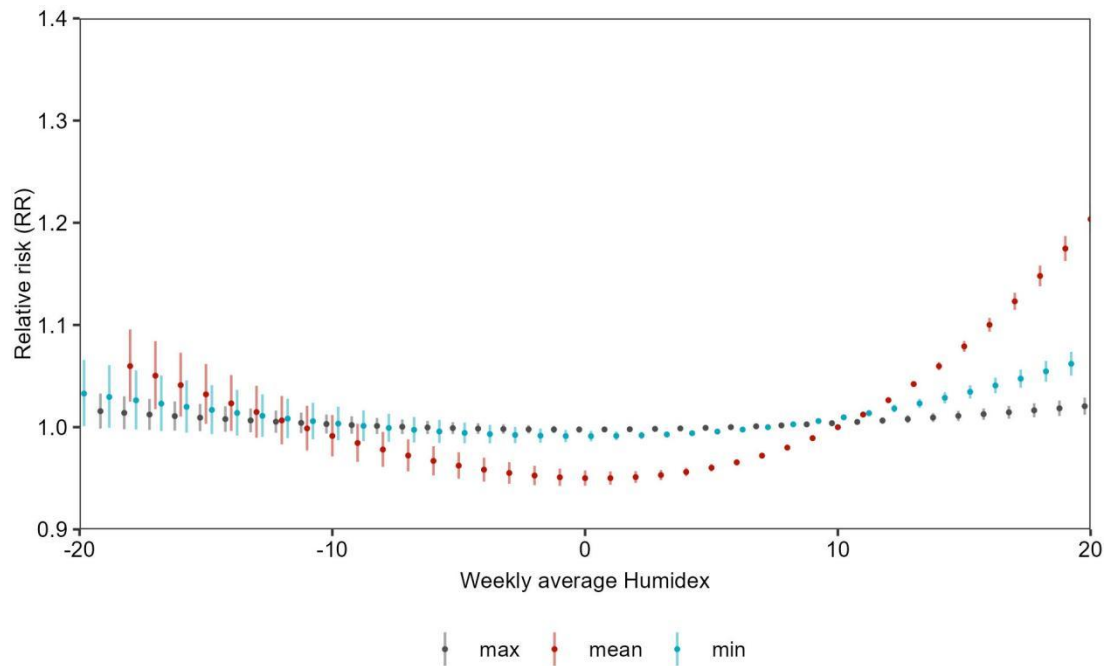
Supplementary Fig 7. Relative risk variation under different model settings via the cross-basis function (a) and other model terms (b). Sensitivity analysis results are exemplified by modelling data from the elderly (aged 65 years or above).

Furthermore, we also tested the sensitivity of the results to the statistical methods used to construct the heat exposure-mortality relationship (S7-8). The default definition is explained in the DDS. We found that the results indicate that the model is sensitive to the characteristics of the input meteorological variables (Supplementary Fig. 8). Due to the highest model accuracy, which we used the mean value as the primary metric for analysis in this study.

DDS: An extreme hot day/night threshold is defined as the period-based (daytime/nighttime) mean temperature exceeding the 95th percentile of its local daily climatology. The location-specific daily climatology is determined using a 15-day-long time window centered on each calendar day over 1961–2022. The DLNM with a quasi-Poisson distribution is used to quantify the geographically dependent relationship between weekly counts of all-cause mortality and weekly mean Humidex.

S7: The DLNM is used to quantify the geographically dependent relationship between weekly counts of all-cause mortality and weekly minimum Humidex.

S8: The DLNM is used to quantify the geographically dependent relationship between weekly counts of all-cause mortality and weekly maximum Humidex.



Supplementary Fig 8. Variation in relative risk under different characteristics of the input meteorological variables of weekly minimum, mean and maximum Humidex. Sensitivity analysis results are exemplified by modelling data from the elderly (aged 65 years or above). Please note that the x-axis is shifted to the left by the minimum mortality Humidex (MMH) for comparison. The MMH estimated using different statistical variables are 34 (max), 15 (mean), and 8 (min), respectively.

Supplementary Table 4. Model accuracy using different statistical summaries.

Here, the validation results are reported as root mean square error (RMSE).

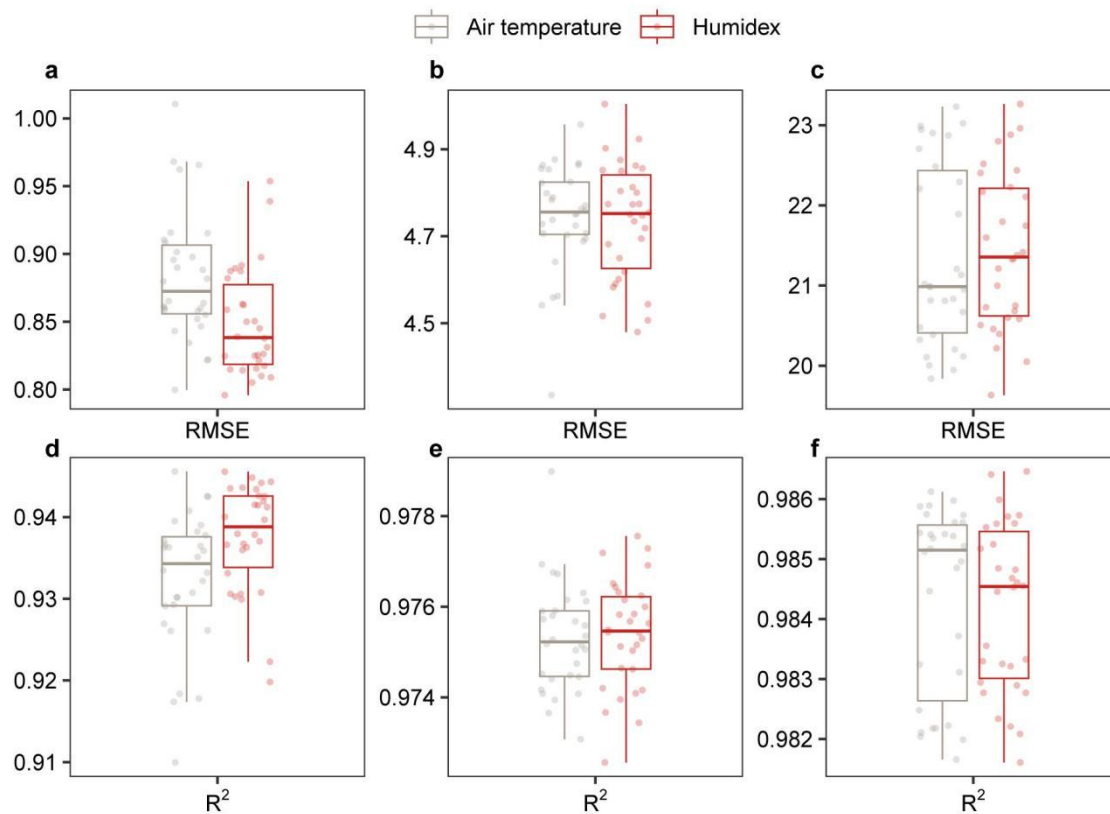
	Age:0-14	Age:15-65	Age:65+
Weekly mean Humidex	0.7	4.2	11.9
Weekly minimum Humidex	0.7	4.3	12.6
Weekly maximum Humidex	0.7	4.2	12.9

Supplementary Note 5: Comparison between air temperature and Humidex in characterizing heat-mortality response

In the comparison of air temperature and Humidex to characterize the relationship between heat exposure and mortality, we validate the robustness of the model at varying temperature exposure intensity and lags without resampling and the predicted accuracy of the estimated heat-related mortality. As shown in Supplementary Table 5, we find that using the humid heat stress index, Humidex, shows more robustness among individuals aged 65 and above at varying heat exposure intensities compared to using dry-bulb air temperature. Also, Humidex and air temperature do not show significant differences in performance in the bootstrapping validation (see Supplementary Fig. 9). However, when comparing the heat-related mortality estimated from our model and other studies, we find that the model using Humidex shows higher accuracy ($R^2 = 0.79$) than using dry-bulb surface air temperature ($R^2 = 0.72$).

Supplementary Table 5. Comparison of model performance using Humidex and air temperature. The root mean square error (RMSE) and mean absolute deviation (MAD) values reported for each group represent the differences in model parameters when models are trained using Humidex and air temperature with data from different time periods. The p-value tests are based on the two-sided 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	MAD	P-value
0-14	Humidex	0.24	0.09	0.99
	Air temperature	0.24	0.09	
15-65	Humidex	0.04	0.02	0.95
	Air temperature	0.03	0.02	
65+	Humidex	0.03	0.02	<0.001***
	Air temperature	0.04	0.03	

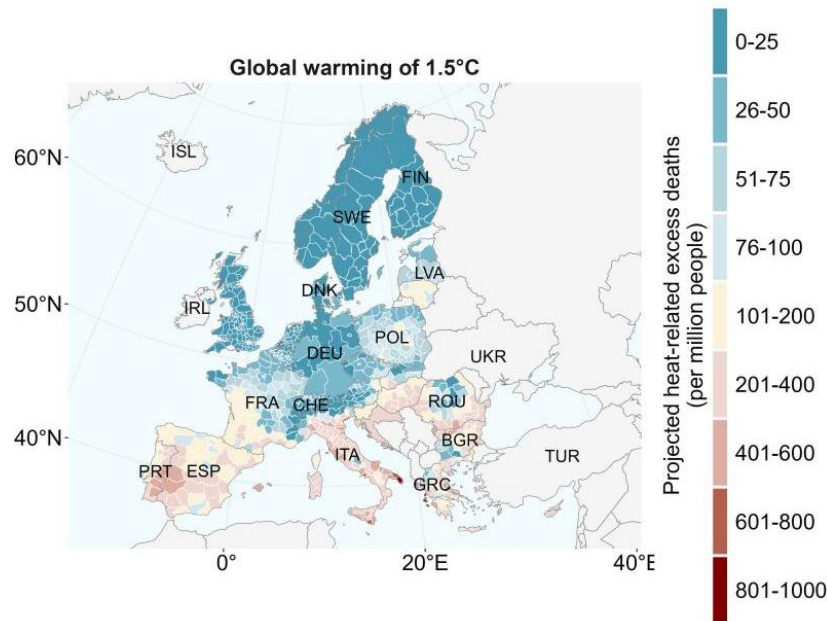


Supplementary Fig 9. Boxplot comparing model accuracy using RMSE across three age groups: 0-14 (a), 15-65 (b), 65+ (c), and R² across three age groups: 0-14 (d), 15-65 (e), 65+ (f). The comparison is performed between models using Humidex (in red) and air temperature (in grey).

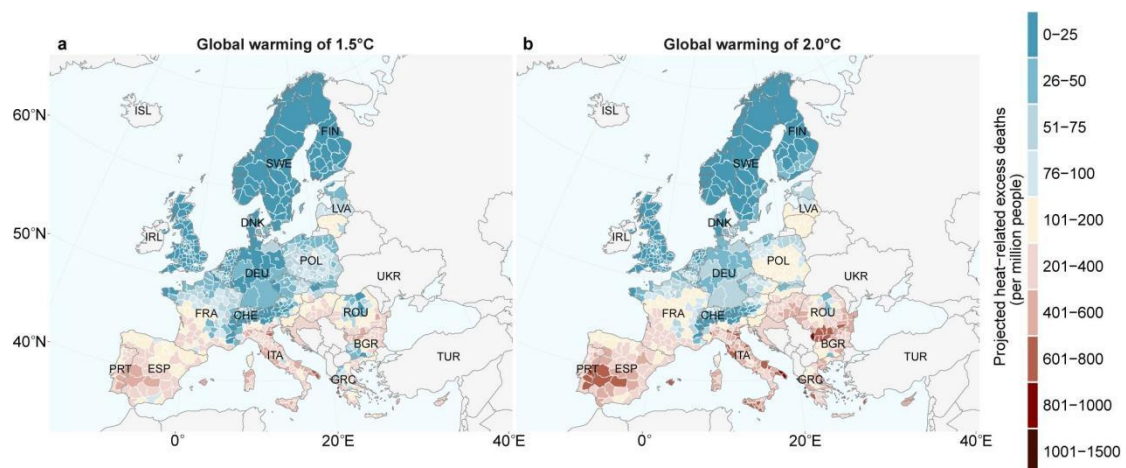
Supplementary Table 6. Number of deaths attributed to moderate and extreme heat among three age groups (0-14, 15-64, 65+) from 2010 to 2022.

		Humidex (°C)	Moderate heat		Extreme heat	
Age	Year	Mean	Deaths	(95% CI)	Deaths	(95% CI)

0-14	2010	20.9	26	0-172	28	0-97
15-64			647	329-1063	980	602-1373
65+			5101	4251-5998	5700	5001-6408
0-14	2011	21.4	21	0-133	9	0-31
15-64			796	483-1186	372	230-522
65+			6918	5998-7892	5700	5001-6408
0-14	2012	21.8	29	0-173	24	0-80
15-64			1047	483-1186	973	619-1342
65+			9364	8042-10,748	7144	6349-7951
0-14	2013	21.3	29	0-168	34	0-118
15-64			980	565-1482	1050	632-1482
65+			8766	7534-10,047	8288	7283-9307
0-14	2014	20.7	23	0-145	9	0-30
15-64			725	412-1155	355	187-531
65+			6365	5387-7431	2367	2044-2696
0-14	2015	21.1	38	0-224	90	0-297
15-64			1512	911-2250	2607	1680-3572
65+			13,123	11,322-15,052	22,937	20,349-25,577
0-14	2016	21.6	45	0-247	30	0-111
15-64			1586	959-2358	1089	673-1526
65+			13,964	12,064-16,029	8882	7815-9973
0-14	2017	21.9	41	0-251	36	0-120
15-64			1793	1074-2665	1546	1013-2106
65+			15,995	13,794-18,335	13,259	11,764-14,786
0-14	2018	22.7	46	0-256	69	0-239
15-64			1740	1051-2578	2043	1285-2837
65+			15,308	13,215-17,593	18,298	16,149-20,488
0-14	2019	22.4	49	0-277	60	0-221
15-64			1960	1190-2886	2124	1357-2925
65+			17,523	15,149-20,069	19,613	17,371-21,898
0-14	2020	20.8	35	0-225	46	0-166
15-64			1649	977-2482	1497	957-2069
65+			15,518	13,316-17,926	15,230	13,442-17,061
0-14	2021	22.7	36	0-192	35	0-126
15-64			1683	1046-2427	2132	1382-2921
65+			15,112	13,131-17,184	17,978	15,956-20,049
0-14	2022	22.7	44	0-278	38	0-135
15-64			2061	1248-3081	1999	1277-2756
65+			21,530	18,554-24,750	20,733	18,391-23,125

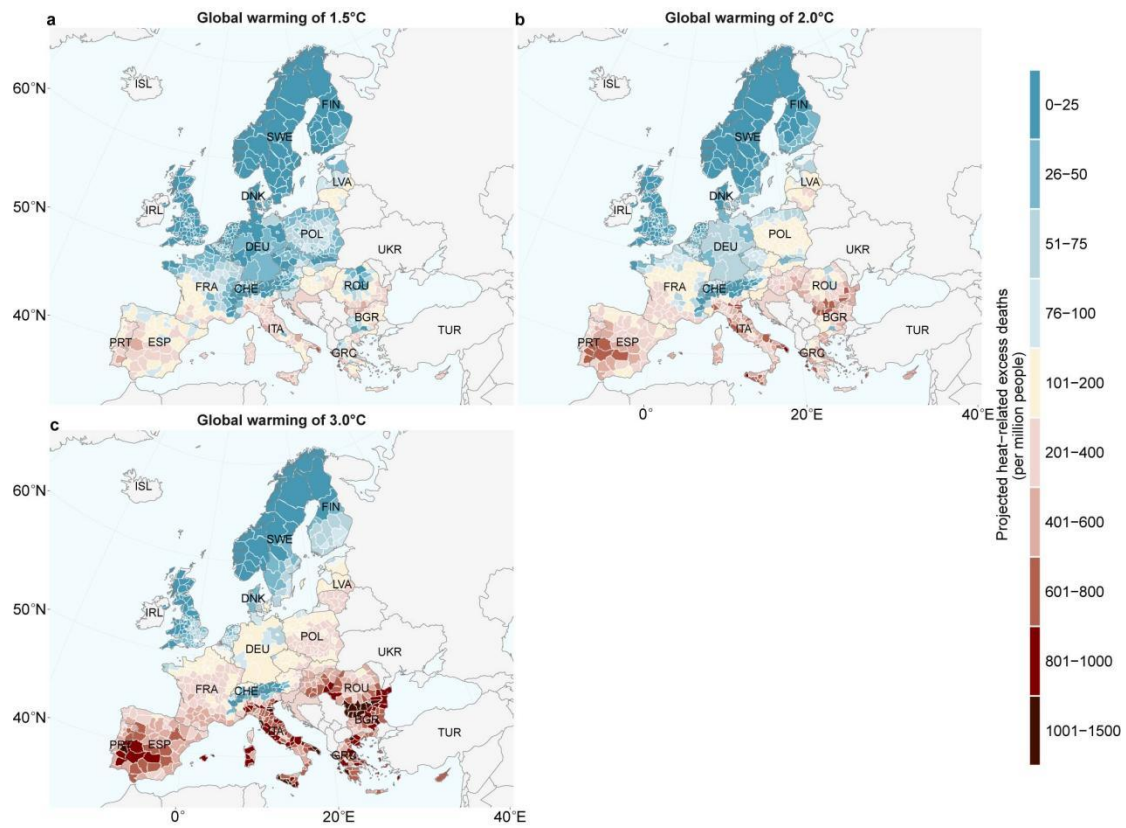


Supplementary Fig 10. Geographic distributions of expected annual average heat-related excess deaths per million people under the 1.5°C level of global warming. Results are based on population-climate scenario SSP1-2.6. Regions with missing data are shaded in grey.

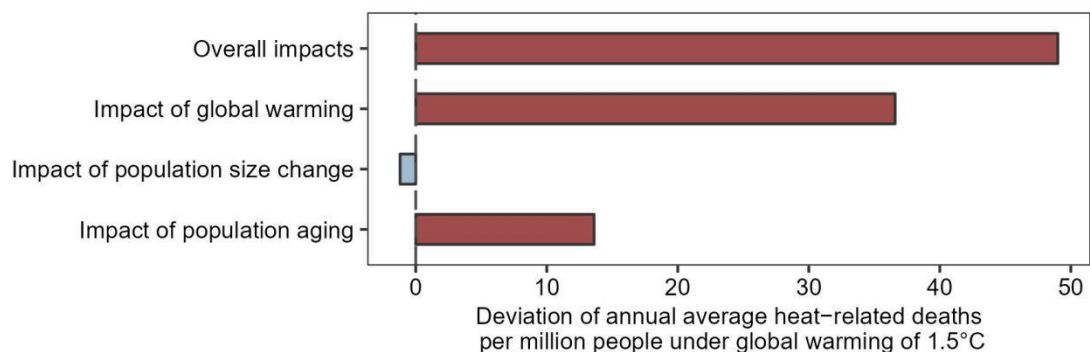


Supplementary Fig 11. Geographic distributions of expected annual average heat-related excess deaths per million people under the 1.5°C (a), and 2.0°C (b) level of global warming. Results are based on population-climate scenario SSP2-4.5.

Regions with missing data are shaded in grey.

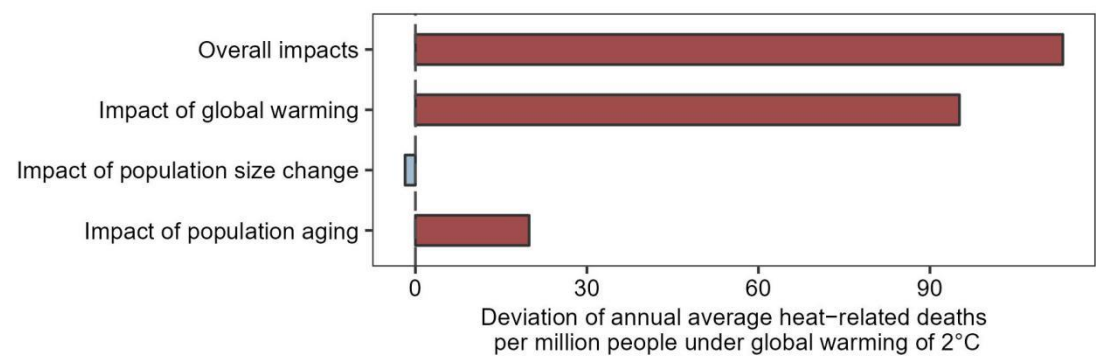


Supplementary Fig 12. Geographic distributions of expected annual average heat-related excess deaths per million people under the 1.5°C (a), 2.0°C (b), and 3.0°C (c) level of global warming. Results are based on population-climate scenario SSP3-7.0. Regions with missing data are shaded in grey.

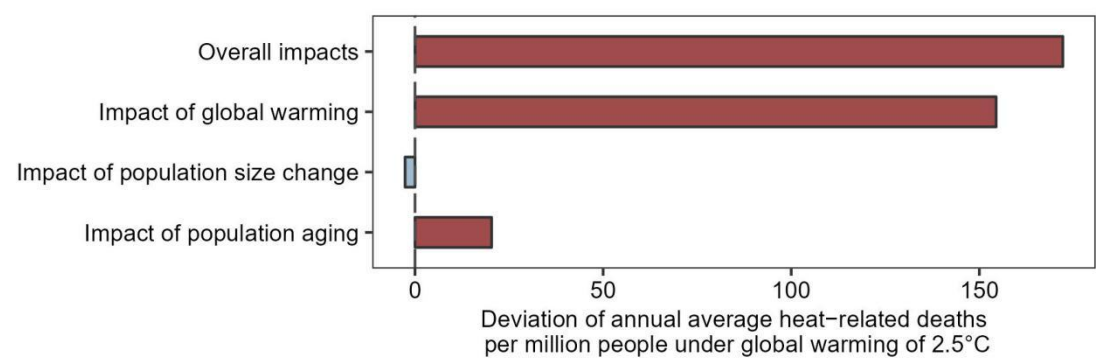


Supplementary Fig 13. The annual average number of heat-related excess deaths due to the changes in climate, population size, and age structure under the 1.5°C

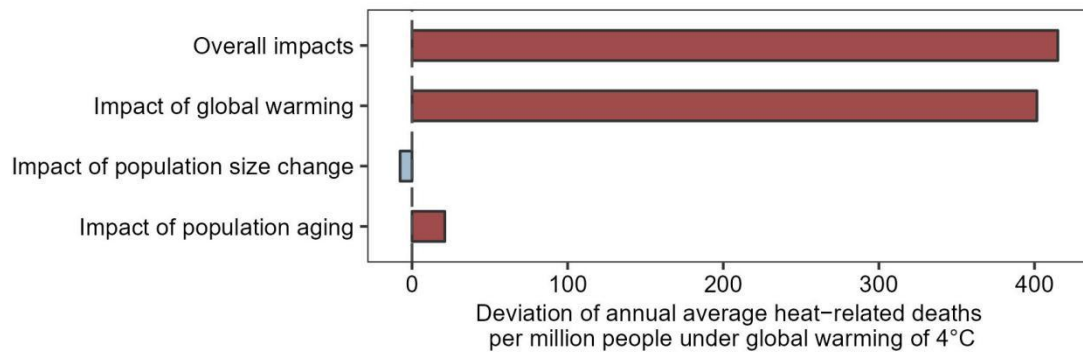
level of global warming. Positive effects are shown in red, while negative effects are shown in blue.



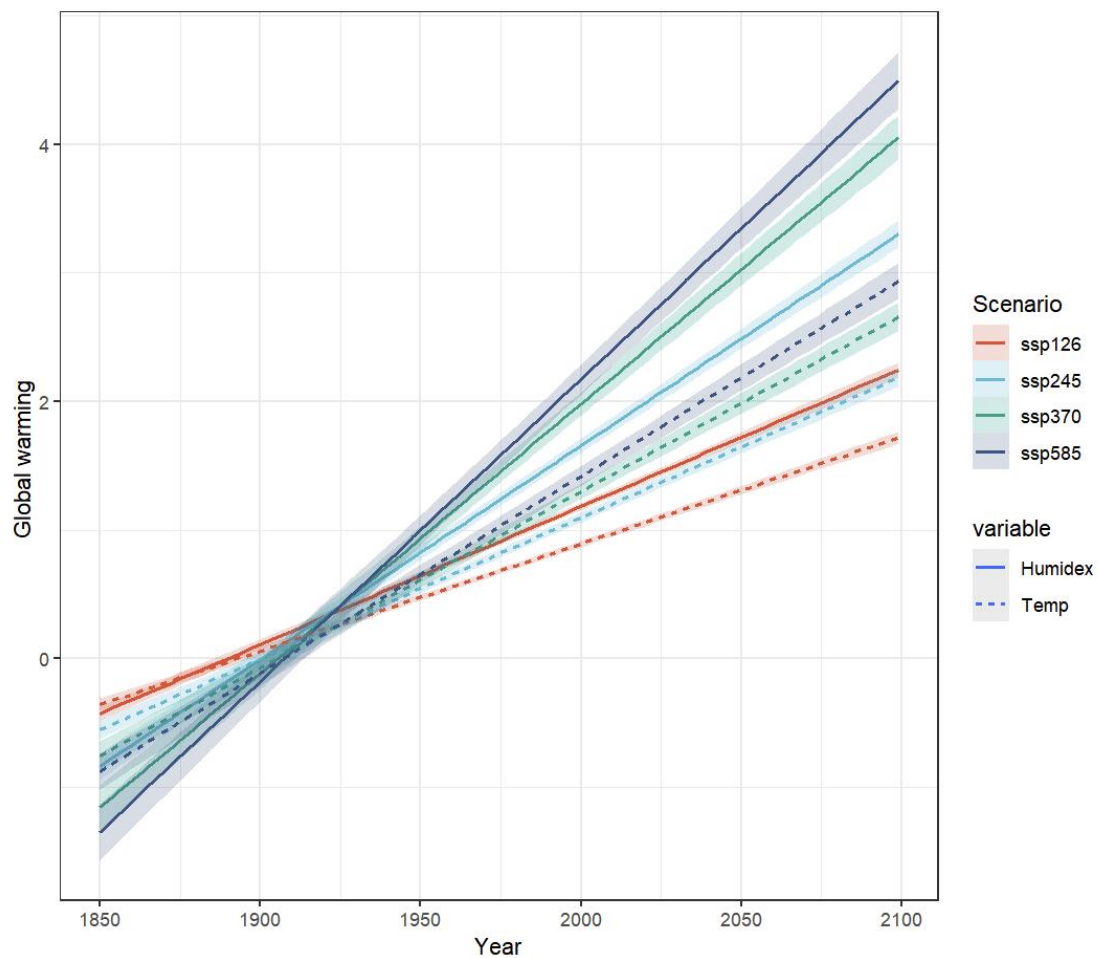
Supplementary Fig 14. The annual average number of heat-related excess deaths due to the climate change, population size, and age structure under the 2.0°C level of global warming. Positive effects are shown in red, while negative effects are shown in blue.



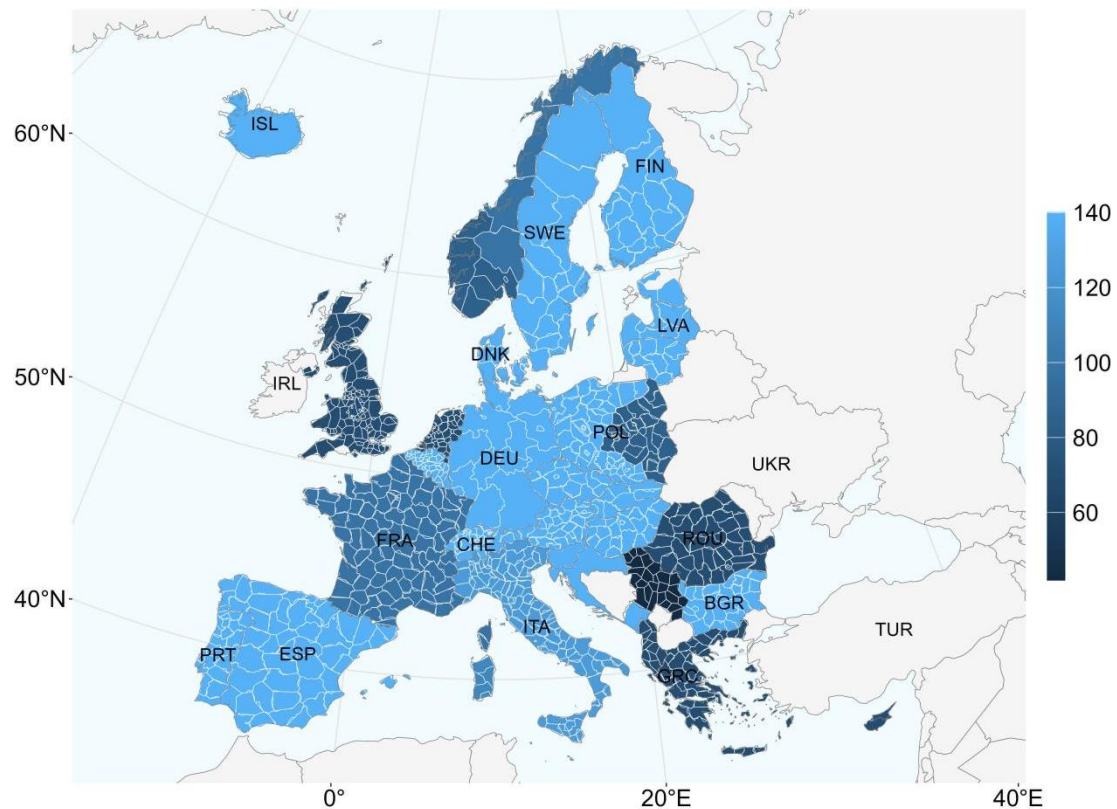
Supplementary Fig 15. The annual average number of heat-related excess deaths due to the climate change, population size, and age structure under the 2.5°C level of global warming. Positive effects are shown in red, while negative effects are shown in blue.



Supplementary Fig 16. The annual average number of heat-related excess deaths due to the climate change, population size, and age structure under the 4.0°C level of global warming. Positive effects are shown in red, while negative effects are shown in blue.



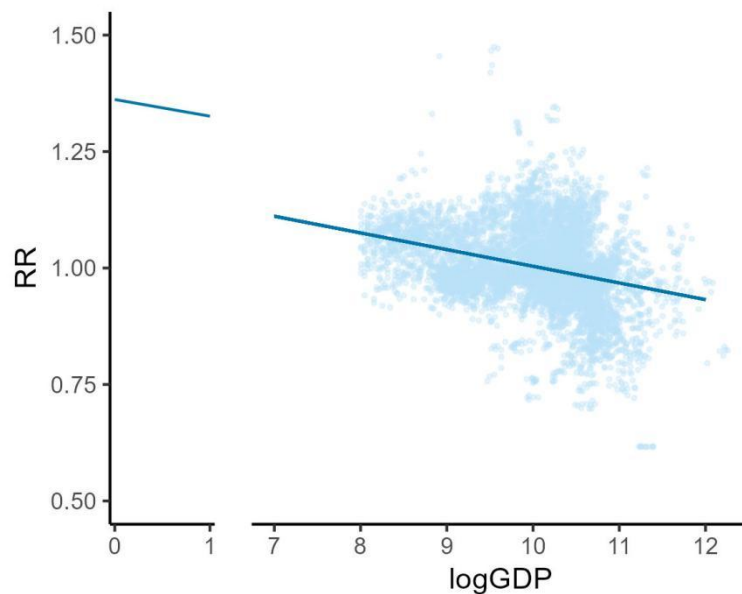
Supplementary Fig 17. Global trends in Humidex and air temperature over time under four scenarios, including SSP1-2.6 (red), SSP2-4.5 (blue), SSP3-7.0 (green), SSP5-8.5 (grey). Solid line represents Humidex, dashed line represents air temperature.



Supplementary Fig 18. Sample sizes of each region used for model training. Regions with missing data are shaded in grey. Lighter blue indicates a larger sample size.

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. Each point indicates the heat-related risk in a specific region under its observed GDP per capita for a specific year. The linear relationship between relative risk and the logarithm of GDP per capita was estimated using ordinary least squares.

Supplementary Note 7: Exploration of Adaptation Changes

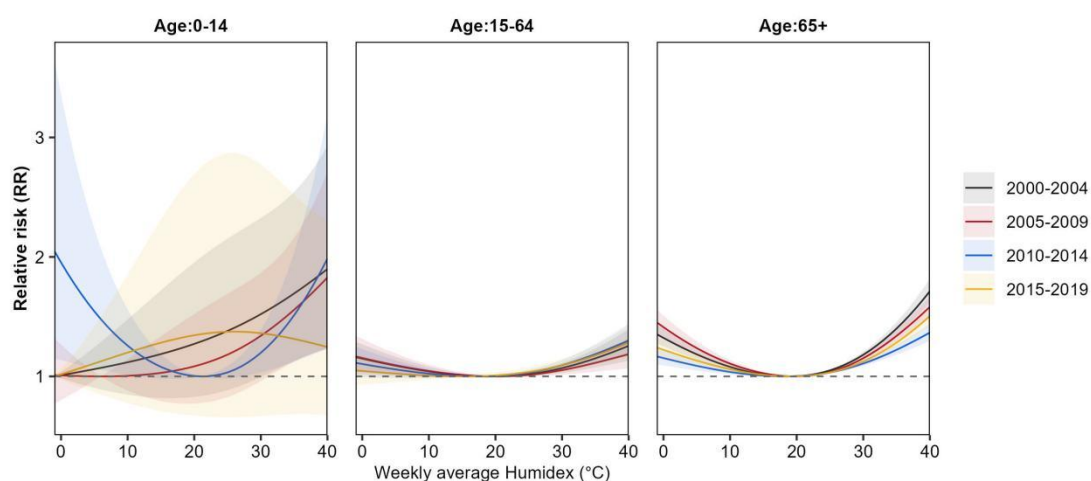
Recent studies ^{6,7} have demonstrated the existence of adaptation processes using historical data, which manifest in two main ways: (1) increased minimum mortality temperature, and (2) flattened RR curves. Interestingly, however, we also noticed that some studies ⁸ have pointed out that these adaptation processes are not always linear and may not unfold uniformly across regions or populations. To explore this further, we conducted a supplementary analysis of historical data (2000–2019) for 19 countries and 359 regions, focusing on trends in adaptation. Specifically:

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.

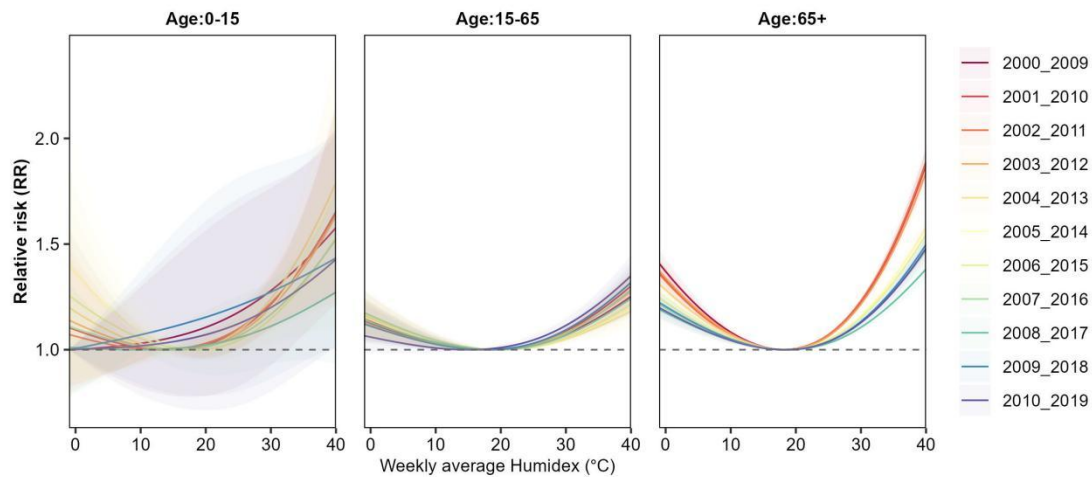
Our findings (Supplementary Fig. 20) indicated a general trend of adaptation, with increasing MMTs and flattening RR curves across different age groups. However, we also observed notable variability, including the anomalous result for the 2010-2014 period, where both the MMH and RR slope exhibited patterns 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 Fig. 21). Results show that the variation in MMH (Supplementary Figs. 22) and the RR

slopes (Supplementary Fig. 23) 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 ⁹ . which cannot be assumed to occur at a constant rate. To quantify the potential impact of adaptation processes on future projections, we recalculated the annual heat-related deaths per million people at different levels of global warming using the heat-mortality curves estimated from 10-year moving windows (Supplementary Table 7). 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.

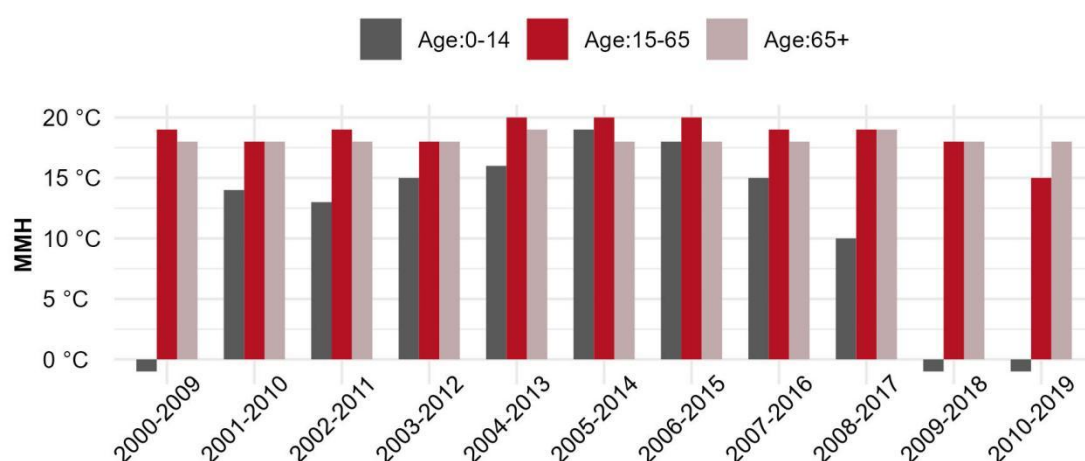


Supplementary Fig 20. Cumulative relative risk-weekly Humidex response curves for three age groups, presented for every 5 years: children (aged 0–14 years), the working-age population (aged 15–64 years), and the elderly (aged 65

years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group.

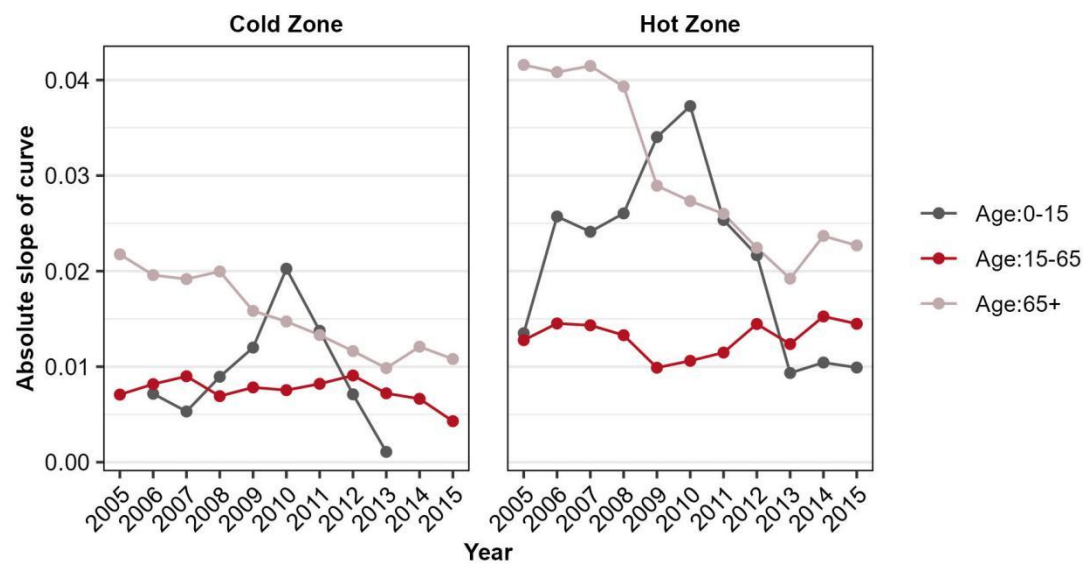


Supplementary Fig 21. Cumulative relative risk-weekly Humidex response curves for three age groups, presented for a 10-year sliding window: children (aged 0–14 years), the working-age population (aged 15–64 years), and the elderly (aged 65 years or above). The cumulative relative risk of death (lines) with a corresponding 95% confidence interval (shadings) is shown for each age group.



Supplementary Fig 22. Variation in minimum mortality Humidex (MMH) across

three age groups: 0-14 (grey), 15-65 (red), 65+ (pink). The data are analyzed using a sliding 10-year window. Each column indicates the MMH estimated by data across each 10-year window in a specific age group.



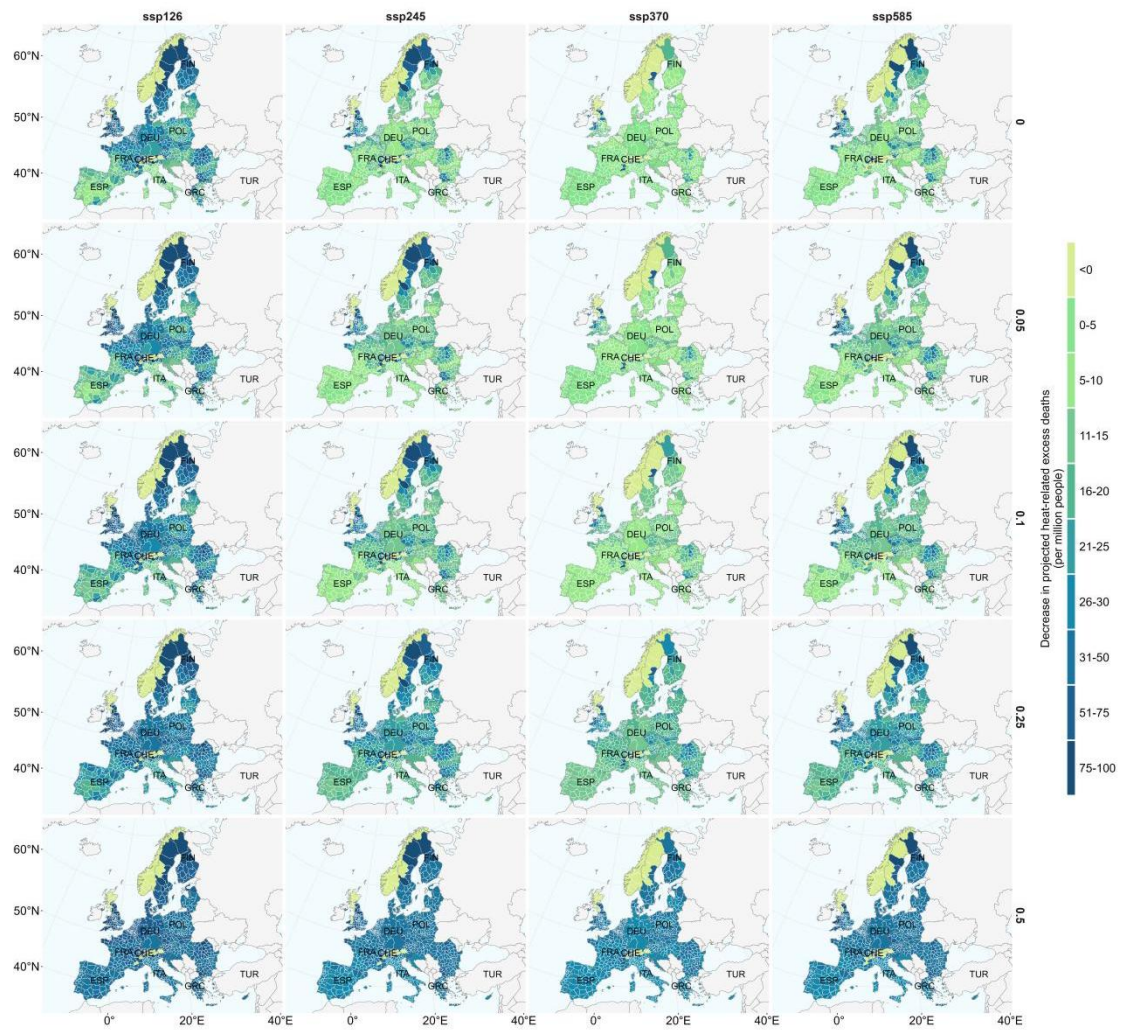
Supplementary Fig 23. Variation of the absolute slope of the cumulative relative risk-weekly Humidex response curves for three age groups. The input data slides in a 10-year window. The data are analyzed using a sliding 10-year window, where the horizontal axis represents the midpoint of each 10-year 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 7. Annual average heat-related excess deaths per million people under 1.5°C, 2.0°C, 3.0°C, and 4.0°C 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.

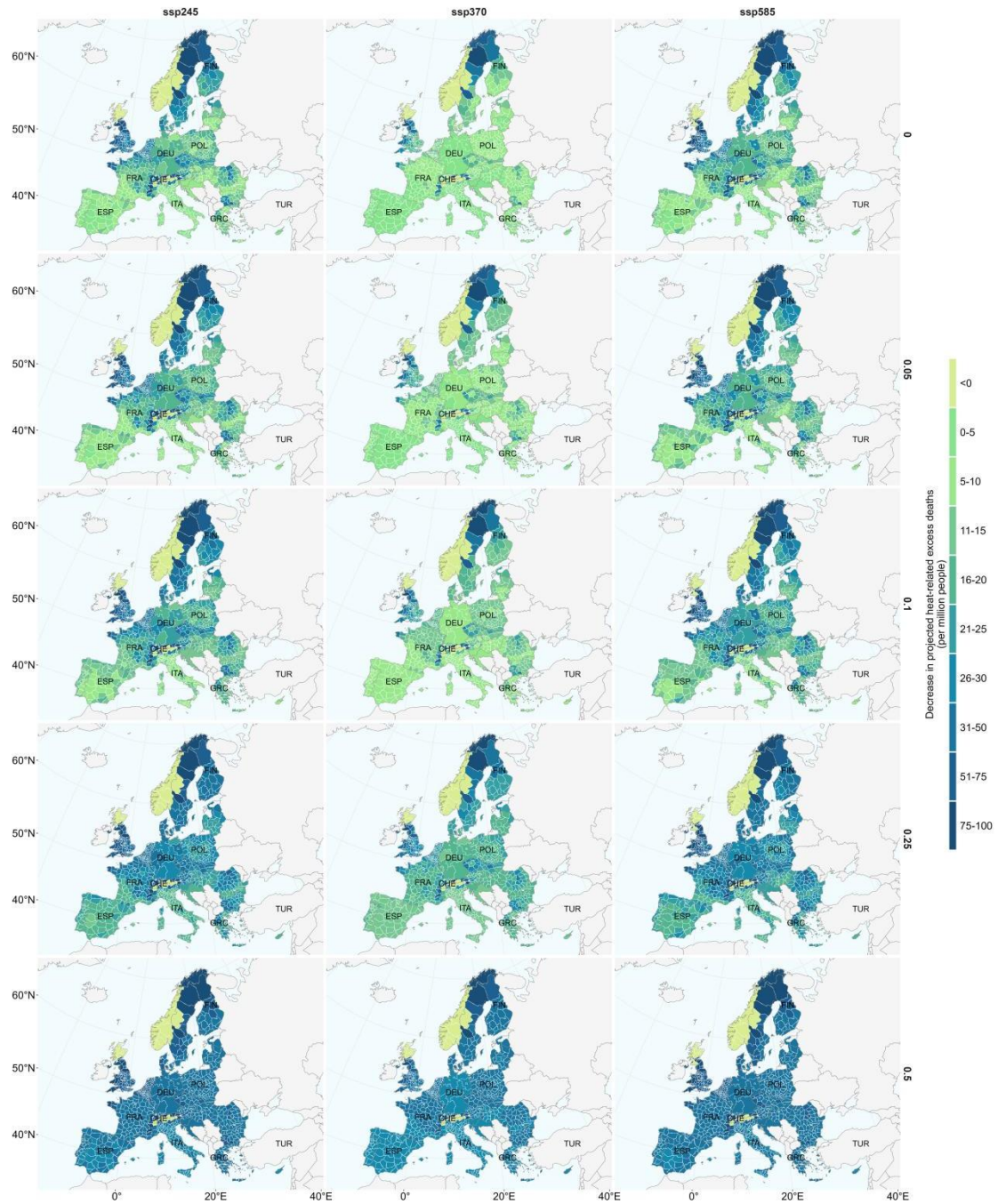
Please note that the estimates focus on 18 countries with 359 regions, where data are available from 2000 to 2019.

War mi ng le ve l	Region	Cumulative heat-related excess deaths from 2024 to 2100 per million people (18 countries)										Model: 2010-2019
		Model: 2000-2009	Model: 2001-2010	Model: 2002-2011	Model: 2003-2012	Model: 2004-2013	Model: 2005-2014	Model: 2006-2015	Model: 2007-2016	Model: 2008-2017	Model: 2009-2018	
1. 5 °C	East ern Euro pe	237.6 (160.2-333.0)	242.9 (164.4-339.3)	244.8 (165.7-341.8)	232.5 (157.0-325.1)	139.1 (87.1-204.3)	153.2 (99.2-219.8)	164.5 (111.3-229.3)	150.3 (101.6-209.8)	123.4 (83.3-172.5)	158.5 (107.2-221.2)	101.6 (51.6-173.4)
	Nort hern Euro pe	66.0 (50.0-89/2)	65.1 (48.5-89.0)	65.5 (48.5-89.6)	62.8 (47.2-85.3)	32.9 (23.3-47.1)	37.3 (26.6-52.7)	45.4 (34.2-61.5)	41.4 (31.5-55.6)	34.9 (27.0-64.4)	42.4 (32.2-73.3)	19.4 (9.6-33.9)
	Sout hern Euro pe	373.8 (282.6-475.9)	379.1 (278.3-481.4)	386.5 (293.2-490.5)	366.6 (277.5-466.1)	237.7 (174.2-307.8)	254.2 (189.6-325.2)	262.0 (119.2-331.3)	234.1 (177.6-296.4)	193.6 (146.6-245.4)	247.8 (187.8-314.2)	188.7 (124.3-263.1)
	Wes tern Euro pe	111.3 (75.5-161.8)	113.4 (77.0-164.9)	115.7 (78.5-168.2)	108.7 (73.8-158.2)	59.2 (36.3-93.4)	68.4 (43.5-104.2)	79.2 (53.8-114.8)	70.4 (47.8-102.1)	57.8 (39.2-83.9)	74.4 (50.5-108.0)	37.4 (17.4-67.5)
	Euro pe	199.9 (143.4-270.0)	203.1 (146.0-274.0)	206.5 (148.5-278.5)	195.6 (140.4-263.9)	118.7 (80.8-166.4)	130.3 (90.7-179.4)	140.2 (101.0-188.4)	125.8 (90.5-169.2)	103.7 (74.5-139.6)	132.9 (95.5-178.9)	110.1 (66.2-166.9)
2. 0 °C	East ern Euro pe	388.6 (269.4-518.9)	395.1 (274.9-525.9)	398.9 (277.8-530.8)	378.6 (263.0-504.8)	239.7 (158.4-328.5)	257.8 (174.6-347.8)	267.4 (186.4-354.7)	242.3 (168.7-321.7)	199.0 (138.3-264.5)	255.0 (177.4-338.8)	200.5 (113.7-295.4)
	Nort hern Euro pe	86.1 (63.5-113.8)	86.1 (62.8-114.3)	86.8 (63.3-115.4)	82.4 (60.5-109.2)	44.3 (30.8-61.8)	50.4 (35.6-69.3)	59.2 (43.6-78.2)	53.4 (39.6-70.2)	44.4 (33.3-61.1)	55.1 (40.7-72.7)	31.5 (18.0-50.7)
	Sout hern Euro pe	539.1 (429.9-664.4)	544.6 (435.2-669.7)	555.5 (444.2-682.6)	527.7 (421.3-649.5)	350.0 (274.3-435.8)	369.1 (292.7-455.4)	375.4 (301.0-459.2)	334.3 (267.7-409.4)	276.7 (221.3-339.0)	354.1 (283.1-434.5)	299.0 (218.7-391.3)
	Wes	160.4	163.4	166.8	156.7	92.0	103.1	113.7	101.0	82.9	106.8	68.8

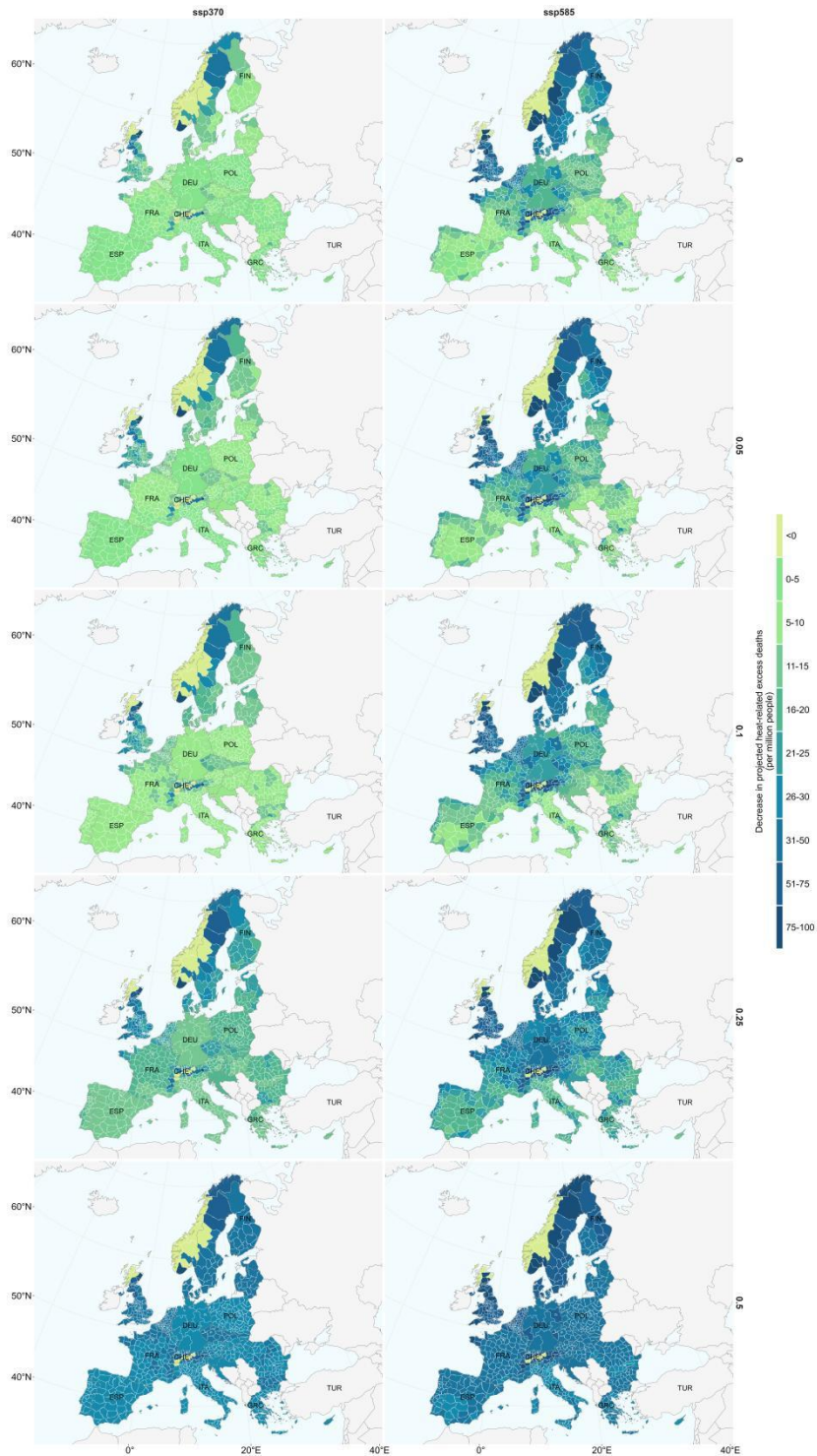
3. 0 °C	tern	(108.4-	(110.7-	(113.1-	(106.0-	(56.8-1	(66.2-1	(77.2-1	(68.4-1	(56.0-1	(72.3-1	(36.0-1
	Euro	221.2)	224.8)	229.2)	216.0)	33.9)	46.4)	56.2)	39.1)	14.3)	47.0)	09.7)
	pe											
	Euro	296.5	300.6	305.8	289.7	183.7	197.7	206.8	184.9	152.4	195.3	187.5
	pe	(219.7-	(223.1-	(227.2-	(214.8-	(131.1-	(143.8-	(153.9-	(137.4-	(113.1-	(145.0-	(124.2-
		384.3)	388.7)	395.2)	374.9)	243.6)	258.8)	266.3)	238.4)	196.7)	252.2)	260.0)
	East	696.9	704.5	711.2	677.0	448.4	469.4	472.8	428.0	351.7	451.1	415.3
	ern	(506.7-	(514.1-	(519.3-	(493.4-	(319.4-	(339.7-	(347.3-	(314.4-	(258.2-	(330.8-	(281.7-
	Euro	877.0)	884.5)	892.6)	850.4)	569.3)	590.4)	590.3)	534.2)	439.1)	-564.3)	531.5)
	pe											
	Nort	137.4	138.8	140.4	132.0	75.2	85.0	94.4	84.2	69.2	87.5	65.9
	hern	(103.3-	(103.9-	(105.1-	(99.1-1	(54.1-1	(62.0-1	(71.0-1	(63.6-1	(52.5-9	(66.0-1	(42.5-9
	Euro	184.1)	186.0)	188.2)	76.9)	06.2)	17.4)	26.2)	12.4)	2.3)	17.1)	9.4)
	pe											
4. 0 °C	Sout	774.9	779.5	794.0	756.6	509.7	528.4	530.8	473.1	391.8	503.7	479.0
	hern	(640.0-	(645.0-	(657.4-	(625.7-	(419.1-	(437.4-	(441.6-	(393.5-	(325.8-	(418.1-	(382.7-
	Euro	922.7)	926.9)	943.8)	900.1)	607.6)	626.5)	626.8)	558.9)	462.8)	596.6)	582.7)
	pe											
	Wes	276.1	280.0	285.3	269.4	171.5	185.2	194.3	172.9	142.2	182.8	155.4
	tern	(205.7-	(209.2-	(213.5-	(200.8-	(122.4-	(135.0-	(145.4-	(129.2-	(106.0-	(136.4-	(100.9-
	Euro	353.3)	357.4)	364.0)	344.4)	225.6)	240.2)	247.5)	220.5)	181.6)	233.5)	217.7)
	pe											
	Euro	469.7	474.2	481.8	457.7	301.1	317.0	323.2	289.2	238.5	306.3	331.6
	pe	(364.9-	(369.1-	(375.5-	(356.0-	(229.8-	(244.8-	(252.9-	(226.0-	(186.3-	(239.1-	(245.3-
		580.6)	585.1)	594.3)	-565.2)	376.2)	392.8)	396.9)	355.3)	293.1)	377.0)	419.3)
	East	1161.1	1167.3	1178.3	1124.1	755.6	776.4	773.7	697.8	573.2	740.8	703.1
	ern	(930.6-	(937.7-	(946.6-	(902.2-	(605.8-	(627.0-	(627.3-	(566.2-	(465.6-	(598.8-	(564.5-
	Euro	1467.8)	1473.2)	1486.5)	1418.2)	955.0)	975.3)	968.7)	872.5)	716.2)	928.3)	887.7)
	pe											
	Nort	211.1	212.9	215.8	202.5	122.8	135.7	144.3	128.1	105.0	133.7	115.8
	hern	(159.7-	(161.3-	(163.5-	(153.3-	(89.5-1	(100.5-	(109.6-	(97.2-1	(79.8-1	(101.4-	(82.1-1
	Euro	275.1)	277.1)	280.7)	263.7)	65.4)	179.7)	187.2)	66.3)	36.4)	173.7)	57.4)
	pe											
4. 0 °C	Sout	1200.9	1202.6	1223.6	1168.4	785.0	802.5	801.2	713.2	589.7	766.0	767.3
	hern	(1022.0	(1024.7	(1043.1	(995.6-	(670.4-	(688.1-	(688.0-	(612.6-	(506.9-	(656.2-	(650.78
	Euro	-1404.6	-376.8)	-1429.3	1356.0)	914.2)	931.3)	929.2)	826.5)	682.7)	-890.2)	96.2)
	pe	)		)								
	Wes	466.0	469.9	478.3	453.3	302.6	318.4	323.5	288.1	237.5	305.5	217.3
	tern	(372.7-	(376.8-	(383.7-	(363.0-	(238.4-	(253.4-	(269.4-	(231.6-	(190.8-	(245.3-	(241.3-
	Euro	581.5)	585.6)	595.7)	565.3)	382.4)	398.8)	401.4)	357.5)	294.8)	379.7)	433.5)
	pe											
	Euro	739.8	743.3	754.9	718.7	480.5	497.2	499.7	446.3	368.0	475.8	545.4
	pe	(607.6-	(611.5-	(621.3-	(590.9-	(393.4-	(409.6-	(413.7-	(369.5-	(304.8-	(393.1-	(444.4-
		902.0)	905.1)	918.8)	875.1)	587.4)	604.4)	604.7)	539.8)	444.9)	576.6)	667.4)



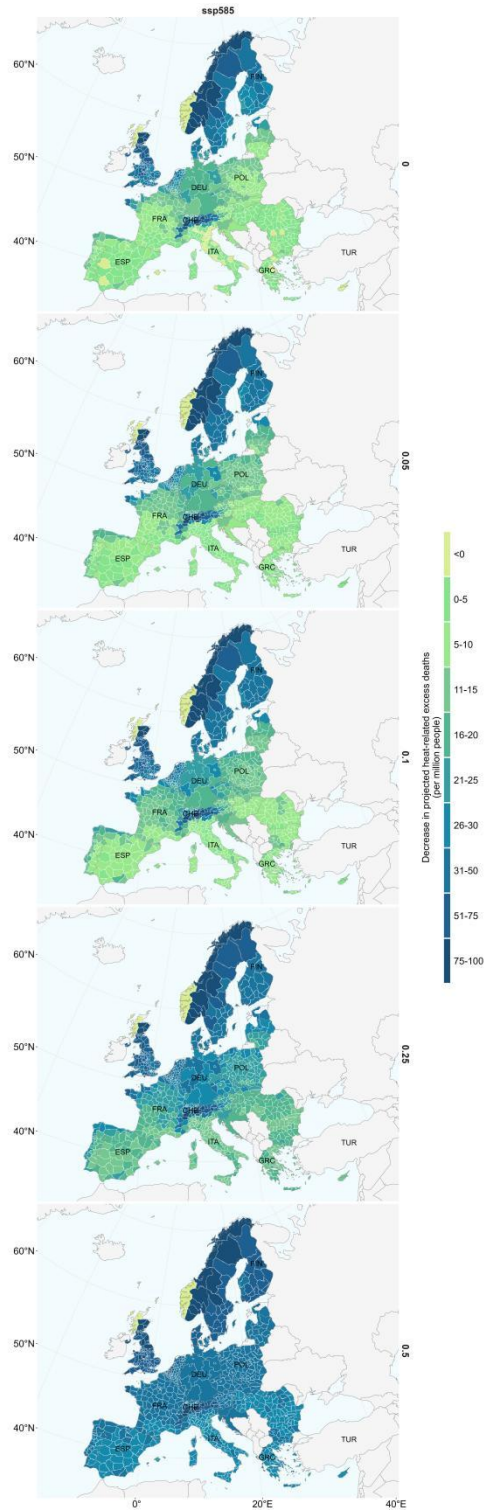
Supplementary Fig 24. Spatial patterns of the decrease in projected heat-related excess deaths at 1.5°C of global warming under five physiological-socioeconomic adaptation scenarios. The darker blue indicates a greater potential for adaptation to mitigate increases in heat-related mortality.



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. The darker blue indicates a greater potential for adaptation to mitigate increases in heat-related mortality.



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. The darker blue indicates a greater potential for adaptation to mitigate increases in heat-related mortality.



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. The darker blue indicates a greater potential for adaptation to

mitigate increases in heat-related mortality.

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