Trends in population exposure to compound extreme-risk temperature and air pollution across 35 European countries: a modelling study

Zhao-Yue Chen, Hicham Achebak, Hervé Petetin, Raúl Fernando Méndez Turrubiates, Yuming Guo, Carlos Pérez García-Pando, Joan Ballester

Summary

Background Despite ongoing efforts to reduce air pollution, the complex relationship between air pollution and climate change presents additional multifaceted challenges. The spatiotemporal co-occurrence of extreme temperatures and air pollution episodes remains understudied. Furthermore, current studies typically employ uniform temperature thresholds across broad areas, overlooking regional differences in health vulnerability. We aim to present a comprehensive assessment of extreme temperatures and air pollution, and to incorporate location-specific risk thresholds.

Methods In this time series modelling study we analysed the changes in extreme-risk temperature (ERT) days for heat and cold in Europe from Jan 1, 2003 to Dec 31, 2020, considering time-varying temperature–mortality relationships based on regional mortality data (from Eurostat) from 35 European countries (543 million people). We used daily estimates of $PM_{2·5}$, PM_{10}, NO_2, and O_3 concentrations from quantile machine learning estimations at 0·1-degree to identify of heat-compound and cold-compound days co-occurring with air pollution levels exceeding WHO guidelines.

Findings Cold-related mortality risk decreased over the study period across Europe, and adaptation to heat-related mortality was less pronounced. Between 2003 and 2020, annual cold-ERT days had decreased by 20·7 days per decade and annual heat-ERT days increased by 2·8 days per decade. Southeastern Europe had higher frequencies of both heat-ERT and cold-ERT days. Heat-O_3 events were the only increasing heat-compound episodes, with 2·6 more days per decade. Conversely, cold-compound episodes decreased by 15·2 days per decade with cold-$PM_{2·5}$ events remaining the predominant threat. Around 349 million Europeans were exposed to at least 1 cold-compound day annually, and around 295 million experienced at least one heat-compound day, including nearly 235 million affected by heat-O_3 compound episodes.

Interpretation By identifying region-specific risk thresholds, our study reveals spatial disparities and changes in ERT events, particularly when coupled with air pollution. These findings are essential for developing targeted adaptation strategies, facilitating subsequent health assessments, and implementing effective measures to safeguard public health.

Funding European Research Council and Ministerio de Ciencia e Innovación.

Lancet Planet Health 2025; 9: e384–96

Published Online April 9, 2025 https://doi.org/10.1016/S2542-5196(25)00048-8

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Introduction

Extreme temperature events and air pollution stand out as two major challenges that imperil global public health.[1,2] Exposure to high temperatures can trigger a series of detrimental health consequences, including heat exhaustion, heatstroke, hyperthermia, and exacerbation of underlying conditions such as cardiovascular disease, respiratory disease, and diabetes.[3] Exposure to cold can lead to hypothermia, frostbite, and cardiovascular or respiratory problems.[4] Over 5 million global deaths per year were found to be associated with non-optimal temperatures between 2000 and 2019, accounting for 9·43% of all deaths worldwide.[5] Because of global warming, the escalating frequency and intensity of extreme heat events pose a challenging threat to human health. Over the past two decades, heat-related mortality has become a major concern in Europe, with over 70 000 excess deaths in the summer of 2003[6] and 60 000 heat-related deaths in 2023 heatwaves.[7] Additionally, the warming rate in Europe exceeds the global average,[8] and projections have indicated a continuous rise in heat-attributable mortality.[9] Air pollution, despite continuous reduction efforts and overall decreasing trends,[10] remains a pressing concern in Europe, contributing to respiratory and cardiovascular health issues. In 2021 alone, the European Environment Agency linked over 253 000 premature deaths to fine particulate matter ($PM_{2·5}$), 52 000 deaths to NO_2, and 22 000 deaths to O_3 surpassing limits recommended by WHO.[11] Additionally, an increase in ozone-associated mortality was reported among European urban population from 2000 to 2017.[12] These figures highlight

Research in context

Evidence before this study

We searched PubMed from database inception to Oct 11, 2024, to identify the publications related to co-occurrence of extreme temperatures and high air pollution episodes in Europe without language restrictions, using the terms "(trend) AND ((temperature) OR (heat) OR (cold)) AND ((compound) OR (co-exposure) OR (interaction)) AND (air pollution) AND (Europe)". This search yielded 36 publications, of which 15 were relevant to our analysis. Most published literature analysed either extreme heat-compound or cold-compound events with air pollution separately, covering small areas or individual countries, and often focusing on compound events or interactions with single pollutant rather than multiple pollutants. We did not find any published literature that analysed the trend, spatial, and composition pattern of extreme heat-air-pollution or cold-air-pollution compound events in broad areas. The spatiotemporal pattern of these compound events remains unclear, largely due to the limitations of data. Current studies primarily rely on pollution data collected from ground-based monitoring stations, which are concentrated in urban areas and face inconsistent data availability over decades. This gap limits our understanding of compound events across the entire population and hinders analysis of multi-decadal changes. Furthermore, current studies often employ uniform thresholds to define extreme temperature events, ignoring regional differences in health vulnerability.

Added value of this study

To our knowledge, this study presents the first quantitative assessment of trends, spatial patterns, and composition of extreme heat-air-pollution or cold-air-pollution compound events in Europe. To better capture the actual diverse vulnerability in the whole continent, we redefined extreme temperature thresholds as extreme-risk temperatures (ERTs), based on location-specified exposure–response associations derived from epidemiological models using mortality databases representing over 543 million people in 35 European countries. We also incorporated temporal changes in mortality risks to reflect adaptation over time. Then, we assessed combined threats of extreme temperatures and main air pollution episodes using 0·1-degree population-weighted estimates of $PM_{2·5}$, PM_{10}, NO_2, and O_3 concentrations. During 2003–20, we estimated that in Europe the mean annual heat-ERT days increased by 2·8 days per decade, heat-compound days increased 1·5 days per decade, cold-ERT days decreased by 20·7 days per decade, and cold-compound days decreased 15·2 days per decade. Southeastern Europe had higher frequencies of both heat-ERT and cold-ERT days, despite warmer climatological conditions. Around 349 million Europeans were exposed to at least 1 cold-compound day annually, and 295 million experienced at least 1 heat-compound day, including nearly 235 million affected by heat-O_3 compound episodes. These findings provide a deeper understanding of spatial disparities and dynamic changes in heat or cold-ERT events across Europe's nomenclature of territorial units for statistics-3 regions over the past two decades.

Implications of all the available evidence

Our study reveals a double-edged impact of global warming in Europe: reduced cold-ERT days but increased heat-ERT days, with clear spatial heterogeneity in region-specific health risk thresholds. Cold-related mortality risk appeared to decrease over time in Europe, and the adaptation to heat-related mortality is less pronounced. Rising summer temperatures are likely to exacerbate vulnerabilities to extreme heat and associated compound episodes, particularly in lower-latitude European regions and more polluted areas like eastern Europe. To better protect vulnerable populations, it is imperative to accelerate progress in current heat adaptation strategies and heat health action planning. Our research also highlights limitations in current air quality management, particularly in addressing heat-O_3 compound episodes exacerbated by global warming. These findings call for collaborative approaches between climate change and air pollution policy makers to tackle both primary and secondary pollutants, potentially breaking the cycle of heat-driven ozone formation, leading to a healthier future for Europeans. Overall, this comprehensive study of extreme temperature and air pollution in Europe over the past two decades supports evidence-based policy implementation for a healthier environment, emphasising the importance of integrated strategies to address these interlinked challenges.

the ongoing and serious impact of both factors on public health in Europe. Moreover, the health impacts from extreme temperatures and air pollution are not fully independent, and their interplay can further amplify adverse health impacts.[2,13–16] For instance, during hot weather, increased breathing rates can lead to higher pollutant inhalation, making individuals more susceptible to air pollution-related respiratory issues.[17,18] Simultaneously, high temperatures can trigger heat-related illnesses, with poor air quality worsening these conditions by imposing additional strain on the cardiovascular and respiratory systems, impairing the body's ability to effectively dissipate heat.[1,19] Previous studies have documented this synergistic effect of heat and air pollution on mortality.[14] In cold weather, cold air itself can be an irritant to the airways, and if this cold air is polluted, it can worsen respiratory symptoms and increase the risk of acute respiratory distress, especially for individuals with pre-existing respiratory conditions.[1,18]

Beyond their potential synergistic health impacts, extreme temperature events also influence the formation of air pollution. Rising summer temperatures and stronger sunlight can intensify the formation of ozone

and other secondary air pollutants. Additionally, extreme heat increases the likelihood and severity of wildfires,[20] and accelerates the release of natural volatile organic compounds from vegetation.[21] Furthermore, during extreme heat or cold events, the heightened demand for cooling or heating systems also contributes to increased emissions from power plants and other energy sources.[2] These factors collectively increase the likelihood of co-occurring extreme temperatures and air pollution, posing a greater threat to public health. However, understanding of this co-occurrence over time remains limited, hindering effective mitigation strategies to protect public health.

Quantifying the temporal evolution of population exposure to extreme temperature events compounded with air pollution faces multiple challenges. On the one side, current studies tend to define extreme heat and cold using uniform thresholds or quantile-defined measures,[19,22,23] often overlooking variations in specific health risks across regions and populations. Socio-economic disparities, the distribution of vulnerable populations, and available climate adaptation measures can influence health outcomes when exposed to similar temperature conditions.[2,7,24] Therefore, relying on uniform thresholds over different regions might fail to capture the actual threat experienced by diverse populations. Identifying geographical disparities in vulnerability to extreme temperatures is essential to optimise resources for implementing targeted adaptation strategies. On the other side, quantifying the co-occurrence of extreme temperatures and pollution events is hampered by the lack of long term, consistent, and accurate datasets for multiple pollutants at high temporal and spatial resolution.[10]

In this Europe-wide study, we aimed to use, for the first time, an epidemiological-based approach to derive the thresholds of extreme-risk temperature events for 1426 nomenclature of territorial units for statistics (NUTS)-3 regions, based on a mortality database representing over 543 million people in 35 European countries. By identifying these thresholds, we aimed to unlock a deeper comprehension of the spatial disparities and temporal changes in the occurrence of extreme temperature events, particularly when compounded with air pollution.

Methods

Population-weighted regional temperature

In this time series modelling study we processed 0·1-degree ERA5-Land reanalysis data[25] from Jan 1, 2003 to Dec 31, 2020 to derive regional population-weighted means of 2 m temperature over European NUTS-3 regions (n=1426). The representation of temperature extremes in this reanalysis has been widely established in previous studies.[1,2] Population-weighting was performed using the annual gridded population of the world dataset[26] (version 4; appendix p 2).

Population-weighted regional air pollution concentrations

We computed daily regional population-weighted levels for $PM_{2·5}$, PM_{10}, and NO_2, and the maximum daily 8 h mean of O_3 over all NUTS-3 regions in 35 European countries from Jan 1, 2003 to Dec 31, 2020. As previously described,[10] these 0·1-degree daily estimations are based on the quantile machine learning model framework, trained with ground-level measurements from European environment information and observation network (Eionet), covering the period from Jan 1, 2003, to Dec 31, 2020. The model development involved the integration of various data sources, including fine-mode and course-mode aerosol optical depth,[27] climate and air quality reanalysis data,[28,29] and geographical features (eg, land-use, road density,[30] topography, and emission reanalysis data). The spatial five-fold validation results showed good model performance (appendix p 14), with correlation coefficients of 0·80 for $PM_{2·5}$, 0·79 for PM_{10}, 0·79 for NO_2, and 0·90 for O_3, when compared with site observations in Europe. The normalised root mean square error predictions in Europe were 1·84% for $PM_{2·5}$, 2·07% for PM_{10}, 8·99% for NO_2, and 3·35% for O_3. The temporal cross-validation showed consistent model performance over the entire period (appendix p 15).

Mortality data

To understand the relationship between extreme temperatures and mortality across Europe, we collected weekly counts of all-cause mortality (n=83 375 442) from Eurostat,[31] spanning from Jan 1, 2003 to Dec 31, 2019, from 823 European NUTS regions (NUTS-1 [n=31], NUTS-2 [n=2], and NUTS-3 [n=790]; appendix p 4). Even though weekly mortality data are not accessible for all NUTS-3 regions (n=1426) within our study countries, NUTS-1 and NUTS-2 regions typically provide broader regional coverage for all NUTS-3 regions (appendix p 4). Eurostat data do not include non-accidental mortality for our study region. Previous research showed similar and robust response curves for non-accidental and all-cause mortality,[32] suggesting that the absence of non-accidental mortality data will have a minimal impact on our findings.

Epidemiological modelling

We used the regional temperature and mortality time series from Jan 1, 2003 to Dec 31, 2019, to calibrate the epidemiological models, which were then used to estimate location-specified extreme-risk temperature (ERT) thresholds. This method involved a three-stage epidemiological modelling approach, as described by Ballester and colleagues.[7] In the first stage, we used a quasi-Poisson regression model, which allows for over-dispersed counts of deaths, to calculate the location-specific temperature–lag–mortality relationship in each of the 823 European NUTS regions.[33] To consider the temporal change in the temperature–lag–mortality relationship, we extended the

See Online for appendix

time-varying quasi-Poisson models by including a linear interaction between time and the cross-basis variables. This approach allowed for us to preserve the complexity of temperature–mortality relationship for a more flexible analysis of temporal trends.

In the second stage, we used a multilevel meta-regression analysis to pool the location-specific coefficients obtained from the first stage. The meta-regression considered (1) the country random effects, (2) the location-specific temperature mean, and (3) the temperature IQR as meta-predictors. We further assessed the potential temporal variation in temperature–mortality associations by comparing pooled temperature–mortality curves predicted for each year.

In the extended third stage, to obtain associations at a finer spatial scale across 1426 NUTS-3 regions, we subsequently used meta-regression to derive the best linear unbiased predictions of location-specific exposure-response curves for each region per year. We further derived ERT thresholds for each NUTS-3 region from their location-specific exposure-response curves. We note that our epidemiological modelling used weekly data due to an absence of daily mortality data. However, previous research showed that weekly mortality data can approximate the short-term (daily) effects of both cold and heat on European mortality.[34]

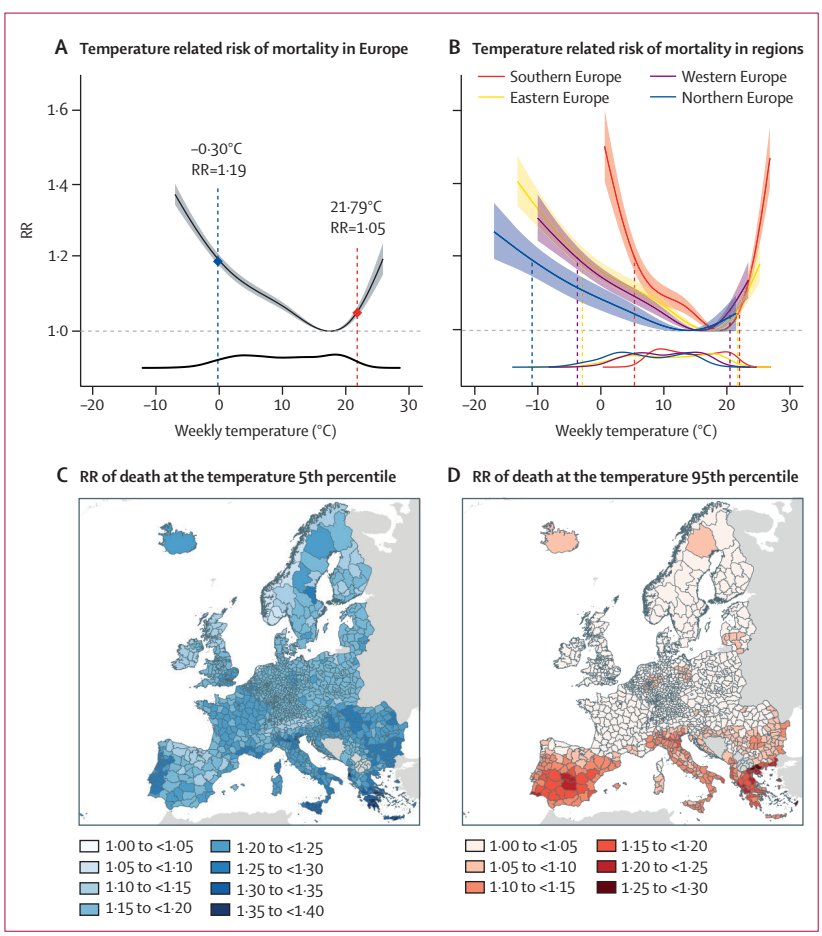

Figure 1: **Temperature-related risk of death from 2003 to 2019**
Pooled cumulative RR of mortality (unitless) in Europe (A) and subcontinental regions (B) from 2003 to 2019, together with 95% CIs (shading) and density plot of regional weekly temperature. Europe regional RR of death (unitless) at the temperature 5th percentile (C) and at the temperature 95th percentile (D). The blue and red points in A represent threshold risks for the 5th and 95th temperatures in Europe; The dashed lines in B represent extreme-risk temperature for cold (RR≥1·19) and heat (RR≥1·05) in pooled regional temperature–mortality association. RR=relative risk.

Estimation of the location-specified ERT thresholds

Using ERT days is a novel approach to identify extreme heat and cold events based on mortality risk, rather than based on fixed temperature thresholds. This method addresses the limitations of traditional methods that rely on uniform temperature percentile (eg, 95th or 5th) approaches,[35,36] which do not consider regional variations in temperature-related health risks. Given the U-shaped relationship between temperature and mortality, both extremely hot and cold temperatures generally increase mortality risk relative to the minimum mortality temperature.[7] This monotonic relationship allows us to replace fixed temperature thresholds with mortality risk thresholds. To establish a consistent threshold risk across regions, we matched the 95th and 5th percentiles of Europe's average weekly temperature (from 2003 to 2019) to the overall exposure-response curve. From this, we established relative risk (RR) thresholds of 1·05 or more for the hottest 5% of days, and 1·19 or more for the coldest 5% of days. Subsequently, these two threshold risks were applied to each location-specific exposure-response curve for each year to classify those days exceeding RR thresholds as ERT days. We chose the 95th and 5th percentiles for threshold risk as primary outcome, to maintain comparability with traditional 95th and 5th percentile temperature definition (appendix p 5). We also performed sensitivity analyses with other percentiles: 92·5th (7·5th), 97·5th (2·5th), and 99th (1st; appendix pp 16, 19–20).

Compound ERT and air pollution days

After identifying heat-ERT and cold-ERT days with exceeded heat-RR or cold-RR thresholds in each location, we also assessed whether the daily WHO recommendations of limit values for any of the air pollutants considered in this analysis was exceeded: 15 mg/m³ for $PM_{2·5}$, 45 mg/m³ for PM_{10}, 25 mg/m³ for NO_2, and 100 mg/m³ for O_3 8 h maximum. When at least one of these limits was surpassed during heat-ERT days we named this a heat-compound episode and when limits were surpassed during cold-ERT days we named this a cold-compound episode. More details of the definition of compound events are in the appendix (p 16).

To understand European population exposure to ERT days and its compound episodes, we analysed (1) the annual ERT days, which quantifies the annual average number of days per person exposed to ERT events, and (2) the annual population exposed to ERT, which represents the annual proportion of residents exposed to

at least 1 ERT day per year. These two metrics were also applied to analyse the compound episodes. The formulas are in the appendix (pp 1–2). In the temporal trend analysis, we calculated the annual Theil–Sen slope for each location, each subcontinental region, and for Europe as a whole from Jan 1, 2003 to Dec 31, 2020. The trends were standardised as changes per decade to standardise comparisons across locations.

All data analyses were conducted in R software (version 4.1.3). The first-stage and second-stage analyses were conducted using the dlnm and mixmeta R packages.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

To describe the mean temperature-mortality association, we pooled the estimates without meta-predictors for Europe and broad subcontinental regions (figure 1A–B). Across Europe, the epidemiological models revealed a U-shaped cumulative association between weekly temperature and mortality from 2003 to 2019 (figure 1A), outlining a monotonical increase in death risk for temperatures both above and below the minimum mortality temperature, at approximately 18·06°C. The pooled temperature–mortality association (figure 1B) revealed warmer optimal temperatures in southern (19·82°C) and eastern Europe (18·51°C) compared with western (17·32°C) and northern Europe (15·22°C). Interestingly, the subcontinent regions with warmer optimal temperature generally displayed a greater sensitivity to heat and cold, exhibiting steeper slopes in RR associated with heat and cold. The percentiles of temperatures corresponding to the RR thresholds are in the appendix (p 16). Across the 823 NUTS regions (figure 1C), southeastern and southern Europe, along with Southwestern France, experienced particularly higher cold-related mortality risks at the 5th percentile of temperature. Meanwhile, the heat RR at the 95th percentile of temperature (figure 1D) exhibited a north–south difference, being particularly high in regions around the Mediterranean Sea. The predicted temperature-mortality relationship for 1426 NUTS-3 regions shows a similar spatial pattern (appendix p 6), suggesting that our meta-prediction approach is robust and can accurately estimate associations at a finer spatial scale. Moreover, the threshold temperature (°C) for cold-ERT days (RR≥1·19) and heat-ERT days (RR≥1·05) also exhibited distinct geographical patterns (appendix p 7).

There was a clear reduction in cold-related mortality risk in Europe between 2003 and 2019 (figure 2A). In contrast, the adaptation to heat-related mortality was less pronounced. For example, the threshold mortality risk of cold (RR≥1·19) shifted from the 10th percentile of temperature in 2003 to the 1st percentile in 2019. The annual change in mortality risk was generally stronger at more extreme temperatures (figure 2B). At the lowest temperature percentile, the RR decreased by 2% (95% CI 0·4–3·3) per year, and at the highest temperature percentile, the decrease was 0·6% (0·3–0·9) per year. Regional variations in adaptation were also evident (figure 2 C–F). The change in adaptation to heat remained relatively small in most regions.

We showed the 18-year means and decadal trends in annual heat-ERT and cold-ERT days, along with associated compound days from 2003 to 2020 (figure 3). Southern and eastern Europe experienced higher frequencies of heat-ERT days than other regions, with

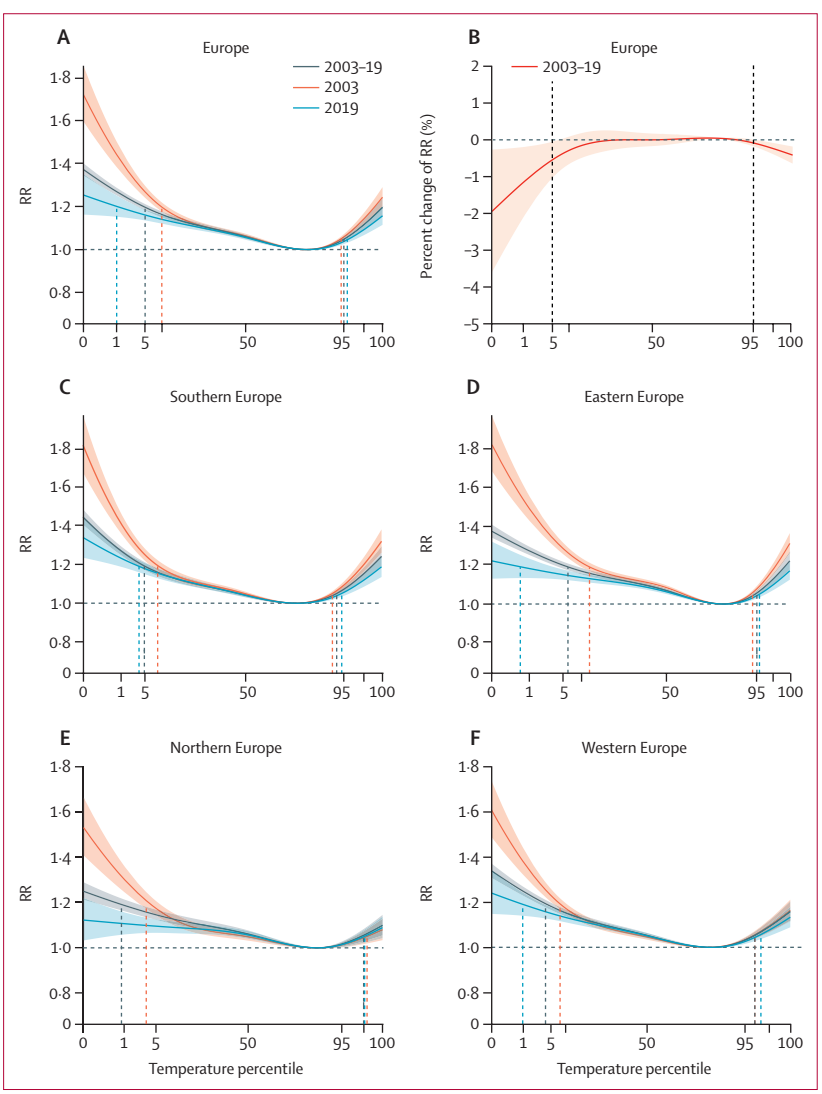

Figure 2: **Temporal change in temperature-related risk of death from 2003 to 2019**
(A) Pooled cumulative RR of mortality (unitless) in Europe, with exposure–response curve in 2003 (red), 2019 (blue), and 2003–19 (black) with 95% CIs. The dashed lines represent the temperature percentile reaching the threshold risk (RR≥1·19 for cold and RR≥1·05 for heat). (B) Mean annual percent change in pooled cumulative RR of mortality (unitless) in Europe from 2003 to 2019. (C–F) Pooled cumulative RR of mortality for subcontinental regions, with corresponding threshold lines as in A. RR=relative risk.

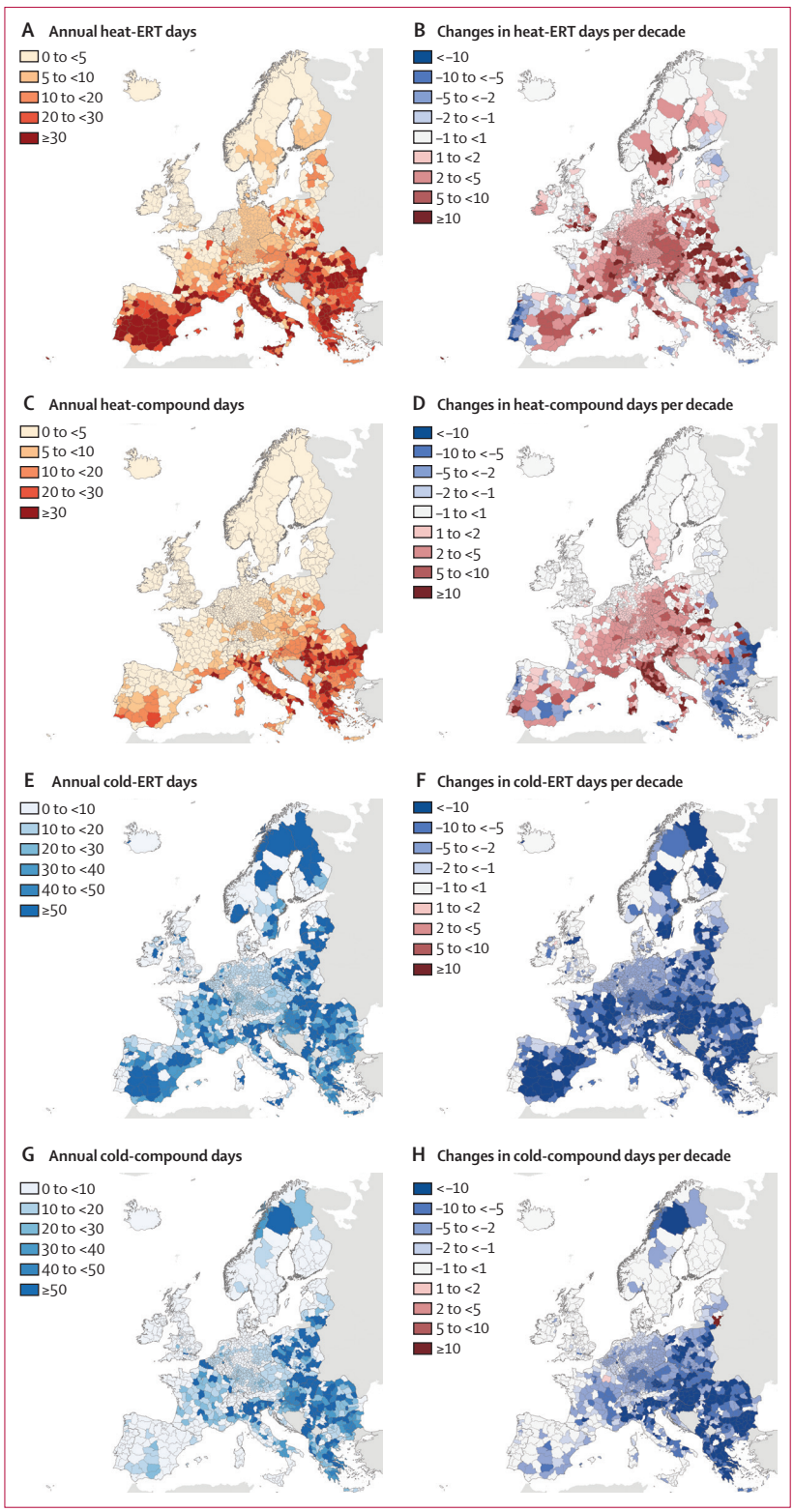

Figure 3: **Regional ERT days and associate compound days in Europe during 2003–20**
Maps of 18-year annual averages and decadal trends in heat-ERT days (A, B), heat-compound days (C, D), cold-ERT days (E, F), and cold-compound days (G, H) in Europe. ERT=extreme-risk temperature.

approximately 30·6 days per year and 23·5 days per year, respectively. Conversely, eastern, northern, and southern Europe were more prone to cold-ERT days than other regions, with a mean of around 43·9, 31·9, and 31·6 days per year, respectively. Both heat and cold-compound episodes are concentrated in southeastern Europe and northern Italy. In most areas of Europe, the frequency of heat-ERT days had increased by 2·8 days per decade (p=0·079) and the frequency of heat-compound days had increased by 1·5 days per decade (p=0·22). The strongest increase in heat-ERT days was observed in middle latitude European areas (figure 3B). In all regions, cold-ERT days significantly decreased by 20·7 days per decade (p<0·0001) and cold-compound days significantly decreased 15·2 days per decade (p=0·0002). These spatial patterns are generally similar to results that did not consider adaptation (appendix p 8), but the decline in cold-ERT days and associated compound episodes was more pronounced after considering adaptation. The countries with the highest frequencies of ERT days and associated compound days are in the appendix (pp 21–24).

There was a significant decrease in cold-ERT days (p<0·0001) and associated compound days (p=0·0002) from 2003 to 2020 (figure 4). Despite the exceptionally high values in 2003, we observed a slight increase trend in the frequencies of heat-ERT days, with significant increases observed in Eastern Europe (around 8·8 days per decade, p=0·046). Compound days consistently comprise a substantial portion of ERT days, with 60% for heat-ERT days and 65% for cold-ERT days. The proportion of compound days in cold-ERT days decreased by 11·74% per decade (p=0·0002), but no significant trend was observed in the proportion of compound days in heat-ERT days. Further details on the regional disparities are in the appendix (pp 17–18). Notably, when applying stricter RR thresholds (ie, 97·5th or 99th percentiles) for defining heat-ERT days, we observe a greater prevalence of heat-compound days (appendix p 19), evidencing that heat-compound episodes tend to co-occur with more extreme heat-ERT days.

We show the changing composition of compound episodes over the years (figure 5). By 2020, heat-compound days primarily consisted of O_3 (58%), $PM_{2·5}$ (36%), or a combination of both (12%). Over 2003–20, the proportion of heat-O_3 compound days (indicating any compound days with exceedance of O_3) increased from 45% to 70%, with an upward trend of 2·6 days per decade (p=0·014; appendix p 17). In contrast, other heat-compound episodes showed a decreasing trend (appendix pp 9, 17). The increasing trend of heat-O_3 compound days was observed across most of Europe, except for northern Europe (appendix p 9). Consequently, O_3-related episodes were becoming the predominant type of heat-compound event in Europe, with eastern Europe being an exception (figure 5). We also observed a significant positive

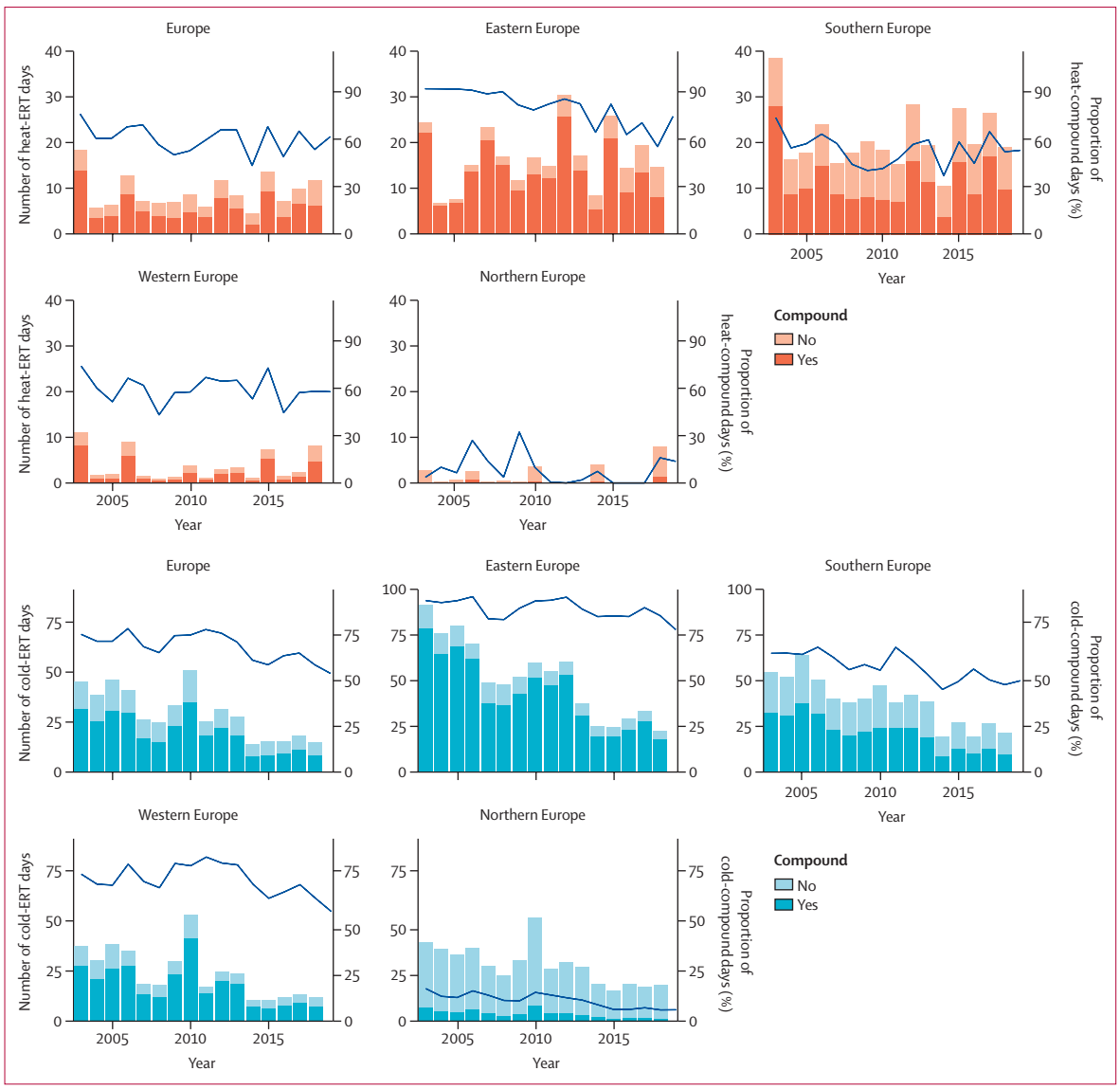

Figure 4: **Annual change of ERT days and associate compound days**
Year-to-year changes of Europe and region-specified heat-ERT days (upper) and cold-ERT days (lower). Dark orange bars refer to heat-compound days, dark blue bars refer to cold-compound days, light red bars refer to heat-ERT days, and light blue bars refers to cold-ERT days. Dark blue lines refer to the proportion of heat-compound and cold-compound days. ERT=extreme-risk temperature.

association between increases in summer temperature and increases in heat-O_3 compound days (p=0·0004; appendix p 10). In contrast, cold-compound episodes remained dominated by days with $PM_{2·5}$ exceedance alone. The proportions and frequencies of other compound days (with exceedance of PM_{10} or NO_2) significantly decreased over the same period (p=0·0003 for both; appendix p 18). Southern and western Europe generally experienced a more diverse mix of cold-compound compositions ($PM_{2·5}$, PM_{10}, or NO_2), and eastern Europe was predominantly affected by combinations involving $PM_{2·5}$ or PM_{10}.

Over 54·28% of Europeans (around 295 million people) were exposed to at least one heat-ERT day annually between 2003 and 2020 (table 1), with exposure increasing by 1·2 million people per decade (p=0·0007). Southern Europe exhibited the highest proportion of exposed population (83·02%), followed by eastern Europe (69·14%), western Europe (38·60%), and northern Europe (21·00%). Additionally, 48·04% of Europeans (around 261 million people) were exposed to at least 1 heat-compound day per year. Nearly 235 million people experienced heat-O_3 compound episodes, with an increase of 3·2 million exposed people per decade (p=0·0007). 64·9% of Europeans (around 349 million people) were exposed to at least 1 cold-ERT day from 2003 to 2020 (table 2), with 4·2 million fewer exposed people per decade (p<0·0001). Similar to the numbers of heat exposure,

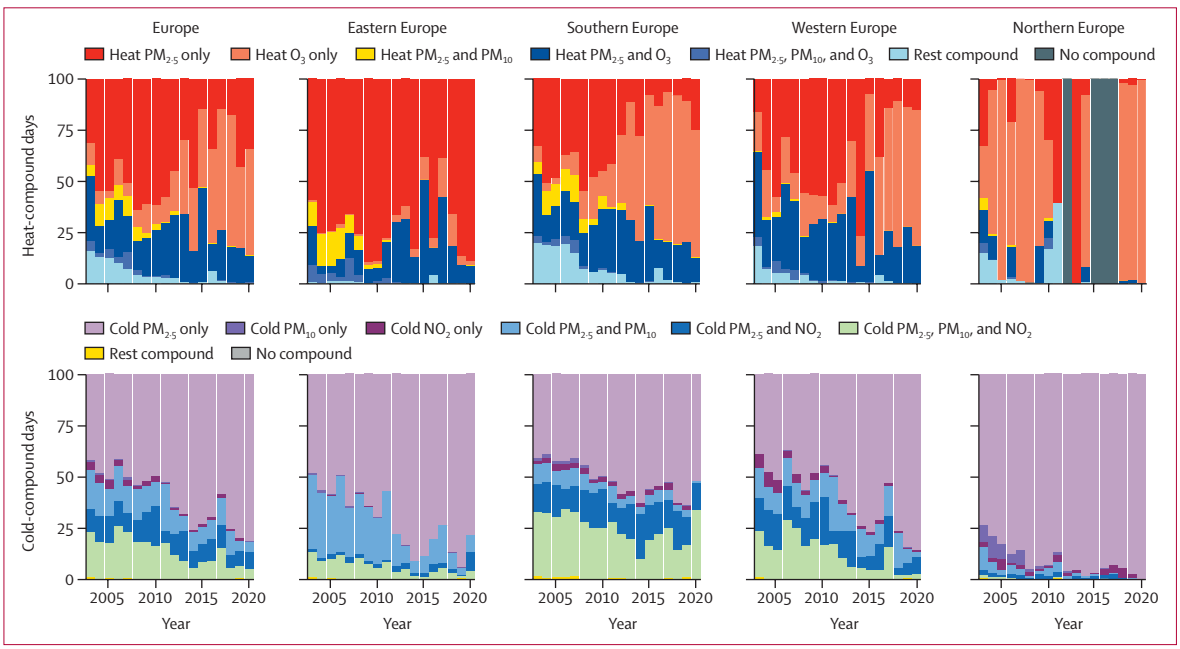

Figure 5: **Annual change in compositions of compound days**
Year-to-year changes in compositions of Europe and region-specified heat-compound days (upper) and cold-compound days (lower).

eastern Europe had the highest proportion (80·39%), followed by southern (69·30%), western (57·75%), and northern Europe (56·79%). Additionally, 58·75% (nearly 316 million people) of people experienced at least 1 cold-compound day, primarily involving cold-$PM_{2·5}$ episodes.

Discussion

To our knowledge, this continent-wide study presents the first quantitative assessment of spatial patterns, trends, and composition of extreme heat-air-pollution or cold-air-pollution compound events across 1426 European NUTS3 regions. The thresholds of ERT days were established by epidemiological models, based on a mortality database across 35 European countries from 2003 to 2019. We observed a significant reduction in cold-related mortality risk in Europe; however, the adaptation to heat-related mortality was less pronounced. We also found a general shift towards a higher frequency of heat-ERT days and a lower frequency of cold-ERT days over the past two decades. The similar shift was observed in compound days, especially for the heat-O_3 compound episodes exacerbated by global warming. We also observed a clear spatial heterogeneity in both heat-ERT and cold-ERT days, underscoring the need for region-specific strategies to address geographical disparities in vulnerability and protect populations at risk.

A strength of this study lies in the use of mortality risk thresholds derived from continental-wide epidemiological models. Unlike previous research that employed uniform temperature threshold for all areas,[19,22,23] our findings revealed that a uniform assumption is not valid in Europe. The vulnerability to extreme temperatures varied widely across different locations, with regions in southern Europe being more sensitive to temperature changes than those in northern Europe. This disparity in vulnerability is partly due to socioeconomic factors,[37] including inadequate housing insulation,[38] lower public health expenditure,[39] and limited access to social support or assistance for vulnerable populations (eg, older and low-income populations).[40–43] Additionally, people in colder climates might have acclimated to temperature fluctuations, taking precautions such as wearing suitable clothing and limiting outdoor exposure during extreme cold events. These disparities underscore the importance of tailoring existing prevention strategies to local demographic and socioeconomic conditions.

This methodological advantage also enables us to consider time-varying mortality risks, reflecting adaptation over time. During 2003–19, Europe demonstrated substantial progress in reducing cold-related mortality risk, reflecting successful adaptation through strategies such as improved medical care or building insulation.[2,7,24] However, adaptation to heat-related mortality was less effective. As a result, the increasing frequency of heat-ERT days continued to increase, regardless of whether adaptation was considered. Climate change has contributed to a warming trend worldwide,[7,42] further exacerbating the frequency of heat-ERT days and reducing the occurrence of cold-ERT days. These findings highlight the need for more progress in current heat adaptation measures and heat–health action plans (HHAPs) to better protect vulnerable populations.

	Heat-ERT population, in millions (%)				Change per decade, thousands of people			
	Heat ERT	Heat compound	Heat-$PM_{2·5}$ compound	Heat-O_3 compound	Heat ERT	Heat compound	Heat-$PM_{2·5}$ compound	Heat-O_3 compound
Europe	294·78 (54·28%)	260·93 (48·04%)	184·48 (33·97%)	234·85 (43·24%)	1205·85*	1179·37*	–391·38*	3165·42*
Southern Europe	110·87 (83·02%)	99·74 (74·69%)	65·40 (48·97%)	95·70 (71·66%)	161·81	136·42	–398·16*	1262·95*
Cyprus	0·89 (100%)	0·89 (100%)	0·89 (100%)	0·79 (88·90%)	99·72*	99·72*	79·72*	464·97*
Malta	0·44 (92·92%)	0·39 (82·72%)	0·0048 (0·95%)	0·34 (73·02%)	30·54	10·02	–136·83*	50·54*
Greece	9·86 (87·93%)	9·59 (85·50%)	8·68 (77·38%)	7·34 (65·45%)	–6·89	–12·23	–29·79*	13·39*
Italy	53·52 (86·40%)	51·97 (83·90%)	39·35 (63·52%)	51·97 (83·90%)	19·57	45·08*	–151·81*	371·13*
Spain	40·30 (83·43%)	32·91 (68·14%)	15·95 (33·03%)	31·42 (65·05%)	37·49	45·71	–49·05*	88·07*
Portugal	5·86 (54·64%)	3·99 (37·18%)	0·53 (4·93%)	3·83 (35·74%)	–18·61	–51·88	–130·40*	25·15
Eastern Europe	71·21 (69·14%)	67·90 (65·92%)	65·54 (63·64%)	50·76 (49·28%)	87·66	30·39	–65·36	716·72*
Albania	2·67 (89·68%)	2·64 (88·55%)	2·59 (87·09%)	2·14 (71·74%)	–3·83	–6·55	–10·41	36·98*
Montenegro	0·57 (88·89%)	0·57 (88·89%)	0·57 (88·89%)	0·50 (77·77%)	–23·59	–23·59	–23·59	230·86*
Bulgaria	6·48 (87·66%)	6·35 (85·98%)	6·28 (85·03%)	3·75 (50·79%)	–36·48	–39·92*	–41·31	18·43*
Croatia	1·84 (86·20%)	1·78 (83·04%)	1·41 (66·08%)	1·76 (82·41%)	–25·19*	–26·90*	–19·61*	34·01*
Serbia	5·94 (84·79%)	5·94 (84·79%)	5·94 (84·79%)	5·45 (77·75%)	–9·35	–9·35	–9·35	34·29*
North Macedonia	1·80 (83·88%)	1·73 (80·97%)	1·73 (80·97%)	1·29 (60·34%)	34·20	20·92	20·92	54·53*
Hungary	4·42 (83·01%)	4·29 (80·59%)	4·01 (75·23%)	3·89 (73·02%)	–59·10*	–62·30*	–60·99*	–25·83
Romania	16·45 (80·60%)	15·49 (75·92%)	15·33 (75·15%)	10·52 (51·56%)	11·58	–8·87	–13·23	26·28*
Slovenia	7·29 (71·65%)	7·02 (69·00%)	6·52 (64·09%)	6·43 (63·21%)	67·31*	60·90*	32·02	77·24*
Slovakia	3·35 (59·74%)	3·28 (58·39%)	3·20 (57·06%)	2·83 (50·44%)	92·31*	96·84*	88·83	163·01*
Poland	20·40 (52·07%)	18·80 (47·99%)	17·94 (45·80%)	12·19 (31·12%)	59·79*	49·23*	41·35*	66·94*
Western Europe	105·97 (38·60%)	91·32 (33·27%)	53·48 (19·48%)	86·54 (31·53%)	1026·76*	1030·55*	146·78*	1170·99*
Austria	0·47 (79·27%)	0·47 (79·27%)	0·14 (22·70%)	0·47 (79·27%)	16·38	23·06	–30·84	55·82*
Switzerland	5·75 (64·21%)	5·32 (59·35%)	3·76 (42·01%)	4·98 (55·55%)	29·68	63·51*	–5·61	78·00*
Czechia	6·72 (61·44%)	6·06 (55·39%)	5·13 (46·89%)	5·48 (50·13%)	56·89	65·15	–9·37	98·46*
France	5·06 (60·25%)	3·69 (43·95%)	1·18 (14·06%)	3·55 (42·33%)	122·24*	102·49*	–11·76	141·97*
Luxembourg	33·65 (52·33%)	28·33 (44·05%)	16·97 (26·40%)	26·55 (41·29%)	200·06*	200·06*	146·72	200·06*
Germany	39·59 (47·51%)	36·34 (43·61%)	22·08 (26·50%)	35·26 (42·32%)	39·76*	50·85*	14·20*	60·32*
Belgium	3·84 (32·88%)	3·76 (32·15%)	1·89 (16·18%)	3·76 (32·15%)	80·42*	85·72*	32·38*	88·69*
Netherlands	4·84 (27·52%)	4·60 (26·15%)	1·44 (8·18%)	4·57 (25·96%)	98·12*	99·90*	2·34	113·84*
Liechtenstein	0·01 (22·60%)	0·01 (22·60%)	0	0·01 (22·60%)	12·19*	12·19*	0	12·19*
UK	5·85 (9·18%)	2·70 (4·24%)	0·89 (1·40%)	1·86 (2·91%)	41·02*	18·79*	8·73*	12·80*
Ireland	0·19 (3·82%)	0·06 (1·12%)	0	0·06 (1·12%)	30·00*	8·83	0	8·83
Northern Europe	6·73 (21·00%)	1·97 (6·14%)	0·05 (0·16%)	1·85 (5·77%)	–70·38	–17·98	–74·64	14·76
Latvia	0·90 (44·19%)	0·19 (9·29%)	0·0024 (0·16%)	0·19 (9·29%)	–72·75	–28·81	–33·08	–14·46
Estonia	1·82 (30·81%)	0·53 (8·99%)	0	0·46 (7·86%)	–51·70*	–16·32	0	–16·32
Denmark	0·40 (24·42%)	0·21 (12·94%)	0·0014 (0·13%)	0·21 (12·94%)	75·60*	10·25	–29·83*	20·74*
Finland	2·32 (22·73%)	0·90 (8·79%)	0·0006 (0·01%)	0·90 (8·79%)	–20·14	–5·04	–0·75	–4·61
Sweden	1·05 (18·47%)	0·05 (0·97%)	0	0·05 (0·97%)	63·45*	35·08*	0	35·08*
Lithuania	0·18 (6·04%)	0·05 (1·69%)	0·05 (1·69%)	0·0005 (0·02%)	–22·76*	–15·08*	–10·98*	–7·61
Norway	0·06 (1·99%)	0·03 (1·00%)	0	0·03 (1·00%)	–12·09	1·94	0	1·94
Iceland	0	0	0	0	0	0	0	0

ERT=extreme-risk temperature. *p<0·05.

Table 1: **Means and trends in national population (millions) and fraction of population (%) exposed to at least one heat-ERT day or its major compound episodes per year from 2003 to 2020**

Current heat-related prevention strategies remain inadequate. A 2024 survey[44,45] revealed that only 20 out of 38 European countries have implemented temperature surveillance systems, and 17 countries still do not have HHAPs. The existing systems also suffer from inconsistent definitions of heat events across countries[44] (ranging from maximum daily temperatures of 26°C in Sweden to 30°C in Cyprus), complicating response coordination and cross-country health impact comparison. Our proposed heat-ERT days offer a standardised approach to harmonise these definitions, ensuring greater equity in HHAPs. Furthermore, only

	Cold-ERT population, in millions (%)			Change per decade, thousands of people		
	Cold ERT	Cold compound	Cold-$PM_{2·5}$ compound	Cold ERT	Cold compound	Cold-$PM_{2·5}$ compound
Europe	348·88 (64·89%)	315·86 (58·75%)	309·36 (57·54%)	−4199·99*	−4288·06*	−3922·90*
Southern Europe	91·45 (69·30%)	74·37 (56·36%)	71·52 (54·20%)	−479·12*	−700·46*	−515·85*
Cyprus	0·79 (93·64%)	0·79 (93·64%)	0·79 (93·64%)	−74·40*	−74·40*	−74·40
Spain	42·27 (89·09%)	30·16 (63·56%)	28·46 (59·99%)	−135·57*	−260·11*	−224·56*
Malta	0·39 (86·13%)	0·23 (52·19%)	0	−16·54	−115·40*	0
Greece	9·57 (84·61%)	9·50 (83·96%)	9·50 (83·96%)	−39·35*	−42·18*	−42·18*
Italy	35·64 (58·33%)	32·13 (52·59%)	31·87 (52·17%)	−111·19*	−128·97*	−127·01*
Portugal	2·78 (25·78%)	1·56 (14·41%)	0·89 (8·26%)	−102·08*	−79·40*	−47·70*
Eastern Europe	83·30 (80·39%)	82·95 (80·05%)	82·95 (80·05%)	−1157·31	−1169·64	−1169·64
Montenegro	0·60 (94·09%)	0·60 (94·09%)	0·60 (94·09%)	−115·06	−115·06*	−115·06*
Albania	2·69 (92·23%)	2·67 (91·77%)	2·67 (91·77%)	−40·53	−41·88*	−41·88*
Bulgaria	6·75 (89·03%)	6·63 (87·41%)	6·63 (87·41%)	−98·16*	−103·26*	−103·26*
Romania	18·67 (87·70%)	18·59 (87·30%)	18·59 (87·30%)	−168·26*	−173·83*	−173·83*
Hungary	8·86 (86·19%)	8·86 (86·19%)	8·86 (86·19%)	−155·24*	−155·24*	−155·24*
Slovakia	4·75 (84·90%)	4·75 (84·90%)	4·75 (84·90%)	−195·27*	−195·27*	−195·27*
Croatia	4·40 (83·01%)	4·38 (82·67%)	4·38 (82·67%)	−78·11*	−78·80*	−78·80*
North Macedonia	1·61 (75·67%)	1·60 (75·23%)	1·60 (75·23%)	−23·79	−27·51	−27·51
Serbia	5·20 (75·54%)	5·20 (75·54%)	5·20 (75·54%)	−43·29*	−43·29*	−43·29*
Poland	28·33 (72·84%)	28·26 (72·66%)	28·26 (72·66%)	−183·95*	−184·85*	−184·85*
Slovenia	1·44 (68·09%)	1·41 (66·68%)	1·41 (66·68%)	−55·65*	−50·65*	−50·65*
Western Europe	156·10 (57·75%)	147·92 (54·73%)	144·75 (53·56%)	−1618·85*	−1709·39*	−1583·00*
Liechtenstein	0·04 (93·75%)	0·03 (87·69%)	0·03 (87·69%)	−4·85	−8·54	−8·54
Luxembourg	0·51 (93·07%)	0·51 (93·07%)	0·51 (93·07%)	−12·32	−12·32	−12·32
France	44·50 (70·55%)	42·18 (66·87%)	41·94 (66·48%)	−173·51*	−178·62*	−178·32*
Belgium	7·98 (70·22%)	7·95 (70·00%)	7·94 (69·88%)	−131·68*	−132·98*	−133·57*
Netherlands	12·03 (69·34%)	11·87 (68·39%)	11·77 (67·80%)	−183·96*	−183·35*	−175·04*
Austria	5·72 (65·15%)	5·60 (63·78%)	5·60 (63·78%)	−122·95*	−129·50*	−129·50*
Switzerland	5·16 (64·19%)	4·61 (57·34%)	4·61 (57·34%)	−168·79*	−205·36*	−205·36*
Germany	51·73 (62·25%)	50·65 (60·95%)	50·60 (60·90%)	−132·54*	−135·31*	−135·46*
Czechia	6·42 (59·39%)	6·35 (58·75%)	6·35 (58·75%)	−546·77*	−537·89*	−537·89*
Ireland	1·99 (40·92%)	1·56 (32·03%)	0·93 (19·18%)	−67·84	−122·87*	−30·01
UK	20·01 (32·13%)	16·61 (26·67%)	14·46 (23·22%)	−73·65*	−62·66*	−37·00*
Northern Europe	18·03 (56·79%)	10·61 (33·41%)	10·14 (31·95%)	−944·71*	−708·57*	−654·41*
Lithuania	2·78 (88·26%)	2·76 (87·46%)	2·76 (87·46%)	−87·51*	−91·36*	−91·36*
Latvia	1·73 (80·55%)	1·52 (70·71%)	1·49 (69·34%)	−168·09*	−192·48*	−197·11*
Iceland	0·22 (65·87%)	0	0	27·12	0	0
Finland	2·99 (53·63%)	1·17 (20·92%)	0·89 (15·96%)	−81·47*	−49·44*	−7·65
Sweden	5·12 (51·90%)	1·98 (20·02%)	1·98 (20·02%)	−127·43*	−112·39*	−112·39*
Norway	1·59 (49·21%)	1·02 (31·49%)	0·95 (29·49%)	−16·14	−41·44*	−29·07
Estonia	0·80 (49·12%)	0·21 (13·15%)	0·21 (12·58%)	−180·59*	−49·13	−48·38
Denmark	2·79 (48·11%)	1·96 (33·75%)	1·87 (32·25%)	−310·58*	−192·33*	−168·45*

ERT=extreme-risk temperature. *p<0·05.

***Table 2*: Means and trends in national population (millions) and fraction of population (%) exposed to at least one cold-ERT day or its major compound episodes per year from 2003 to 2020**

nine countries have developed local HHAPs, and just four have specifically targeted vulnerable populations.[44,45] This situation demonstrates a crucial gap in locally specified adaptation, which is underscored by our findings on varying temperature vulnerabilities and adaptation across Europe. Finally, our continental-scale analysis enhances the understanding of subnational heat-related health impacts, providing valuable insights for more effective resource allocation.

Our research also highlights the substantial and persistent role of air-pollution compound events during extreme temperatures, a factor often neglected in previous

studies. These events contribute to 60% for heat-ERT days and 65% for cold-ERT days. Although PM_{10} or NO_2 compound days have substantially decreased in response to European air quality control efforts, our findings indicate a shift towards O_3 as the primary pollutant associated with heat-compound days and $PM_{2·5}$ as the primary pollutants associated cold-compound days. This finding is particularly concerning given the synergistic health impacts between heat and exposure to either ozone or $PM_{2·5}$.[14,19,46,47] These synergistic effects could arise from shared biological pathways.[48] Higher temperatures can increase thermoregulatory stress and increase pollutant uptake through elevated blood flow, skin permeability, and respiratory rate.[49,50] Furthermore, heatwaves and pollutants can independently trigger accelerated oxidative stress injury and systemic inflammation, further impairing the body's defenses.[14,19,47,48] Thus, targeted interventions for O_3 and $PM_{2·5}$ are crucial.

Despite progress in overall air pollution reduction, heat-ozone episodes remain as the only increasing compound event in Europe, affecting over 235 million people. Our analysis reveals a significant positive association between increases in summer temperature and increases in heat-O_3 compound days. This increase might be partly attributed to photochemical enhancement,[51] biogenic emissions,[52] wildfire contributions,[53] and reduced ozone titration in urban areas related to decreases in NO_2 levels.[54] Extreme heat accompanied with strong sunlight accelerates ozone formation through photochemical reactions.[51] Additionally, higher temperatures during heat further boost biogenic volatile organic compound emission from vegetation,[21] contributing to increased O_3 formation.[52] Moreover, wildfires during extreme heat also release primary particulate matter as well as O_3 and particulate matter precursors into the atmosphere.[53] Interestingly, those days with higher ERT (eg, using the 97·5th or 99th percentile instead of the 95th percentile) showed a higher proportion of days classified as heat-compound days (appendix p 19). The increase might be related to strong solar radiation and stagnant air conditions during heatwaves, which favour ozone and precursor organic aerosol accumulation.

As global warming intensifies heat waves, compound heat-O_3 episodes are becoming an inevitable and pressing concern in Europe, which experiences a faster-than-global-average warming rate.[8] The conventional air pollution control strategies, mainly focused on primary pollutants, might not adequately mitigate the formation of ozone or secondary pollutants under high temperatures. The increase of heat-O_3 episodes calls for collaborative approaches between climate change and air pollution policy makers to tackle both greenhouse gas emissions and precursor pollutant formation. Such joint efforts could potentially break the cycle of heat-driven ozone formation, leading to a healthier future for Europeans. This integrated approach is crucial as tropospheric O_3 itself acts as a greenhouse gas, contributing to the trapping of heat in the lower atmosphere.[55] Reducing O_3 levels can mitigate the severity of global warming, creating a positive feedback loop by reducing further O_3 generation. Additionally, effective policies for wildfire prevention and traffic management can also reduce additional O_3 and particulate matter secondary emissions into the atmosphere.

This study has some limitations worth acknowledging. First, due to data availability, we employed weekly mortality and temperature data in the epidemiological models. Consequently, the use of 7-day moving averages of temperature in extracting ERT days might smooth out daily fluctuations, potentially overlooking some extreme temperature peaks. Secondly, applying uniform WHO air pollution guidelines across all regions might not fully capture the potential varying health effects of exposures to air pollutant on different locations. The availability of weekly mortality data constrained the development of localised air pollution-mortality models, because health impacts from air pollutants typically lag by 1–3 days. This limitation also prevented an investigation into the interactive effects of air pollutants and extreme temperatures. Future research should prioritise the development of localised models incorporating daily mortality data to better capture regional variations in population susceptibility and improve understanding of these complex interactions. Lastly, though the resolution of temperature and air pollution data might not be ideal, it remains sufficient for the NUTS-3 level analysis, given the average NUTS-3 area of 2828 km².

In general, global warming presents a double-edged impact in Europe: reduced cold-ERT days but increased heat-ERT days. However, adaptations to heat-related mortality have lagged behind those for cold-related mortality. To better protect vulnerable populations, it is imperative to accelerate progress in current heat adaptation strategies and heat–health action planning. As summer temperatures continue to rise,[9,56] conventional air quality policies targeting primary pollutants also fall short of addressing the growing threat of heat-O_3 compound episodes. Strengthening collaborative approaches between climate change and air pollution policy makers will be crucial for ensuring a healthier future for Europeans.

Contributors

In this project, Z-YC, HA, CPG-P, HP, YG, and JB conceptualised the study and acquired funding. Z-YC, RFMT, HA, and JB collected and processed the data. Z-YC and CPG-P contributed to the methodology. Z-YC, HA, HP, RFMT, CPG-P, and JB had access to the raw data and verified the data. Z-YC and JB prepared the initial draft of the paper. All authors revised the manuscript and approved the final version.

Declaration of interests

We declare no competing interests.

Data sharing

Reanalysis temperature data primarily came from the ERA5_land dataset. The weekly counts of all-cause mortality (n=83 375 442) were collected from Eurostat,[31] spanning from Jan 1, 2003 to Dec 31, 2019. The daily mean observations of $PM_{2·5}$, PM_{10}, NO_2, and maximum daily 8 h average O_3 were collected from two main databases in the European environment information and observation network (Eionet): the Airbase

(2003–12) and the Air Quality e-Reporting (2013–20). High-resolution gridded population data are from the Gridded Population of the World, Version 4 database.[26] These datasets are publicly available on their respective platforms.

Acknowledgments

Z-YC, RFMT, HA, and JB gratefully acknowledge funding from the EU's Horizon 2020 and Horizon Europe research and innovation programmes under grant agreement 865564 (European Research Council [ERC] Consolidator Grant EARLY-ADAPT), 101069213 (ERC Proof-of-Concept HHS-EWS), and 101123382 (ERC Proof-of-Concept FORECAST-AIR). Z-YC also acknowledges support from the grant PRE2020-091985 funded by MCIN/AEI/10.13039/501100011033 and by European Social Fund invests in your future. HA also acknowledges funding from the EU's Horizon Europe research and innovation programme under grant agreement 101065876 (Marie Skłodowska-Curie Actions Postdoctoral Fellowship TEMP-MOMO). HP has received funding from the Ministerio de Ciencia e Innovación through the MITIGATE project (PID2020-113840RA-I00 funded by MCIN/AEI/10.13039/501100011033) and the Ramon y Cajal grant (RYC2021-034511-I, MCIN/AEI/10.13039/501100011033 and EUs NextGenerationEU–Plan de Recuperación, Transformación y Resiliencia). HP and CPG-P acknowledge funding from the Ministerio para la Transición Ecológica y el Reto Demográfico as part of the Plan Nacional del Ozono project (BOE-A-2021-20183), the Recovery, Transformation and Resilience Plan funded by the European Commission, Grant RED2022-134824-E (Aerosol, Clouds, and Trace Gases Research Infrastructure Spain) funded by MICIU/AEI/10.13039/501100011033, the AXA Research Fund, and the Department of Research and Universities of the Government of Catalonia through the Atmospheric Composition Research Group (code 2021 SGR 01550). YG was supported by the Leader Fellowship (APP2008813) of the Australian National Health and Medical Research Council. ISGlobal authors acknowledge support from the grant CEX2018-000806-S funded by MCIN/AEI/10.13039/501100011033, and support from the Generalitat de Catalunya through the CERCA Programme. During the preparation of this work the authors used Claude in order to check grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Editorial note: The Lancet Group takes a neutral position with respect to territorial claims in published maps, tables, and institutional affiliations.

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