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PII: S0160-4120(25)00177-1
DOI: https://doi.org/10.1016/j.envint.2025.109426
Reference: EI 109426

To appear in: *Environment International*

Received Date: 20 August 2024
Revised Date: 5 February 2025
Accepted Date: 28 March 2025

Please cite this article as: J. de Bont, A. Rajiva, S. Mandal, M. Stafoggia, T. Banerjee, H. Dholakia, A. Garg, V. Ingole, S. Jaganathan, I. Kloog, B. Krishna, K. Lane, R.K. Mall, J. Menon, A. Nori-Sarma, D. Prabhakaran, A.S. Tiwari, Y. Wei, G.A. Wellenius, J. Schwartz, P. Prabhakaran, P. Ljungman, Synergistic associations of ambient air pollution and heat on daily mortality in India, *Environment International* (2025), doi: https://doi.org/10.1016/j.envint.2025.109426

Synergistic associations of ambient air pollution and heat on daily mortality in India

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Highlights:

- Unique multi-city study evaluating the interaction between air pollution and heat in India.
- We used two advanced spatiotemporal models to estimate daily exposure levels.
- We observed substantial synergistic interaction between air pollution and heat in India.
- Heat-related mortality was 1.5 times higher at the most extreme $PM_{2.5}$ levels.
- Efforts to reduce common sources of air pollution and climate change to lower daily mortality.

Abstract:

Background: Limited studies have evaluated the interaction between ambient air pollution and heat on mortality, especially in regions such as India, where extreme levels of both exposures occur frequently. Accordingly, we aimed to investigate the potential synergistic effects between ambient air pollution and heat on daily mortality in India.

Methods: We applied a time-series analysis for ten cities in India between 2008-2019. We assessed city-wide daily particulate matter ≤2.5μm ($PM_{2.5}$) and temperature levels using two nationwide spatiotemporal models. We estimated city-specific exposure-outcome associations through generalised additive Poisson regression models, and meta-analysed the associations. To evaluate the interaction between $PM_{2.5}$ and air temperature (modelled at lag 0–1), a product term was incorporated between linear $PM_{2.5}$ and non-linear air temperature. From this model, we estimated the effect of air pollution for increasing levels of temperature, and vice versa.

Findings: Among ~3.6 million deaths, we found that the association of $PM_{2.5}$ on mortality was particularly stronger beyond the 75th percentile of temperature. When we compared the associations of $PM_{2.5}$-mortality at the 75th and 99th temperature percentile, we observed an increase from 0.8% (95% CI: -0.3%, 1.9%) to 4.6% (95% CI: 2.9%, 6.5%) increase in mortality per 10 μg/m^3 increments, respectively. In addition, we observed a 22.0% (95% CI: 13.5%, 31.2%) increase in daily mortality risk due to an increase in temperature from the 75th to the 99th city-specific percentiles. Percent change in mortality risk increased linearly from 8.3% (95% CI: 2.2%, 14.9%) when daily $PM_{2.5}$ was 20 μg/m^3 to 63.9% (95% CI: 38.7.%, 93.7%) at 100 μg/m^3.

Interpretation: Our findings reveal a substantial synergistic interaction between ambient air pollution and temperature in India. This calls for efforts to tangibly reduce common sources of air pollution and

climate change to immediately lower their combined effects on daily mortality and mitigate their long-term health consequences.

Key words: India, ambient air pollution, heat, interaction, climate change.

1. Introduction

Climate change is considered the biggest health threat facing humanity, as stated by the World Health Organization (World Health Organization, 2021). Climate change can affect human health through multiple exposure pathways such as extreme weather events (e.g. floods, droughts), increased disease vectors, and ambient air pollution and extreme temperatures, among many others (Romanello et al., 2023). Among these, extreme temperatures have been identified as the most important factor in weather-related deaths globally (Abbafati et al., 2020; Ebi et al., 2021). Particulate matter air pollution (both indoor and ambient) has an even larger public health impact and is considered the leading contributor to the Global Burden of Disease, leading to 8.0% of the total disability-adjusted life-years (DALYs) (Brauer et al., 2024). People in south Asia, sub-Saharan Africa, and parts of north Africa and the Middle East at greatest risk (Brauer et al., 2024; Health Effects Institute, 2024). Clearly both air pollution and high temperature individually represent public health threats but studies evaluating interactive effects between these two environmental factors are limited, potentially underestimating their joint health effects and mitigation opportunities (Anenberg et al., 2020).

Pointedly, the combustion of fossil fuels is a source of both air pollution and greenhouse gases, the latter of which contribute to both climate change and are the target of climate mitigation strategies. By reducing fossil fuel combustion for energy production, these strategies will also concurrently decrease air pollution (Keswani et al., 2022). This dual benefit will help in reducing the health effects of both climate change and ambient air pollution (Keswani et al., 2022). The need to mitigate the effects of climate change is especially critical in India, where temperatures have been rising over the past decades, and a majority of the population is exposed to extreme levels (Mazdiyasni et al., 2017).

To date, the potential synergistic effects of extreme air pollution and high temperature on health remain inconclusive (Anenberg et al., 2020; Cheng et al., 2024; Hu et al., 2022; Rai et al., 2023; Stafoggia et al., 2023; Zafeiratou et al., 2024). A review found that 48% of the included studies identified an interaction between air pollution and heat on various health outcomes (Anenberg et al., 2020). Most studies have mainly explored if one exposure modified the other exposure-mortality relationship, such as a recent meta-analysis that did not establish that particulate matter ≤2.5μm ($PM_{2.5}$) modified temperature-related mortality (Hu et al., 2022; Li et al., 2017). The most comprehensive study so far included 620 cities across 36 countries and, in contrast, suggested an interaction between air temperature and air pollution on daily mortality (Stafoggia et al., 2023). Nevertheless, comparing these studies is challenging due to the heterogeneous methodologies used to evaluate the interaction between both exposures, and the limited data available from low- and middle-income countries (LMICs) such as India. This is important because the intersection of high concentrations of ambient air pollution and extremes of heat are more likely to occur in LMICs situated in the global south. Furthermore, understanding the health implications of co-occurring environmental extremes can inform more targeted strategies for policymakers and healthcare professionals to manage the combined impacts of both exposures.

Our objective was to carry out a comprehensive analysis across multiple Indian cities, using two national spatiotemporal exposure models to estimate daily air pollution and temperature levels. We used a distinctive dataset of daily mortality levels from ten different cities in India. Our specific aim was to investigate the synergistic effect between ambient air pollution and heat on daily mortality in India.

2. Methods

2.1. Daily mortality data collection

We collected daily counts of all-cause mortality from the death registries of 10 city municipal corporations in India, spanning various climate zone classifications from arid to tropical monsoon and temperate climates. The included cities were Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Kolkata, Mumbai, Pune, Shimla, and Varanasi. The period of data collection extended from 2008 to 2019, with varying length of available data for each city, from 3 to 9 years. The selection of these 10 cities was based on data availability and the feasibility of collaboration. In the absence of International Classification of Diseases (ICD) codes for most cities to estimate cause-specific mortality, we cleaned and aggregated the de-identified mortality records obtained from the municipalities to estimate daily counts of all-cause mortality for each municipal corporation.

2.2. Exposure assessment

We generated daily average $PM_{2.5}$ concentrations and mean temperature at 1 km x 1 km spatial resolution across India using two separate hybrid ensemble averaging approaches (temperature model currently under review) (Mandal et al., 2024). Briefly, we collected ground monitoring-based observations of daily average $PM_{2.5}$ and PM_{10} across 1056 locations as well as 650 temperature stations and an extensive set of predictors including satellite-based observations, meteorology, land-use patterns, emissions inventories, and reanalysis-based data. We trained our models using four machine learning methods (deep learning, random forests, gradient boosting, and extreme gradient boosting) on the training data (80% of the available monitors) for both the air pollution and temperature model (Mandal et al., 2024). The temperature model additionally used Extreme Random Forests as a predictor model. The optimised models were implemented on the left-out validation data (20% of the monitors) to obtain learner-specific predictions and combined using a Gaussian process regression for the PM model and a Gradient Boosting method for the temperature model as well as to obtain the final predictions. This methodology allowed us to obtain $PM_{2.5}$ and temperature exposures in regions with no monitoring data across time as well as variances across different land spaces. The daily ensemble averaged predictions for $PM_{2.5}$ had a cross-validated R^2 of 86% and mean absolute error ranging between 14.1 - 25.4 μg/m^3 across India. The daily ensemble averaged predictions for temperature had a cross-validated robust R^2 of 93% and mean absolute error ranging between 0.9 - 1.4 °C across the country. In this study, we estimated daily population weighted air pollution and temperature levels including all 1km x 1km grid cells contained within the boundaries of each of the 10 municipal boundaries included in the study.

2.3. Statistical analysis

Individual associations of air pollution and heat

We previously published the individual effect of $PM_{2.5}$ using the method described subsequently and have included it here to facilitate interpretation and comparison to the interaction effect (de Bont et al., 2024). We applied a two-step analytical framework to evaluate the associations of $PM_{2.5}$ and temperature with daily mortality. We first estimated city-specific associations and subsequently performed a meta-analysis of these associations in the second step. We applied a quasi-Poisson generalised additive model to evaluate the city-specific associations. These models were adjusted for several time-varying covariates, including a penalised spline function of calendar day (nine degrees of freedom[*df*] per year) to accommodate long-term and seasonal trends, and a day-of-week indicator to address weekly variations. For air pollution estimates we additionally adjusted for temperature as prior literature has indicated that temperature is an important confounder of air pollution - mortality relationships, while the inverse (air pollution as a confounder of temperature) is less clear (Hu et al., 2022; Li et al., 2017). For both $PM_{2.5}$ and air temperature, we modelled the average level of the current and previous day (lag 0-1), which is the most commonly used lag in the literature on acute air pollution and heat effects on mortality (A et al., 2015; Liu et al., 2019; Stafoggia et al., 2023). We conducted separate analyses for each exposure, considering a linear association for $PM_{2.5}$ and a nonlinear association for temperature, modelling temperature with a natural spline with 4 degrees of freedom (4df). The effect estimates were expressed as percentage change in daily mortality per 10 μg/m^3 increase for $PM_{2.5}$ and for heat for an increase in mean temperature from 75th to 99th of the city-specific distributions. In the second step, a random-effects meta-analytical model was employed to aggregate the city-specific estimates of associations between $PM_{2.5}$ and heat with mortality. I^2 statistics and Cochran's Q-test were computed to assess between-city heterogeneity.

Interaction between air pollution and heat

The two-step analytical framework was also applied to evaluate the interaction between air pollution and heat. To do so, we added an interaction term between air pollution (lag 0-1) modelled as a linear term and air temperature (lag 0-1) modelled as nonlinear term by adding a natural spline (Stafoggia et al., 2023). We defined 'interaction' on a multiplicative scale as the deviation from the expected combined effect of air pollution and heat on mortality if they were acting independently. By adding an interaction between a spline and a linear term, we obtain a 3-d curve presenting relative risks at all combinations of PM concentrations and temperature percentiles. Hence, the interaction term allows us to extrapolate the change in mortality per 10 μg/m^3 increase of $PM_{2.5}$ from the 1st to the 99th air temperature percentiles of each city distribution. We additionally were able to extrapolate the percent change in mortality due to the increase in mean temperature from the 75th to 99th percentile, corresponding to an increase of daily average concentration of $PM_{2.5}$ from 20 μg/m^3 until 100 μg/m^3. The selection of these predefined $PM_{2.5}$ ranges was guided by an examination of city-specific air pollutant distributions at different temperature percentiles. We did not observe sufficient observations below 20 μg/m^3 and above 100 μg/m^3 (Figure S1). In general, as temperatures increase, $PM_{2.5}$ levels typically fall as convective currents collect and disperse local pockets of high pollution into the upper atmosphere away from measurement and inhalation (Li et al., 2015; Yang et al., 2017). In our data, some cities reached their peak pollution levels, around 100 μg/m^3, during the hottest days (Figure S1). However, there were some cities that exceeded this pollution level, but only during significantly colder days when $PM_{2.5}$ was less dispersed (Liu et al., 2020). We further evaluated the p-value for interaction by extracting the interaction terms (beta estimates) from the interaction model for each city. We then meta-analysed these estimates and applied a Wald test to determine statistical significance of the interaction. To visualise the interaction between air pollution and temperature for each city, we showed three-dimensional surfaces by applying thin-plate splines (Wood, 2003).

Sensitivity analyses

We conducted multiple sensitivity analyses to assess consistency of our findings. First, to evaluate the robustness of our adjustments for time trends, we applied different *df*/year from 6 to 10*df*/year compared to 9 from our main analyses. Second, we evaluated different lag patterns including a 4-day moving average (lag 0-3) for both exposures, and for temperature we additionally evaluated a 11-day moving average (lag 0-10), in order to capture delayed effects of heat. In addition, we applied a lag structure using a DLNM model using the same lag patterns instead of the moving average to validate our primary lag approach. Third, we focused on the hottest period of the year as our analysis was focused on heat, by restricting our analyses to the four consecutive hottest months for each city (models were adjusted including a penalised spline smooth with 3*df*/year and a day-of-week indicator). We selected four months to capture only the summer season and to avoid overlap with the monsoon period.

3. Results

In these 10 cities in India, over 3.6 million deaths occurred from 2008 to 2019. The average daily $PM_{2.5}$ levels were the highest in Delhi (113 µg/m^3) and Varanasi (82 µg/m^3), while the lowest in Shimla (28 µg/m^3) (Table 1). On days when the temperature exceeded the 75th percentile, cities such as Ahmedabad, Mumbai, and Shimla experienced higher daily mean $PM_{2.5}$ levels compared to the annual daily mean. Conversely, mean $PM_{2.5}$ levels were lower in Delhi, Kolkata, and Varanasi during the warmest days, but showed higher levels during the coldest days (Figure S1). Daily mean temperatures were the highest in Chennai (32.4 °C) and the lowest in Shimla (15.6 °C). In line with the air pollution levels, cities such as Ahmedabad, Mumbai, and Shimla had higher mean temperatures during extreme air pollution events (above the 75th percentile). In contrast, in Delhi, Kolkata, and Varanasi, the mean temperature was lower during these high pollution events.

Table 1: descriptive of the study population.

City	Time period	Daily deaths, mean (SD)	$PM_{2.5}$ mean µg/m^3 (SD)	$PM_{2.5}$ above 75th temp, mean µg/m^3 (SD)	Temperature, Mean °C (SD)	Temperature, above 75th $PM_{2.5}$, Mean °C (SD)
Ahmedabad	2008 - June 2019	122 (24)	37.9 (9.7)	45.2 (13.8)	27.0 (4.8)	31.0 (3.1)
Bangalore	2008 - 2012	121 (17)	33.0 (6.5)	37.5 (4.8)	23.6 (2.1)	24.8 (2.5)
Chennai	2010 - 2019	164 (23)	33.7 (9.0)	32.4 (6.3)	28.6 (2.4)	27.0 (2.7)
Delhi	2011 - 2018	284 (44)	113.0 (64.5)	82.4 (25.9)	24.5 (7.2)	17.0 (4.8)
Hyderabad	2008 - June 2011	78 (13)	38.9 (10.4)	42.3 (7.5)	27.1 (3.6)	26.3 (4.6)
Kolkata	2010 - 2019	172 (32)	55.2 (35.3)	32.3 (9.2)	26.5 (4.3)	20.3 (2.6)
Mumbai	2009 – Nov. 2015	251 (28)	41.7 (18.5)	35.0 (12.6)	26.8 (2.3)	25.2 (2.1)
Pune	2008 - 2012	68 (11)	45.3 (22.6)	43.7 (15.6)	24.6 (3.2)	22.0 (2.5)

Shimla	2008 – Aug. 2012	4 (2)	28.4 (6.9)	31.3 (9.4)	15.6 (4.7)	17.7 (4.3)
Varanasi	2008 – Nov 2018*	22 (6)	82.1 (35.3)	63.5 (12.6)	25.9 (6.4)	18.2 (4.0)

* No data was available for Varanasi in 2017

Air pollution and mortality at different temperature levels

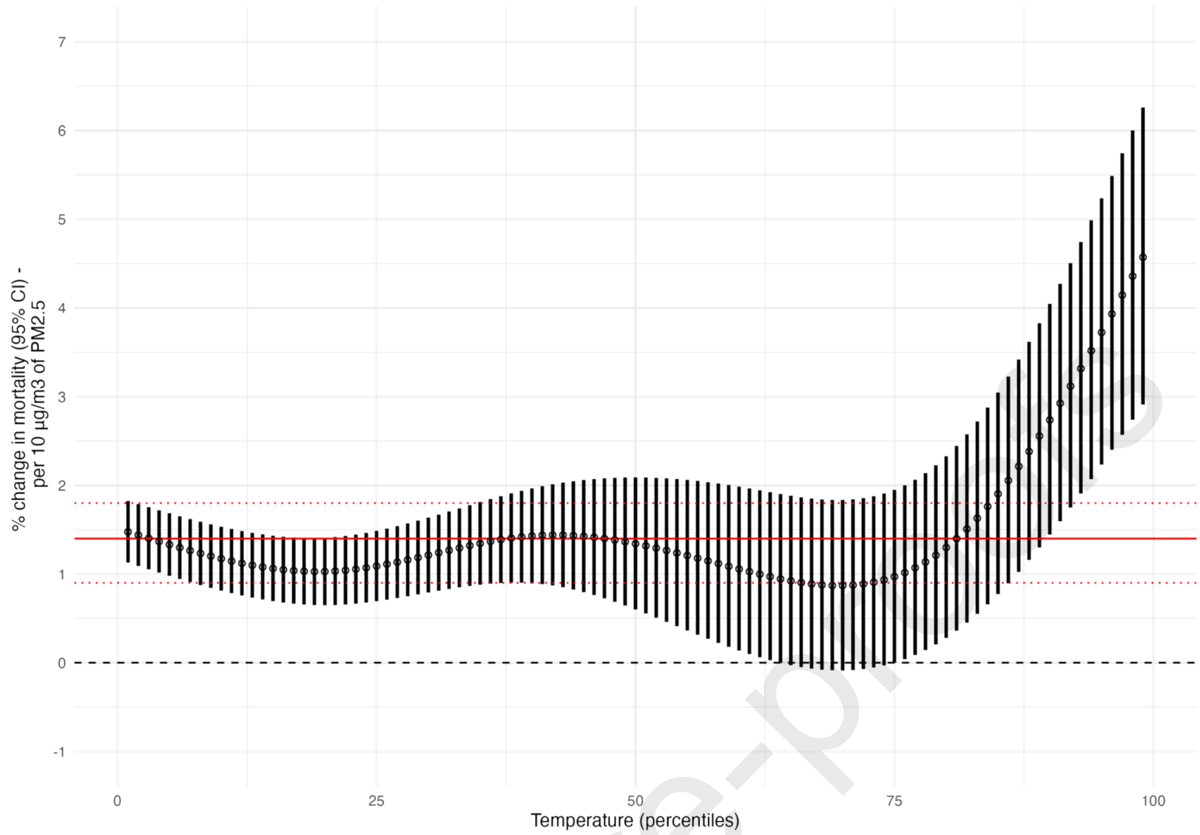
As in our previous publication (de Bont et al., 2024), we observed that a 10 µg/m^3 increment in $PM_{2.5}$ was associated with a 1.4% (95%CI, 0.9%, 1.8%) increase in daily mortality (Figure S2). In our interaction analysis, we found that the association of $PM_{2.5}$ on mortality was stronger at higher temperature percentiles (p-value for interaction <0.001), particularly beyond the 75th percentile (Figure 1 and Table S1). Specifically, the associations of $PM_{2.5}$ increased from a 0.8% (95% CI: -0.3%, 1.9%) percent change in mortality per 10 µg/m^3 increase in $PM_{2.5}$ when the daily temperature was at the 75th percentile, to a 4.6% (95% CI: 2.9%, 6.5%) percent change at the 99th percentile. This increasing trend after the 75th percentile was observed in most cities, particularly in Chennai, Delhi, and Kolkata (Figure S3). In Varanasi, we observed an increasing trend from the 25th to the 75th percentile, which then decreased thereafter.

Heat and mortality at different air pollution levels.

In our heat analyses, we observed a 22.0% (95% CI: 13.5%, 31.2%) increase in daily mortality rate due to an increase in temperature from the 75th to the 99th city-specific percentiles. The association of increased temperature with mortality was highest in the cities of Ahmedabad (38.1% [95% CI: 33.4%, 43.0%]) and Varanasi (60.3% [95% CI: 50.6%, 70.6%]), whereas it was lowest in Bangalore (7.1% [95% CI: 3.4%, 11.0%]) (Figure S2). No statistically significant associations were observed in Shimla.

In our interaction analysis, we observed a linear increase in the association of temperature with mortality as air pollution levels increased (p-value for interaction <0.001) (Figure 2 and table S1). Specifically, the percent change in mortality risk due to an increase in temperature from the 75th to the 99th city-specific percentiles increased from 8.3% (95% CI: 2.2%, 14.9%) when daily $PM_{2.5}$ was 20 µg/m^3 to 63.9% (95% CI: 38.7.%, 93.7%) at 100 µg/m^3. Between 24 µg/m^3 and 55 µg/m^3, all cities contributed to the meta-analyses, observing an increase from 11.1% (95% CI: 3.8%, 18.9%) to 29.6% (95% CI: 19.9%, 38.8%), respectively. This increasing trend was observed in most cities, particularly in Ahmedabad, Chennai, Delhi, and Kolkata, whereas a decreasing trend was only observed in Varanasi (Figure S4).

Figure 1: The association between air pollution (per 10 µg/m^3) and daily all-cause mortality across temperature percentiles (the red line represents the % change in mortality, and the dashed lines show the 95% CI from the non-interaction model).



Note: the effect estimates are shown in Table S1.

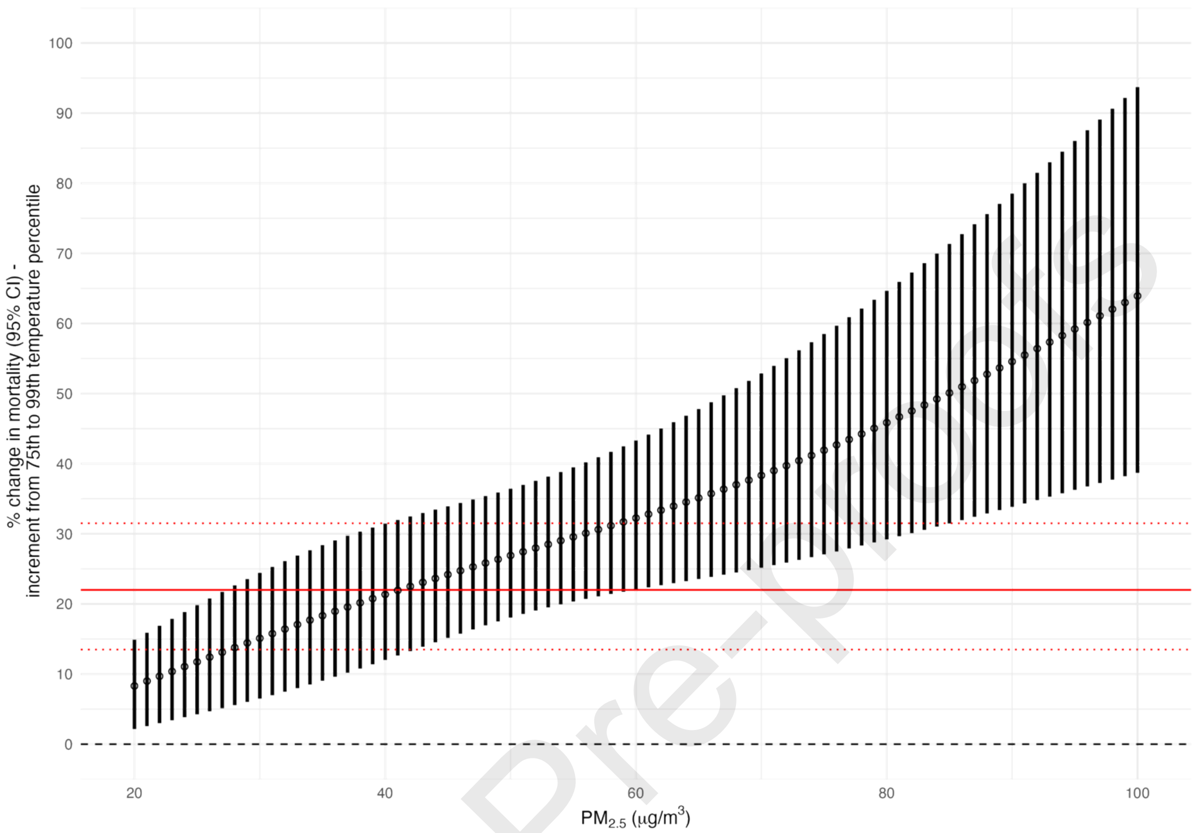
Thin-plate spline regression:

The results of the thin-plate spline regression for almost all cities showed higher mortality risk at higher temperatures compared to higher air pollution levels (Figure 3). In addition, In the cities of Ahmedabad, Bangalore, Chennai, Delhi, Kolkata, Pune and Varanasi, we observe a consistent increase of mortality at high temperature percentiles as $PM_{2.5}$ levels increase from 20µg/m³ to 100µg/m³. For Hyderabad, Mumbai and Shimla, there was no clear interaction observed.

Sensitivity analyses.

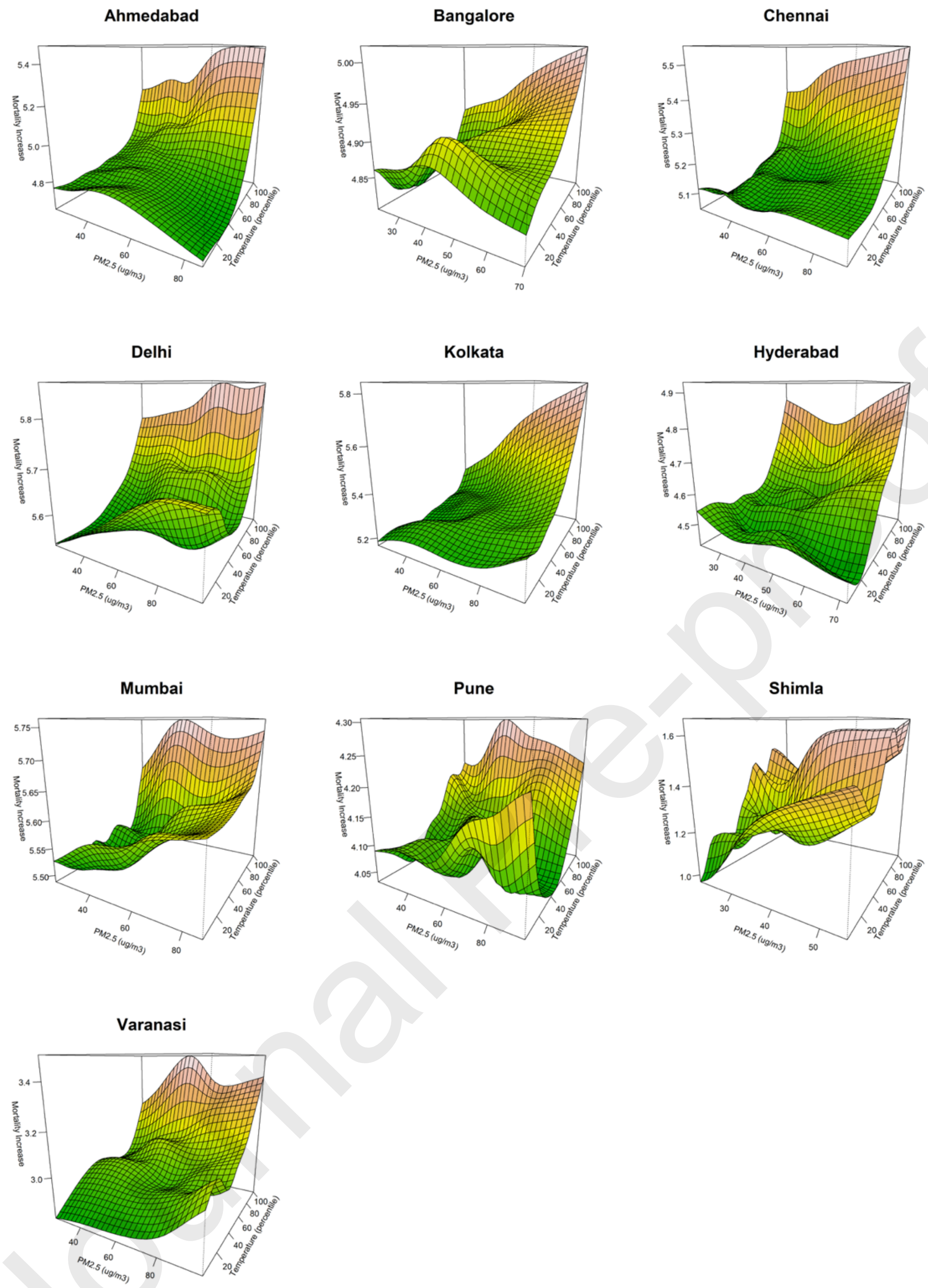
In our sensitivity analyses for both air pollution and heat, we found similar associations when adjusting for different time trends by varying the *df* per year (from 6 to 10 *df/year*) (Figure S5). When exploring different lag patterns, we observed similar effect estimates using a lag of 0-3 for both air pollution and heat. However, we did observe a reduction in the association between heat and mortality using the lag 0-10. We observed nearly identical estimates using the DLNM lag structure compared to our main moving average approach. Further, we observed a slightly larger association when we evaluated the increased effect of temperature from the 50th, rather than the 75th used in the main analysis, to the 99th percentile on mortality. When we limited our analyses to the four consecutive hottest months and in line with our main results, we found that the association of $PM_{2.5}$ on mortality was stronger beyond the 75th percentile of temperature Figure (S6). We further observed lower effect estimates of air pollution below the 50th percentile of temperature during the hottest months. In addition, we observed stronger associations between heat and mortality during the hottest months (Figure S7). The interaction effect of air pollution on the association between heat and mortality followed a similar effect estimate until 70 µg/m³ (Figure S7). After 70 µg/m³, the effect estimates were slightly lower than our main approach.

Figure 2: The association between air temperature (an increment from 75th to the 99th percentile distribution) and all-cause mortality at different $PM_{2.5}$ levels (the red line represents the % change in mortality, and the dashed lines show the 95% CI from the non-interaction model).



Note: the effect estimates are shown in Table S1.

Figure 3: Thin plate splines showing the synergistic interactions between $PM_{2.5}$ (between 20 and 100 µg/m³) and temperature (percentiles) on mortality.



4. Discussion

Across 10 cities in India characterised by frequent days of either extreme air pollution or high temperatures, we observed that both $PM_{2.5}$ and temperature were positively associated with mortality. We observed that the associations between $PM_{2.5}$ and daily mortality were more pronounced at higher temperatures. We further found that heat-related mortality was substantially amplified with rising levels of $PM_{2.5}$, with the percent change in heat-mortality being almost 1.5 times higher at the most extreme $PM_{2.5}$ levels. The synergistic associations between $PM_{2.5}$ and temperature on mortality were consistently evident in three-dimensional visualisations across the different cities, highlighting the crucial interaction between these environmental factors across India.

The individual associations of ambient air pollution and heat on mortality in our study are higher compared to larger global multi-city meta-analyses studies (Liu et al., 2019; Stafoggia et al., 2023). A comparable study including 372 cities worldwide reported a 0.4% increase in mortality for every 10 μg/m³ increase in $PM_{2.5}$, which is lower than the 1.4% increase observed in our study published previously (de Bont et al., 2024; Stafoggia et al., 2023). Furthermore, the same study found that a temperature increase (from the 75th to the 99th percentile) across 620 cities was associated with an 8.9% rise in mortality, substantially lower than our observed 22% increase (Stafoggia et al., 2023). These differences in effect size could be attributed to the extreme levels of air pollution and temperature observed in the cities in our study, as well as variations in socio-demographic structures, vulnerable subpopulations, air pollution composition and toxicity, and climatic differences.

Our study showed substantial interactions at the extreme levels of both air pollution and temperature. Previous studies have generally reported inconclusive results, as highlighted by a meta-analysis showing that only 19 out of 39 studies observed interactions between air pollution and heat (Anenberg et al., 2020). Methodological differences in evaluating these interactions make direct comparisons challenging. However, one study using a similar statistical approach, including approximately 480 cities worldwide (excluding cities from India), reported that the associations of PM2.5 increased from 0.1% per 10 μg/m³ at the 75th percentile of temperature to 1.2% at the 99th percentile (Stafoggia et al., 2023). In contrast, our study found a substantially higher increase in associations, ranging from 0.8% to 4.6%, with consistently higher effect estimates across all temperature percentiles and nearly fourfold greater effects at the highest temperature percentile. Additionally, a similar increase was observed during the hottest months at the highest percentiles, although no effects were observed below the 50th percentile. Results at lower percentiles should be interpreted cautiously, as temperature percentiles were calculated for the entire year, which led to very few observations in these ranges when the dataset was restricted to the hottest months. Future studies should explore seasonal effects in greater detail, as this was beyond the scope of our analysis.

When comparing our estimates of temperature effects at different air pollution levels to those of Stafoggia et al. (2023), their study reported that an increase in temperature (from the 75th to the 99th percentile) resulted in an increase in mortality from 8.9% at 20 μg/m³ of $PM_{2.5}$ to 12.3% at 40 μg/m³. In contrast, our study observed larger temperature effects, ranging from 8.3% to 21.4%, within the same pollution range. These differences could be related to the varying absolute temperatures corresponding to the percentiles in each study area. Moreover, our study uniquely captured a wider range of daily $PM_{2.5}$ values, extending up to 100 μg/m³ compared to 40 μg/m3 in the previous study, where a temperature increase was associated with a 63.9% change in mortality. These findings underscore the importance of considering the potential synergies between these two exposures, as neglecting them could lead to underestimations of the actual health burden and compromise the effectiveness of climate change adaptation plans. We also observed some inconsistencies in the data, such as the decreasing trend in interactive effects in Varanasi. This trend may be attributed to unique regional characteristics, including differences in $PM_{2.5}$ composition, local adaptation factors, or variability in baseline health status. These aspects warrant further investigation to better understand the underlying mechanisms.

Biological mechanisms

The pathways explaining the combined effect of air pollution and heat on mortality are still poorly understood. Seasonal climate variation alters the patterns of air pollution composition. During the hottest months, increased temperatures can alter the toxicity and composition of $PM_{2.5}$, while promoting the formation of other pollutants such as ozone and secondary particles through chemical reactions (Im et al., 2022; Kinney, 2008). Further, heat stress can also impact human thermoregulation mechanisms, reducing the ability to detoxify air pollutants and increasing vulnerability due to an elevated ventilation rate, which leads to greater intake and distribution of air pollutants (Gordon, 2003; Stafoggia et al., 2023; Zafeiratou et al., 2024). Additionally, common pathophysiologic pathways might be activated when exposed to both air pollution and high temperatures. Research indicates that both exposures can increase oxidative stress, inflammatory responses, cellular damage, apoptosis, and C-reactive protein, a biomarker of systemic inflammation—factors that are associated with higher mortality risk (Gordon, 2003; Stafoggia et al., 2023; Zafeiratou et al., 2024).

Importance and public health implications

This study provides unique evidence of interactions at the extreme levels of both air pollution and temperature. The escalating crisis of climate change is becoming increasingly relevant, particularly in India and many other LMICs. These regions are not only facing rising levels of air pollution exposure, but also experiencing more frequent, longer, and more intense heatwaves. As a result, the combined burden of both exposures is likely to become larger. Therefore, there is an immediate need for strategies, both short-term and long-term, to mitigate the combined effects of air pollution and climate change on both morbidity and mortality. Actions to reduce air pollution can be implemented within a shorter time frame than those to mitigate the impact of rising temperatures. Moreover, reducing air pollution will also have long-term effects on climate change by decreasing carbon emissions. Given several common pollutants for air pollution and climate change, these actions will have almost immediate effects on reducing mortality from both air pollution and heat with co-benefits for health. Further, an important adaptation strategy is the development of integrated surveillance and warning systems that take into account both climate hazards and air pollution levels. When these systems define the thresholds for air pollution and temperature extremes, it may be necessary to lower the threshold for each exposure during days of high air pollution and temperature episodes.

Strength and limitations

This study has several strengths. Firstly, to the best of our knowledge, it is the most extensive multi-city study conducted in India that focuses on the interaction between $PM_{2.5}$ and temperature in relation to mortality. The data included over 3.6 million deaths from the most densely populated cities in India, which experience extreme levels of air pollution (ranging from 20 to 100 $\mu g/m^3$) and temperature extremes. Secondly, we applied two advanced spatiotemporal models to estimate the daily levels of $PM_{2.5}$ and temperature. This approach enabled us to go beyond the limitations of fixed site monitors and generate population-weighted exposure metrics for each city included in the study. Lastly, we employed a sophisticated statistical model to account for the potential nonlinear interaction between air pollution and temperature. This approach simplified the interpretation of the interaction, facilitating our understanding of this complex interaction.

Some limitations should be acknowledged in this study. First, there is a disparity in the quality and completeness of death registration data across different regions in India, leading to missingness in deaths by the civil registration system. We hypothesise that these omissions are likely random in relation to the daily fluctuations in air pollution and temperature levels, and we expect that this is unlikely to bias our effect estimates. Second, we estimated daily levels of $PM_{2.5}$ and mean temperature at the city-level by averaging all the 1x1km gridded predictions within the boundaries of the city produced by both of our spatiotemporal models. This spatiotemporal modelling approach is a major improvement over previous studies that primarily relied on data from monitoring stations. However, we acknowledge that our approach may introduce some non-differential misclassification of exposure, potentially leading to an underestimation of our results (Zeger et al., 2000). In addition, we did not have data on individual residential or work addresses, residential mobility, or indoor temperature and air pollution levels. This induces exposure error, however some of that error is Berkson (e.g. individual variations around the city average) and some is non-differential. Moreover, given that the focus of our study was on day-to-day variability in outdoor exposures rather than fine-scale spatial contrasts, we consider these factors to be a minor limitation with limited impact on the overall interpretation of our findings. Third, although we included 8 of the 10 most populated cities in India, our study was limited by the lack of data from additional cities and extended time periods, restricting generalizability to other cities, rural areas, or time periods not covered by the data. As well, we lacked data on cause of death and vital sociodemographic data such as age, sex, socioeconomic status, along with other potential individual-level effect modifiers. We anticipate future research evaluating the interaction between air pollution and heat might vary across different individual and contextual levels. Finally, while we were able to estimate $PM_{2.5}$ at high spatial and temporal resolution, future studies should incorporate other relevant pollutants, such as nitrogen dioxide and ozone, which may also interact with heat but were not consistently available for all cities and for all years in our study.

5. Conclusion

Although it has been well-documented that daily $PM_{2.5}$ exposure and high ambient temperature separately both increase day to day mortality, this study conducted in India, with both extremely high air pollution levels and high daily temperatures, showed strong evidence of augmented mortality risk on days with simultaneously occurring extremely high levels of daily $PM_{2.5}$ levels and temperature. This is particularly concerning with the clear trend of global warming which increases the likelihood of more high pollution-high temperature days in most cities of India and elsewhere. The imperative of reducing $PM_{2.5}$ emissions and promoting and facilitating heat adaptation represents a clear opportunity to help reduce short-term mortality from both exposures as well as justify the investment case for interventions for both air quality management and heat adaptation. Given the common pollutants responsible for both issues and the co-benefits for health from mitigating carbon emissions, timely and relevant programs and policies for both air pollution and heat adaptation should be strategically pursued to improve public and planetary health.

Funding:

This project was funded by the Swedish Research Council for Sustainable Development ("FORMAS") (2020-00446).

Acknowledgments:

TB acknowledges financial support from Climate Change Programme, Department of Science and Technology (DST/CCP/CoE/80/2017-G) and Banaras Hindu University under IoE grant (6031), and Municipal Corporation of Varanasi for providing mortality data. BK acknowledges support from the John D. and Catherine T. MacArthur Foundation, and the William and Flora Hewlett Foundation to the Centre for Policy Research. We further thank and acknowledge Pune Municipal Corporation for providing the all-cause mortality data. RK Mall acknowledges support from the Climate Change Programme, Department of Science and Technology, New Delhi to Mahamana Centre of Excellence in Climate Change Research (DST/CCP/CoE/80/2017(G)).

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