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Joint effect of heat and air pollution on mortality in 620 cities of 36 countries

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Abstract

Background: The epidemiological evidence on the interaction between heat and ambient air pollution on mortality is still inconsistent.

Objectives: To investigate the interaction between heat and ambient air pollution on daily mortality in a large dataset of 620 cities from 36 countries.

Methods: We used daily data on all-cause mortality, air temperature, particulate matter ≤ 10 µm (PM_{10}), PM ≤ 2.5 µm ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) from 620 cities in 36 countries in the period 1995–2020. We restricted the analysis to the six consecutive warmest months in each city. City-specific data were analysed with over-dispersed Poisson regression models, followed by a multilevel random-effects meta-analysis. The joint association between air temperature and air pollutants was modelled with product terms between non-linear functions for air temperature and linear functions for air pollutants.

Results: We analyzed 22,630,598 deaths. An increase in mean temperature from the 75th to the 99th percentile of city-specific distributions was associated with an average 8.9 % (95 % confidence interval: 7.1 %, 10.7 %) mortality increment, ranging between 5.3 % (3.8 %, 6.9 %) and 12.8 % (8.7 %, 17.0 %), when daily PM_{10} was equal to 10 or 90 µg/m^3, respectively. Corresponding estimates when daily O_3 concentrations were 40 or 160 µg/m^3 were 2.9 % (1.1 %, 4.7 %) and 12.5 % (6.9 %, 18.5 %), respectively. Similarly, a 10 µg/m^3 increment in PM_{10} was associated with a 0.54 % (0.10 %, 0.98 %) and 1.21 % (0.69 %, 1.72 %) increase in mortality when daily air temperature was set to the 1st and 99th city-specific percentiles, respectively. Corresponding mortality estimate for O_3 across these temperature percentiles were 0.00 % (−0.44 %, 0.44 %) and 0.53 % (0.38 %, 0.68 %). Similar effect modification results, although slightly weaker, were found for $PM_{2.5}$ and NO_2.

Conclusions: Suggestive evidence of effect modification between air temperature and air pollutants on mortality during the warm period was found in a global dataset of 620 cities.

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

Appendix A. Supplementary material
Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108258.

Keywords

Air temperature; Air pollution; Effect modification; Epidemiology; Mortality

1. Introduction

Air pollution and climate change are closely linked: many ambient air pollutants contribute to climate change and changes in climate have impacts on air quality (Kinney, 2018). Several air pollutants are responsible for the health burden, specifically particulate matter (PM), nitrogen dioxide (NO_2), and ozone (O_3) (WHO, 2021; Vicedo-Cabrera et al., 2020; Liu et al., 2019; Orellano et al., 2020; Dominski et al., 2021; Meng et al., 2021). PM is a mixture of solid and liquid particles originating from different sources, with both anthropogenic (vehicular traffic, domestic heating, industry) and natural (wildfires, desert dust) sources causing adverse effects on human health (WHO, 2021). NO_2 is a gaseous air pollutant originated from burning fossil fuels (coal, oil, gas or diesel) at high temperatures. Its largest sources are motor vehicles and industrial plants, therefore NO_2 concentrations are highest in urban and industrial areas (WHO, 2021). O_3 is a highly reactive secondary pollutant originating from the reaction between anthropogenic and biogenic precursors such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight (WHO, 2021). Numerous epidemiological studies have shown that short-term exposure to PM, NO_2, and O_3 are associated with adverse health outcomes, including increased daily mortality and morbidity (Vicedo-Cabrera et al., 2020; Liu et al., 2019; Orellano et al., 2020; Dominski et al., 2021; Meng et al., 2021; Stafoggia et al., 2010).

The association between extreme ambient temperatures, especially during the warm season, and daily mortality has been extensively documented in the epidemiological literature (Gasparrini et al., 2015; Anderson and Bell, 2009; Basu, 2009; Song et al., 2017). Most studies report immediate (i.e., up to 3 days) associations with non-linear effects of high summer temperatures (Gasparrini et al., 2015). Such associations are observed in different geographical areas, with some heterogeneity related to several factors such as climatic conditions to which local populations are acclimatized, local population characteristics, and the diverse vulnerability of the underlying population, among others (Gasparrini et al., 2015; Anderson and Bell, 2009; Basu, 2009; Song et al., 2017; Gasparrini et al., 2015; Lavigne et al., 2014; Zhao et al., 2021; Sera et al., 20192019).

The interaction between heat and ambient air pollution on human health is less investigated. Most of the studies have been conducted in single cities or multiple cities from the same region, often using heterogeneous methodological approaches to adjust for time-varying confounders or to test for the presence of effect modification between air pollutants and temperatures on human health (Chen et al., 2017; Anenberg et al., 2020; Li et al., 2017). Furthermore, most studies have considered either air pollution as an effect modifier of the air temperature-mortality relationship, or vice versa (Chen et al., 2017; Anenberg et al., 2020; Li et al., 2017; Rai et al., 2023).

The objective of this multicentre analysis was to investigate the joint short-term effects of heat and air pollutants on all-cause mortality on a global scale. We used the Multi-Country

Multi-City (MCC) Collaborative Research Network dataset (Gasparrini et al., 2015) and applied a comprehensive, consistent modelling framework to estimate the health risks and compare the associations at the global and continental level.

2. Methods

2.1. Data collection

Daily time-series data on mortality counts, mean air temperature, and air pollution for 620 cities across 36 countries were retrieved from the database of the MCC Network, a voluntary-based collaborative research network where investigators provide daily data on mortality counts, air pollutants concentrations and air temperature to be used for environmental epidemiology investigations (Gasparrini et al., 2015). The years of data available differed by city. We restricted the study periods to start at 1995 and selected only the warm seasons, defined for each city as the six consecutive warmest months for the whole study period, based on air temperature data. Furthermore, we only included cities with at least three years of data.

Mortality data was represented by daily counts of deaths due to non-external causes (International Classification of Diseases codes 0–799 [9th revision] or codes A00–R99 [10th revision]), or by all-cause deaths when data on non-external causes were not available.

For each city, data on daily mean air temperature from stations included in local monitoring networks were considered. Daily average concentrations of PM_{10}, $PM_{2.5}$ and NO_2, and daily maximum 8-hour moving average O_3 concentrations, were collected from urban and suburban air quality monitoring stations for subsets of cities: 372 cities had data on PM_{10}, 486 on $PM_{2.5}$, 386 on O_3, and 411 on NO_2. For NO_2 and O_3, when data were available in parts per billion (ppb), they were converted into micrograms per cubic meter (μg/m^3) using 1 ppb = 1.88 μg/m^3 and 1 ppb = 1.96 μg/m^3 conversion factors, respectively. Details on data collection are provided in the appendix (p 2).

2.2. Statistical analysis

We adopted a two-stage design, where city-specific data were analysed in the first stage, and pooled results were obtained in the second stage.

For each city, we assumed an over-dispersed Poisson distribution for the daily mortality counts, and applied time-series regression adjusted for long-term and seasonal time trends and the day of the week. Air temperature, PM_{10}, NO_2 and O_3 were modelled at lag 0–1 (average of current and previous day exposures) based on previous publications using the same data (Vicedo-Cabrera et al., 2020; Liu et al., 2019; Meng et al., 2021; Gasparrini et al., 2015). $PM_{2.5}$ was modelled as a single-day lag (lag 0) because approximately 100 cities (mostly located in the U.S.) had data only every third day. Long-term and seasonal time trends were adjusted for by fitting year-specific natural splines with 4 degrees of freedom (d.f.) and a natural spline of calendar year with one knot every three years, and day of the week was modelled as a categorical variable. Firstly, we analysed each exposure individually, by modelling air temperature with a natural spline with four d.f. and air pollutants with linear terms. Models for air temperature were fit with and without adjustment for air pollutants, while models for air pollutants (one per each pollutant) were always fit with adjustment for air temperature. In each city, effects were estimated as a % change in mortality, with 95 % confidence intervals (95 % CI), per an increase in mean temperature from the 75^{th} to the 99^{th} percentile. The effect of air pollutants was estimated per a 10 $\mu g/m^3$ increment in the exposure. This choice was motivated by comparability with the existing literature, although we acknowledge that 10 $\mu g/m^3$ captures different amounts of daily variability both across locations and across pollutants.

Secondly, in each city, we modelled the interaction between mean air temperature and air pollution on mortality by defining a product term between the natural spline of air temperature and the linear term of air pollutant. From this model, we calculated the % change in mortality associated with 75^{th}-99^{th} percentile increase in temperature, for increasing levels of air pollutants concentrations: from daily averages of 10 $\mu g/m^3$ to 90 $\mu g/m^3$ (for PM_{10}), from 1 $\mu g/m^3$ to 40 $\mu g/m^3$ (for $PM_{2.5}$), from 40 $\mu g/m^3$ to 160 $\mu g/m^3$ (for O_3), and from 1 $\mu g/m^3$ to 60 $\mu g/m^3$ (for NO_2). These ranges were chosen based on inspection of city-specific air pollutants distributions on warm-season days with air temperature between 75^{th} and 99^{th} distribution (Figure S1 of the appendix). Similarly, from the same joint model, we calculated the % change in pollutant-related mortality for increasing levels of mean air temperature, from the 1^{st} to the 99^{th} percentile of city-specific distributions. Since we modelled the interaction using a product term in the log-linear model, it is implicit that we modelled a "multiplicative" interaction, rather than an additive one. We acknowledge that also the latter was of interest for our study hypothesis, however it raised methodological complexities which were beyond the scope of the paper. More details on the methodological approach are reported in the appendix (pp 3–4).

In the second stage, we pooled the city-specific estimates of the main effects, and the estimates of level-specific effects from the effect modification analysis, with multilevel random-effects *meta*-analyses, where the countries and cities were modelled as nested random effects (Vicedo-Cabrera et al., 2020; Liu et al., 2019; Gasparrini et al., 2015). Similarly, we pooled the city-specific estimates of the product terms between air temperature and each air pollutant as a formal test of interaction. See the appendix (p 4) for further details.

We carried out a series of sensitivity analyses to check the robustness of our main findings to different modelling choices and definitions. Since our main focus was on heat, we restricted the "warm" season to the three warmest consecutive months instead of six for each city (as done in the main analysis). Secondly, we estimated the main effect of air temperature or air pollutants using the alternative lags 0–3 (average of same-day and previous 3-days exposure) or 0–10 (average of same-day and previous-10 days exposure, only for air temperature), in order to capture possible cumulative effects on multiple days. Furthermore, we checked the robustness of our results concerning the time trend adjustment, by modelling it with natural splines with two or six d.f. per year, instead of four. Finally, we used the 50th percentile of air temperature as reference point, instead of the 75^{th}, to estimate the association between air temperature and mortality. More details are reported in the appendix (p 4).

All analyses were conducted using the R statistical software, version 4.1.2 (The R Foundation for Statistical Computing, Vienna, Austria), using the *mgcv*, *spline* and *dlnm* packages in the first-stage analysis and the *mixmeta* package in the second-stage analysis.

3. Results

A map of the geographical distribution of the 620 cities is shown in Fig. 1 (air temperature data), and in Figure S2 (four panels reporting data for the individual pollutants); country-specific descriptive statistics are reported in Table 1, while those for individual cities are reported in the appendix, Table S1. We analysed 22,630,598 deaths from non-external causes (284 cities) or all-causes (336 cities) occurring in 36 countries. The warm season average ambient air temperature ranged from 9 °C in Reykjavik (Iceland) to 36 °C in Kuwait City (Kuwait), with a temperature difference of 4–6 °C between the 75th and the 99th percentile for most cities. PM_{10} and $PM_{2.5}$ warm-season average concentrations varied greatly across cities, with lower values observed in several U.S., Canadian and Scandinavian cities, and highest concentrations detected in “hot spot” areas, such as Kuwait City and Shanghai (China). O_3 concentrations also varied across the 376 cities with available data, ranging from 31 μg/m^3 in Sidney (Australia) to 175 μg/m^3 in the Valley of Mexico. NO_2 mean concentrations ranged between 4 μg/m^3 (in two cities from Japan and the U.S.) and 87 μg/m^3 (in Teheran, Iran).

The pooled estimates of the associations between each environmental exposure and mortality are reported in Table 2. Overall, an increase in air temperature from the 75th to the 99th percentile of the city-specific distribution was associated on average with an 8.9 % (95 % confidence interval [95 % CI]: 7.1 %, 10.7 %) increase in mortality. 10 μg/m^3 increases in lag 0–1 PM_{10}, lag 0 $PM_{2.5}$, lag 0–1 O_3 and lag 0–1 NO_2 daily concentrations were associated with changes in mortality of 0.41 % (95 % CI: 0.28 %, 0.53 %), 0.61 % (95 % CI: 0.40 %, 0.82 %), 0.26 % (95 % CI: 0.15 %, 0.36 %), and 0.57 % (95 % CI: 0.38 %, 0.77 %), respectively. Sensitivity analyses showed that a different definition of the warm season or different lags and model adjustments did not substantially alter the main findings (Table 2).

Overall, we found higher average associations between mean ambient air temperature and mortality on days with high air pollution concentrations (Fig. 2, Table S2 and Figure S3). Increments in mortality when temperature increased from the 75th to the 99th percentile ranged from 5.3 % (95 % CI: 3.8 %, 6.9 %) to 12.8 % (95 % CI: 8.7 %, 17.0 %) when daily mean PM_{10} concentrations were 10 and 90 μg/m^3, respectively. Estimates of temperature-related mortality for concentrations of max-8 h O_3 equal to 40 and 160 μg/m^3 were 2.9 % (95 % CI: 1.1 %, 4.7 %) and 12.5 % (95 % CI: 6.9 %, 18.5 %). Similarly, increments in air temperature between 75th and 99th percentiles were associated to 3.9 % (95 % CI: 2.7 %, 5.1 %) and 12.3 % (95 % CI: 8.6 %, 16.1 %) increases in daily mortality when daily mean $PM_{2.5}$ was equal to 1 or 40 μg/m^3, and to 5.4 % (95 % CI: 1.9 %, 8.9 %) and 11.0 % (95 % CI: 8.4 %, 13.8 %) when daily mean NO_2 was equal to 1 or 60 μg/m^3. Estimates of association between air temperature and mortality increased, on average, steadily from lower to higher pollutants concentrations, were statistically different across levels of air pollutants (Fig. 2, Table S2 and Figure S3), and presented substantial differences across macro-regions, with more pronounced effect modification in European and Australian cities, and little to no effect modification in North American and South African cities (Figure S4).

PM_{10}, $PM_{2.5}$ and O_3 associations with mortality changed little with temperature until about the 80th percentile, but then increased, so that they were highest on hottest days (Fig. 3 and Table S3: mortality increased on average by 1.21 % (95 % CI: 0.69 %, 1.72 %), 1.11 % (95 % CI: 0.27 %, 1.95 %) and 0.53 % (95 % CI: 0.38 %, 0.68 %) per 10 μg/m^3 increments in PM_{10}, $PM_{2.5}$ and O_3, respectively, on days when air temperature was at its 99^{th} percentile. Corresponding estimates on days at the 1^{st} percentile of air temperature were 0.54 % (95 % CI: 0.10 %, 0.98 %), −0.41 % (95 % CI: −1.59 %, 0.79 %) and 0.00 % (95 % CI: −0.44 %, 0.44 %). Continent-specific estimates were largely heterogeneous, with a suggestion of a stronger effect modification in European and Australian cities (Figure S5). We found no clear effect modification of air temperature in the NO_2-mortality association (Fig. 3 and Table S3).

Overall, we found strong evidence of interaction (on a multiplicative scale) between air temperature and each air pollutant: the p-values of the meta-analytical estimates of the product terms were: 3.6e-10 for temperature*PM_{10}, 3.2e-05 for temperature*$PM_{2.5}$, 1.6e-08 for temperature*O_3, and 5.0e-04 for temperature*NO_2 (reported in footnotes of Tables S2 and S3).

4. Discussion

To the best of our knowledge, this is the first epidemiological study reporting the joint effects of high air temperature and air pollution exposures, considering PM, NO_2 and O_3, on daily mortality in countries across all continents. We found evidence of higher heat-related mortality effects with higher levels of daily PM, NO_2 and O_3, as well as increased PM- and O_3-related mortality for higher levels of mean air temperature during the warm months (but not for NO_2). Results were largely heterogeneous across different geographical regions, mostly driven by results in the European and United States cities, and were robust when alternative model adjustments and definitions of the warm season were considered.

The acute effects of heat (Basu, 2009; Song et al., 2017) and air pollution (WHO, 2021; Vicedo-Cabrera et al., 2020; Liu et al., 2019; Orellano et al., 2020; Dominski et al., 2021; Meng et al., 2021) are well established and relatively consistent throughout the literature. Guo et al. investigated the association between non-optimal air temperature and all-cause mortality in 306 communities from 12 countries, and estimated increments in mortality, when temperature increased from optimal values to 99^{th} location-specific percentile, ranging from 4 % in the United States and 30 % in Italy, consistent with the estimate we report in Table 2, despite the substantial differences in terms of data and methods between their study and ours (Guo et al., 2014). Previous analyses of the association between all-cause mortality and daily PM (Liu et al., 2019), O_3; (Vicedo-Cabrera et al., 2020) and NO_2 concentrations (Meng et al., 2021) using data from the MCC collaborative network also provided results very consistent with the ones presented in our Table 2, despite differences in the study locations, all-year versus warm season analysis, and other methodological choices.

However, given that people are simultaneously exposed to multiple environmental risk factors, such as air pollutants and extreme heat, it is important to expand the knowledge basis on the interactive effects of these exposures on health outcomes in order to define appropriate mitigation and response measures. The evidence of interactive effects of air pollution and temperatures has grown in recent years (Chen et al., 2017; Anenberg et al., 2020; Li et al., 2017; Rai et al., 2023; Chen et al., 2018; Analitis et al., 2014; Jhun et al., 2014; Ren et al., 2008; Scortichini et al., 2018; Shi et al., 2020). However, it is still inconclusive, with some areas of the world remaining unstudied and several studies focusing on one-way interactions and/or single pollutant investigation. A recent review on the joint effects of heat and air pollution reported that 19 of the 39 studies carried out in Europe, the United States, Canada, Russia, Taiwan, South Korea, India, Hong Kong, and China showed positive interactive effects on the human health outcomes studied, with the strongest evidence between heat and exposure to O_3 and $PM_{2.5}$ (Anenberg et al., 2020). Findings from our study can be compared with existing evidence in the literature on the positive interactive effects of heat and air pollution on mortality (Rai et al., 2023; Chen et al., 2018; Analitis et al., 2014; Jhun et al., 2014; Ren et al., 2008; Scortichini et al., 2018; Shi et al., 2020). A meta-analysis found a statistically significant modification of the acute effects of PM_{10} or O_3 on total and cardiovascular disease mortality by temperature (Anenberg et al., 2020). Two multi-centre European studies found significant interactions between temperature and air pollution (considering both PM and O_3) and comparable results for this region (Chen et al., 2018; Analitis et al., 2014). A review on the interaction between PM_{10} and air temperature found that most studies reported that temperature modifies the associations between PM and mortality and results on the interactive effect of PM and temperature seem to be robust (Li et al., 2017). On the other hand, results on the interactive effect of air temperature and O_3 seem to be less consistent across regions, countries and cities, showing both positive and negative associations as well as no interaction (Anenberg et al., 2020; Li et al., 2017). A study conducted in 97 U.S. cities using the National Morbidity Mortality Air Pollution Study (NMMAPS) database found that the interaction between O_3 and temperature was not statistically significant. However, there was a suggestive indication that high temperatures may exacerbate physiological responses to short-term O_3 exposure (Jhun et al., 2014).

Personal exposure to ambient air pollutants and outdoor temperatures may be greater in warmer conditions because people tend to spend more time outdoors and open windows more often, especially in countries and periods with limited use of air conditioning (Li et al., 2017; Scortichini et al., 2018). Furthermore, it has been shown that the source, composition and oxidative potential of PM vary seasonally, and some research suggested that more toxic components of PM are higher during the summer season and in the presence of high temperatures (Zhang et al., 2010).

The physiological mechanisms underlying the synergistic association between temperature and air pollutants on mortality are not yet clearly defined; however, a few hypotheses have been proposed as they act on common pathways. High temperatures can increase thermoregulatory stress and alter the physiological response to toxicants, leading to a higher susceptibility to air pollution effects as the uptake, and distribution of air pollutants in the human body is enhanced by the increase in ventilation rate (Li et al., 2017; Gordon, 2003).

Heat may also promote thrombosis through increasing blood viscosity and cholesterol levels secondary to dehydration and salt depletion (Bouchama et al., 2007). It has also been suggested that exposure to PM is associated with systemic and pulmonary inflammation and increased risk of coagulability by increasing blood levels of C-reactive protein and fibrinogen levels (Rückerl et al., 2011). O_3 and NO_2 also increase oxidative stress causing inflammation of the airways and increased permeability of the lung lining, thus impairing host defences against respiratory infections as well as fibrinolysis, thus reducing the efficiency of preventing clot formation and clearance (Anenberg et al., 2020; Li et al., 2017; Chen et al., 2018).

Several strengths should be acknowledged. Firstly, the study included 620 cities from 36 countries across the globe, with very diverse ambient air temperature and air pollution levels in the warm season, and applied common protocols for statistical analysis, representing the largest study on this topic to date to the best of our knowledge. This allowed us to compare results across locations by removing those sources of heterogeneity stemming from different study designs. Secondly, we applied flexible non-linear three-dimensional functions to estimate mortality increments corresponding to joint variations in air pollutants and high temperatures. This made the effect modification results (of air pollutants on temperature-related mortality and vice versa) comparable, as they were obtained from the same joint relationship. Thirdly, we included four key pollutants (PM_{10}, $PM_{2.5}$, NO_2 and O_3) in our analysis, each with a solid background of harmful short-term effects on mortality, and interactive effects with high ambient temperatures. Finally, the extensive sensitivity analyses supported our main results and provided evidence of the robustness of our findings.

The study also has some limitations. Despite the large number of cities included in the analysis, these are non-representative of the entire world population. In fact, there still are areas with limited coverage (the Middle East, Latin America, Australia) or no coverage at all (Northern and Central Africa, Northern Asia). Even within the most represented areas, some countries or regions contributed with data from a limited number of cities (for some countries, just one city), making the study representative of the 620 included cities, rather than the urban populations of the 36 represented countries. Further, rural populations are not represented. Future studies will focus on trying to address this issue by extending the collaborative network to these under-represented areas or countries with few cities, retrieving data, where available and possibly including mortality records from sub-urban and rural areas to investigate different population characteristics, activity patterns, built environment, and air pollution composition. A second limitation of the study is the ecological approach, which assumed constant exposure within the city on a given day, with exposure estimated using averages of limited sets of monitoring stations, which might not fully represent the study areas, and induce some exposure measurement error Unfortunately, we did not have information on the location of the deceased subjects within each city, nor exposure data at a spatial scale finer than the city itself. However, since the focus of the study was on day-to-day variability, and not on fine-scale spatial contrasts, we consider that as a minor limitation with negligible consequences on the overall interpretation, although we recognize that sub-scale heterogeneity in effects, as well as potential residual bias due to exposure measurement error, may exist. Finally, we only analysed natural-cause (or all-cause) mortality data and not cause-specific mortality. A recent review by Anenberg et al. looking at the interactive effect of air pollution and heat found consistent evidence for both total and cause-specific (cardio-respiratory) health outcomes, although the number of the latter studies was limited (Anenberg et al., 2020). We have recently filled this gap by analysing cause-specific mortality data available from the MCC collaborative network: we reported suggestive evidence of effect modification of air pollutants in the relationship between daily air temperature and cardiorespiratory mortality in 482 cities from 24 countries (Rai et al., 2023).

In conclusion, this multicentre study produced new and compelling evidence of the joint effects of high ambient temperatures and air pollution on daily mortality on the global scale. Climate change will increase both average and extreme temperatures (Romanello et al., 2021; IPCC. Climate Change, 2022), as well as indirectly impact air pollution levels by increasing the frequency of stagnation events, enhancing photochemical production of secondary pollutants and increasing "natural" gaseous and PM emissions influenced by warmer and drier conditions having a detrimental impact on human health. (IPCC. Climate Change, 2022; Chen et al., 2020; Vicedo-Cabrera et al., 2021) Public health interventions in response to climate change should consider the synergistic health effects of heat and air pollution focusing on adaptation actions for vulnerable subgroups and promoting mitigation measures that account for both exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

Data will be made available on request.

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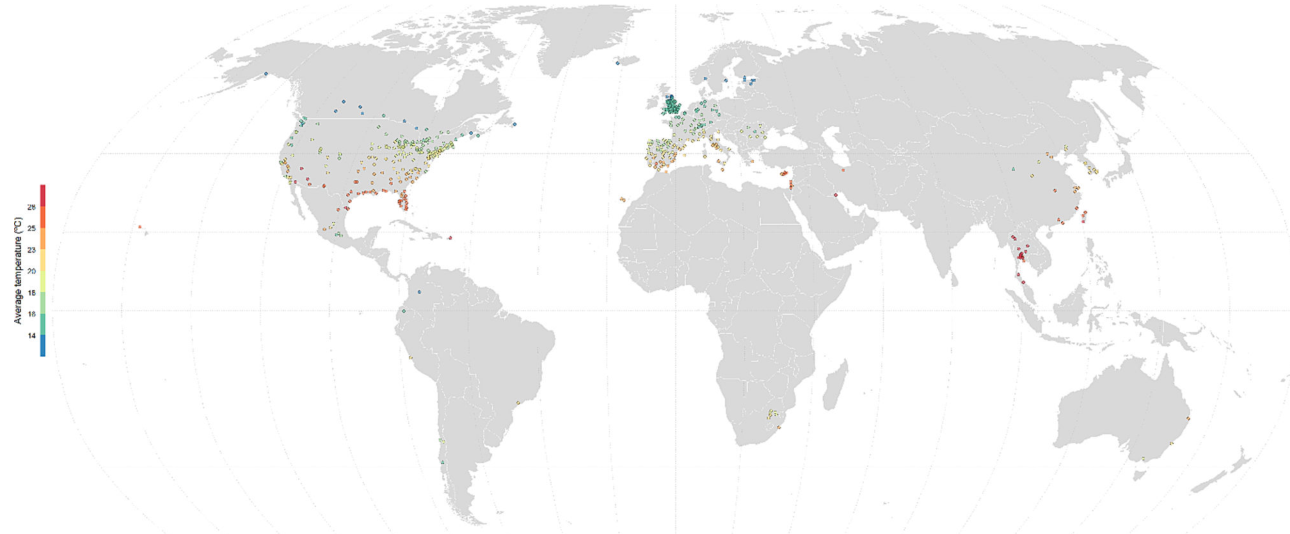

Fig. 1.

Distribution of the cities with data on air temperature and either of the four pollutants. Colour shading represents the average of daily ambient temperature during the warm period in the studied cities.

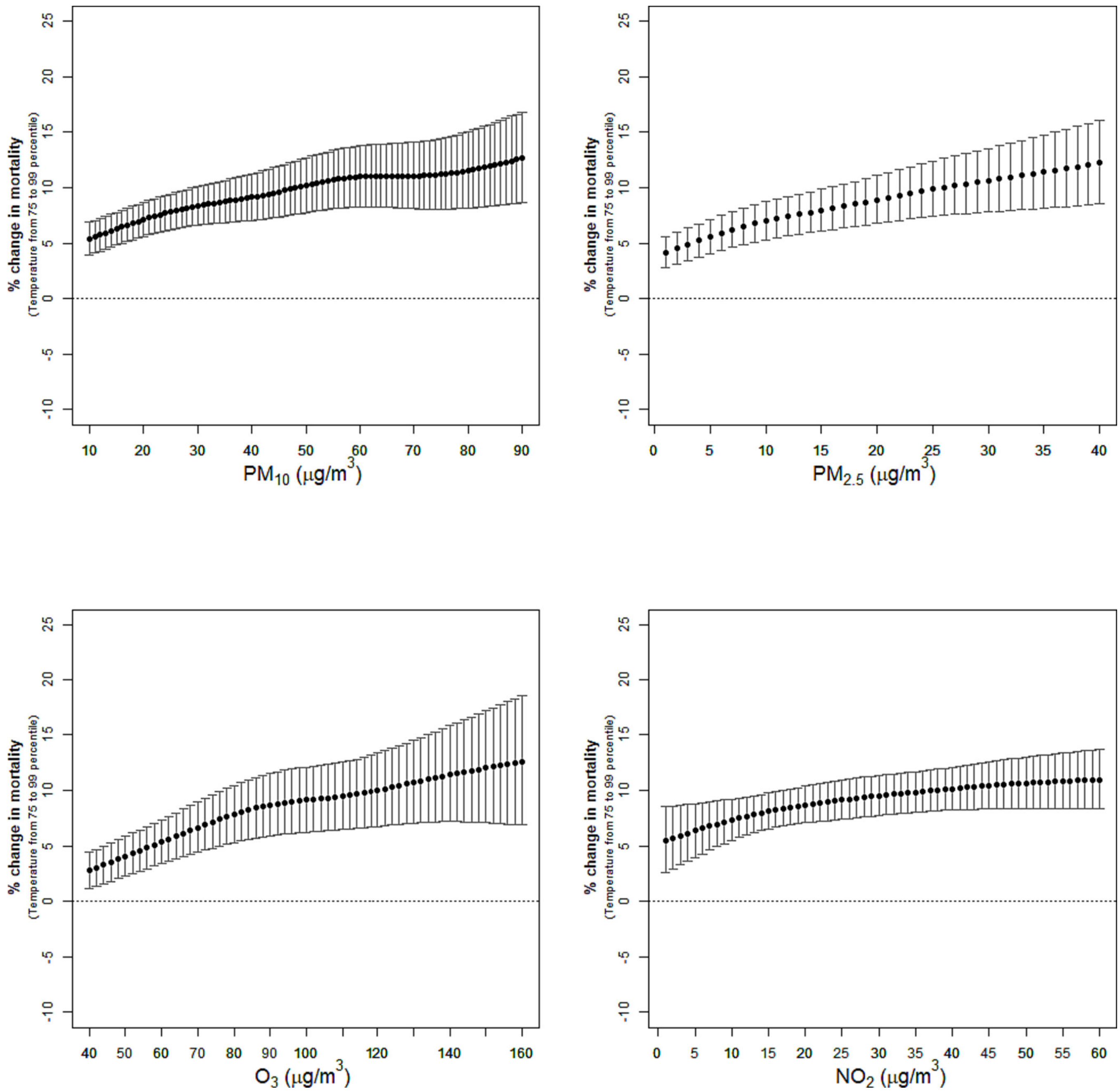

Fig. 2.

Association between daily mean air temperature and all-cause mortality by levels of daily mean air pollutants: % change in mortality, and 95% confidence intervals, per increments of air temperature from the 75^{th} to the 99^{th} percentile of city-specific distributions, for different daily mean concentrations of the four pollutants. Results of the random-effects *meta*-analysis.

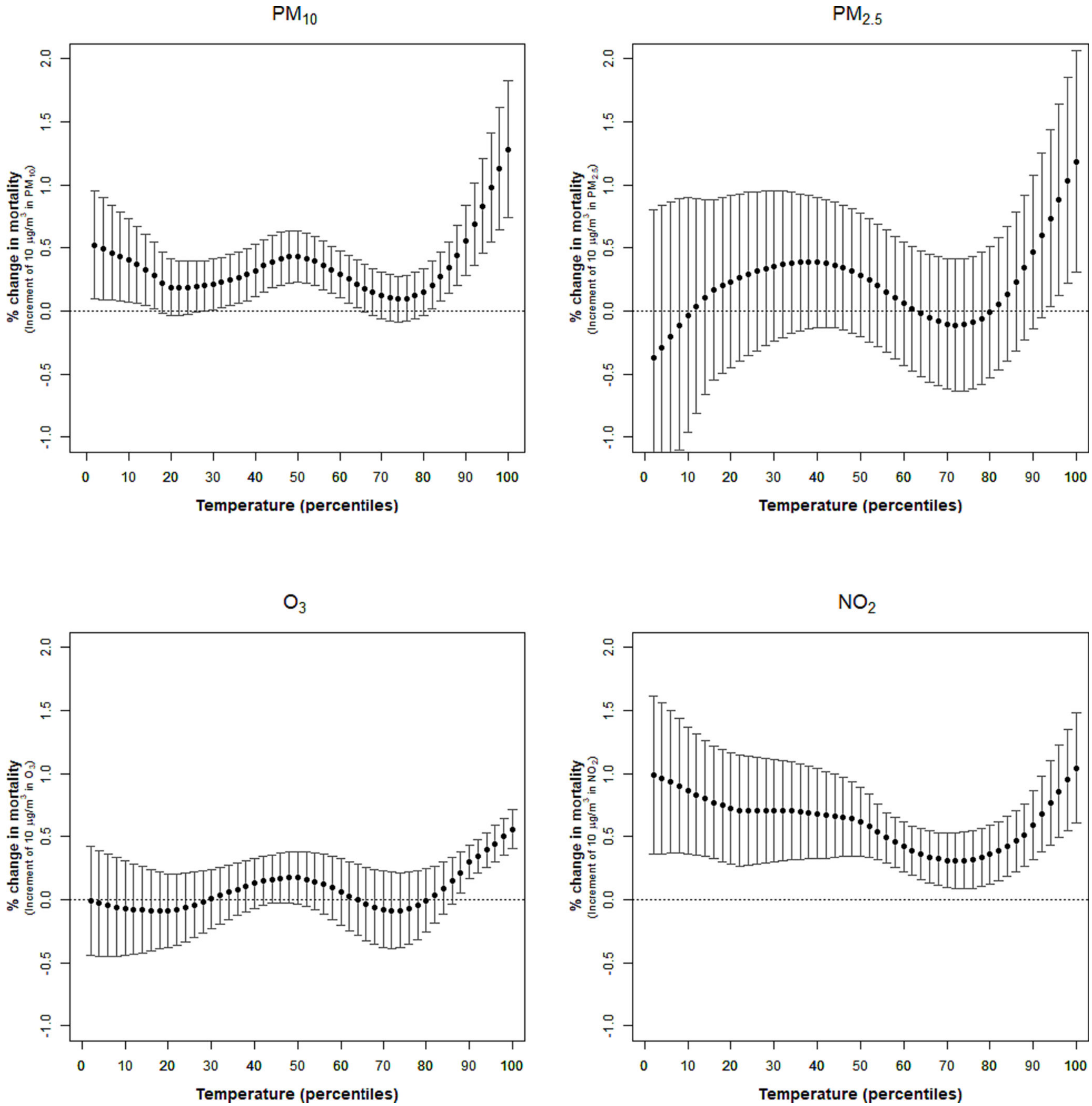

Fig. 3.

Association between daily mean air pollutants and all-cause mortality by percentiles of daily mean air temperature: % change in mortality, and 95 % confidence intervals, per 10 µg/m^3 increments of air pollutants, for different percentiles of air temperature city-specific distributions. Results of the random-effects *meta*-analysis.

Table 1

Environmental and mortality data relative to the warm period only (defined as the six warmest consecutive months in each city): data by country.

Country	N.cities	Period		Mortality		Air temperature			PM$_{10}$*		PM$_{2.5}$†		O$_3$‡		NO$_2$§	
				N. deaths	daily mean	daily mean	75th-99th percentiles		daily mean	SD	daily mean	SD	daily mean	SD	daily mean	SD
Australia	3	2000	2009	241,720	46	21	24	29	20	10	7	5	33	11	17	9
Brazil	1	1997	2011	433,127	171	22	24	27	37	14	–	–	–	–	85	38
Canada	25	1995	2015	1,172,352	13	15	19	26	19	12	8	7	81	31	21	13
Chile	3	2004	2014	144,477	32	17	19	25	45	26	20	13	–	–	18	15
China	14	1996	2015	567,084	48	23	27	32	90	55	50	34	–	–	45	23
Colombia	1	1998	2013	183,207	63	14	15	16	62	20	–	–	–	–	30	10
Cyprus	5	2005	2019	33,777	3	26	28	33	41	41	18	24	–	–	23	10
Czech Republic	1	1995	2009	95,671	35	15	19	25	30	16	–	–	96	27	28	9
Ecuador	1	2014	2018	21,987	24	16	16	19	–	–	15	5	–	–	25	7
Estonia	4	2002	2020	54,359	5	13	17	24	16	11	6	4	52	16	10	9
Finland	1	1995	2014	60,750	17	13	17	24	17	14	14	12	–	–	8	6
France	20	2000	2017	914,028	14	18	21	28	20	9	12	7	–	–	20	11
Germany	12	1995	2015	1,341,855	29	16	19	26	23	13	12	6	74	32	27	12
Greece	1	2001	2010	137,232	75	25	29	33	45	19	23	10	93	22	51	17
Iceland	1	2002	2018	10,364	3	9	11	15	17	14	–	–	–	–	–	–
Iran	1	2002	2015	315,677	132	26	29	35	88	51	–	–	–	–	87	73
Israel	4	2000	2020	184,415	12	25	28	31	43	59	17	17	–	–	19	12
Italy	18	2006	2015	376,961	12	22	25	31	27	12	–	–	92	27	–	–
Japan	49	1995	2019	2,531,598	26	23	27	31	31	17	13	8	84	32	15	9
Kuwait	1	2010	2016	15,903	12	36	39	43	220	202	–	–	–	–	–	–
Malta	1	2006	2019	18,816	8	24	27	31	39	15	18	8	–	–	36	15
Mexico	9	2000	2012	857,491	58	21	23	31	50	24	27	11	117	48	–	–
Norway	1	2000	2018	36,656	11	12	15	22	18	8	9	4	–	–	–	–
Peru	1	2010	2014	88,703	97	21	22	24	82	26	–	–	–	–	25	11
Portugal	6	1995	2018	461,206	24	20	23	30	24	16	10	7	79	24	16	13
Puerto Rico	1	2009	2016	13,241	9	28	29	30	30	18	–	–	–	–	–	–
Romania	8	2008	2016	174,385	14	19	23	29	28	14	13	7	–	–	22	12

Country	N.cities	Period		Mortality		Air temperature			PM_{10} *		$PM_{2.5}$ †		O_3 ‡		NO_2 §	
				N. deaths	daily mean	daily mean	75th-99th percentiles		daily mean	SD	daily mean	SD	daily mean	SD	daily mean	SD
South Africa	7	2004	2013	478,780	55	21	23	27	44	28	25	18	73	29	–	–
South Korea	7	1999	2015	810,954	37	22	25	30	46	24	–	–	74	31	40	18
Spain	51	2001	2014	768,533	7	21	24	30	29	15	13	8	78	23	26	12
Sweden	1	1995	2010	71,764	24	14	17	23	14	7	8	5	69	19	27	11
Switzerland	8	1995	2013	110,620	4	16	20	26	21	11	15	8	91	36	29	15
Taiwan	3	1995	2014	523,614	47	28	29	31	50	23	27	13	115	42	36	14
Thailand	18	1999	2008	404,853	13	29	30	33	44	24	–	–	–	–	21	12
United Kingdom	123	1995	2018	2,138,448	7	15	17	22	20	10	11	4	–	–	24	13
United States	209	1995	2006	6,835,990	16	21	26	32	28	15	13	8	93	35	27	16

[*] Canada 8 cities, Colombia 2001–2013, Mexico 7 cities, Portugal 5 cities, Romania 3 cities, South Africa 6 cities, Spain 42 cities 2001–2014, UK 31 cities, United States 89 cities.

[†] China 3 cities 2013–2015, Chile 2008–2014, Cyprus 2 cities, Estonia 3 cities 2008–2018, Germania 11 cities 2004–2015, Greece 2007–2010, Israel 3 cities, Japan 48 cities, Mexico 2 cities 2003–2012, Portugal 4 cities 2004–2018, Romania 7 cities, South Africa 5 cities, Spain 11 cities, Sweden 2001–2010, Switzerland 4 cities, Taiwan 2007–2014, UK 119 cities, United States 203 cities.

[‡] Italy 14 cities, South Africa 6 cities, Spain 49 cities, United States 189 cities. For Japan, ozone data was derived from the measurements of photochemical oxidant, which is primarily ozone (≥90 %), followed by others such as peroxyacetyl nitrate (PAN), hydrogen peroxide (H2O2) and organic hydroperoxides.

[§] France 18 cities, Spain 48 cities, UK 36 cities, United States 130 cities.

Table 2

Association between daily mean air temperature, air pollutants and all-cause mortality in the warm season: % change in mortality, and 95% confidence intervals, at the specified increment of the exposure. Meta-analytical results of the main model and of the sensitivity analyses*.

Exposure	Increment (percentiles)	Model	N. cities	% change	95 % CI	
Air temperature	75^{th}-99^{th}	Main model	620	8.89	7.12	10.68
		Adj. lag 0–1 PM_{10}	372	8.56	6.99	10.16
		Adj. lag 0 $PM_{2.5}$	486	8.00	6.16	9.88
		Adj. lag 0–1 O_3	386	8.76	6.28	11.29
		Adj. lag 0–1 NO_2	411	8.87	7.25	10.51
		Warm season as 3 months	620	9.02	7.07	11.01
		Time trends 2 d.f./year	620	8.79	7.03	10.59
		Time trends 6 d.f./year	620	8.59	6.86	10.35
		Lag 0–3	620	8.66	6.59	10.76
		Lag 0–10	620	5.84	4.01	7.70
	50th-99th	50th pct as reference	620	10.65	8.30	13.05
PM10	10 μg/m^3	Main model	372	0.41	0.28	0.53
		Warm season as 3 months	369	0.52	0.29	0.74
		Time trends 2 d.f./year	372	0.40	0.25	0.55
		Time trends 6 d.f./year	372	0.41	0.28	0.54
		Lag 0–3	369	0.25	0.13	0.37
PM2.5	10 μg/m^3	Main model	486	0.61	0.40	0.82
		Warm season as 3 months	482	0.58	0.31	0.85
		Time trends 2 d.f./year	486	0.64	0.43	0.86
		Time trends 6 d.f./year	486	0.55	0.34	0.77
		Lag 0–3	389	0.34	0.05	0.62
O3	10 μg/m^3	Main model	386	0.26	0.15	0.36
		Warm season as 3 months	386	0.23	0.11	0.35
		Time trends 2 d.f./year	386	0.21	0.09	0.33
		Time trends 6 d.f./year	386	0.26	0.15	0.37
		Lag 0–3	386	0.26	0.14	0.39

Exposure	Increment (percentiles)	Model	N. cities	% change	95 % CI	
NO2	10 μg/m^3	Main model	411	0.57	0.38	0.77
		Warm season as 3 months	411	0.54	0.37	0.70
		Time trends 2 d.f./year	411	0.52	0.32	0.73
		Time trends 6 d.f./year	411	0.57	0.38	0.76
		Lag 0–3	411	0.54	0.32	0.75

* "Main model": exposure modelled with a natural spline with 4 d.f. (air temperature) or a linear term (air pollutants) at lag 0–1, warm season defined as the 6 consecutive warmest months; "Adj. poll": model adjusted for the specified air pollutant (at the specified lag), with a linear term; "Warm season as 3 months": warm season defined as the 3 consecutive warmest months; "time trends 2.d.f./year": time trend modelled with 2 d.f./year instead of 4; "time trends 6.d.f./year": time trend modelled with 6 d.f./year instead of 4; "lag 0–3": exposure modelled with a lag 0–3 term (instead of lag 0–1); "lag 0–10": air temperature modelled with a lag 0–10 term (instead of lag 0-.