Hot and Dirty Air: The Joint Effects of Heat and Pollution on the Risk of Heart Failure Hospitalization in Older Adults

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This thesis by **Jake Stevens** is accepted in its present form by the Brown University School of Public Health as satisfying the thesis requirements for the degree of Master of Public Health.

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Table of Contents

INTRODUCTION.....1

METHODS.....2

STUDY POPULATION.....2

ENVIRONMENTAL DATA.....3

ANALYSIS.....4

RESULTS.....6

DISCUSSION.....7

FUTURE RESEARCH.....8

LIMITATIONS.....9

CONCLUSION.....10

LIST OF TABLES.....11

TABLE 1. DEMOGRAPHICS OF MEDICARE HEART FAILURE HOSPITALIZATIONS.....11

LIST OF ILLUSTRATIONS.....12

FIGURE 1. CASE DAY HEAT INDEX AND $PM_{2.5}$ OVER STUDY PERIOD.....12

FIGURE 2. EFFECTS OF HEAT INDEX ON HEART FAILURE HOSPITALIZATIONS BY $PM_{2.5}$.....12

FIGURE 3. RERI ESTIMATES.....13

SUPPLEMENTARY.....14

REFERENCES.....15

Introduction

Climate change is having dramatic effects on human health (Campbell-Lendrum et al., 2023). In the US, we are seeing increases in heat waves, wildfires, and other extreme weather events that strongly affect health outcomes and have caused billions of dollars in economic losses (Ebi et al., 2021). Since the 2010s, many studies in the US have established associations between extreme ambient air temperature and higher mortality (Gasparrini et al., 2015; Lee et al., 2014). Similar associations have been found with fine particulate matter ($PM_{2.5}$) and higher mortality risk, as early as the 1993 Harvard Six Cities Study, with more recent studies on larger populations in the US confirming these associations (Dockery et al., 1993; Kioumourtzoglou et al., 2015). Recently, more researchers have been studying the interaction of extreme air temperature and air pollution, and the potential increased mortality risk (Hu et al., 2022; Stafoggia et al., 2023).

Aging populations are of particular concern as they are more vulnerable to elevated temperatures and air pollution. Older individuals have impaired thermoregulatory control, including decreased perspiration and skin blood flow (Balmain et al., 2018). This thermal dysregulation increases demand on the heart to supply blood and oxygen to the rest of the body, and increases the risk of cardiovascular events (Singh et al., 2024). Short-term exposure to $PM_{2.5}$ also increases the risk of cardiovascular events by increasing inflammation in the pulmonary circulation, which then extends to the systemic circulation, causing stress and damage to the heart. Thus, there is a biological basis that the combined effects (interaction) of heat and $PM_{2.5}$ can exacerbate these cardiovascular events.

Multiple case-crossover studies have previously studied the interaction of heat and $PM_{2.5}$ on all-cause and cardiovascular mortality with US populations, with significant findings showing the presence of additive and multiplicative interaction of extreme heat and elevated $PM_{2.5}$ levels (Castro et al., 2025; Rahman et al., 2022). One recent study found evidence of combined and synergistic effects of acute exposure to high temperatures and elevated $PM_{2.5}$ on heat-related hospitalizations in the Medicare population (Mock et al., 2026). Globally, one study in China looked at the synergistic effects of extreme temperature events and $PM_{2.5}$ on myocardial infarctions (MI) (Xu et al., 2023). However, to our knowledge, no one has yet studied how the co-occurrence of elevated temperature and $PM_{2.5}$ increases the risk of heart-failure hospitalizations. Heart failures are of particular interest as a recent study found the highest burden from extreme hot temperatures was for heart failure (Alahmad et al., 2023), and heart failures are the leading cause of hospitalization in the Medicare population in the United States (Wadhera et al., 2018).

To address this gap and inform policy recommendations, we investigated the joint effects of temperature and $PM_{2.5}$ on hospitalizations with an indication of heart failure by conducting a time-stratified case-crossover study. We hypothesized that there would be an increase in the risk of heart failure hospitalizations as daily mean temperature increased, and the co-occurrence of higher $PM_{2.5}$ would have an additive interaction, or exacerbate this relationship.

Methods

Study Population

This study used Medicare data from 2016 to 2023. All Medicare Fee-for-Service (FFS) beneficiaries in the continental United States with an inpatient hospitalization with a heart failure indication were included. Heart failure was determined using the International Classification of Diseases (ICD-10), mainly the I-50 code (See supplementary for full list of ICD codes). To focus on the role of heat, our analysis was limited to hospitalizations during the warmer months (May to September). Additionally, any participants who were missing residential ZIP codes were excluded.

Environmental Data

Daily mean heat index was estimated using the XGBoost-IDW Synthesis (XIS-Temperature) model (Just, Arfer, Rush, & Kloog, 2025). Briefly, XIS is a point-based spatiotemporal prediction model that incorporates both rasterized and continuous fields, allowing us to make daily predictions for precise locations in the contiguous United States. The model includes 13 different predictors that can influence temperature at a given point, such as vegetation, surface imperviousness, and distance from water. These predictors, along with an inverse distance weighting (IDW) feature that interpolates the relevant temperature measurement from the quality-controlled meteorological observation sites (e.g., more than 22,000 nationally in 2023) that collect temperature data within 100 km, are in the modeling approach that combines extreme gradient boosting (XGBoost) and IDW. To account for humidity, we used the XIS-Temperature estimates along with the XIS-Humidity model (Arfer & Just, 2026) to calculate the estimated heat index using the equation provided by the National Weather Service (Rothfusz, 1990). The XIS-Humidity model represents humidity as the dew point in kelvin.

Daily $PM_{2.5}$ means were estimated using the XGBoost-IDW Synthesis (XIS-PM) model (Just, Arfer, Rush, Lyapustin, et al., 2025). Briefly, this model takes $PM_{2.5}$ measurements from the Environmental Protection Agency's Air Quality System (AQS) and uses an inverse distance weighting (IDW) feature, which interpolates same-day particulate measurements from sites within 500 km. XIS uses aerosol optical depth from satellites along with additional predictors to make predictions at arbitrary points.

The daily exposures take into account that Medicare does not provide individual addresses but residential ZIP codes. Therefore, the exposure data is from point estimates from

Analysis

We studied the joint exposure of heat and PM with heart failure using a time-stratified case-crossover study design (Maclure, 1991). Case days were defined as the date of heart-failure hospitalization. To account for time-variant confounding, such as seasonality or day of week, control days for each case were chosen by the same day of the week within the same month and year. The within-person matching also controls for time-invariant covariates.

We fit a conditional logistic regression model to estimate the associations between heat and particulate matter on heart failure hospitalizations that included heat index, $PM_{2.5}$, and an interaction term between the two terms. To account for non-linearity, we incorporated a natural spline with 3 degrees of freedom for heat index. $PM_{2.5}$ was categorized as above or below 9μg/m^3 either on case or control day, a concentration that is also the current Annual Standard for $PM_{2.5}$ under the National Ambient Air Quality Standards. We estimated the odds of heart failure hospitalizations under various temperature and $PM_{2.5}$ scenarios using only exposure terms from the same day (lag_0).

To understand the additive interaction between heat and $PM_{2.5}$, we calculated the relative excess risk due to interaction (RERI), which quantifies the risk with exposures to both heat and $PM_{2.5}$ greater than the risk of individual effects (Knol et al., 2011; VanderWeele & Knol, 2014). RERI can be a more relevant public health measure than multiplicative interaction alone, as it measures excess risk on an additive scale to show population-level burden and preventable risk. Studying whether elevated $PM_{2.5}$ increases the risk of heart failure hospitalization during times of higher average heat index could provide evidence for targeted interventions to reduce emissions during heat events. Instead of dichotomizing it, the heat index was kept as a non-linear term to study how the excess risk changed across varying temperature exposures, rather than at a single level. The reference level for heat index was 15 ℃, which was chosen due to minimal attribution of heart failure hospitalizations seen in previous models. Therefore, we calculated RERI using the contrasts of changing from various levels of heat index, with the exposure of $PM_{2.5}$ as a binary exposure previously described. The reference level for $PM_{2.5}$ was below 9µg/m^3.

The formula for RERI is as described below:

$$RERI = OR_{11} - OR_{10} - OR_{01} + 1$$

$$OR_{11} = \text{Odds of heat and } PM_{2.5} \text{ exposure}$$

$$OR_{10} = \text{Odds of heat exposure only}$$

$$OR_{01} = \text{Odds of } PM_{2.5} \text{ exposure only}$$

A RERI value of 0 indicates no interaction, while values above 0 indicate the presence of synergistic effects. These contrasts were obtained from the previously described model. Along with the RERI estimate, 95% confidence intervals were calculated using the delta method, as described by Hosmer and Lemeshow (Hosmer & Lemeshow, 1992). The delta method was chosen because it approximates standard errors by accounting for the covariance structure in confidence intervals. The variance formula combines the contrast estimands with the covariance matrix from the model to incorporate uncertainty. With the complexity of non-linear exposures and a large sample size, the delta method was the preferred choice over computationally expensive bootstrap resampling methods (Richardson & Kaufman, 2009). The odds ratio-based RERI estimate will approximate the RERI, which is typically a function of relative risks. However, in the case-crossover study design, the odds ratio approximates the incidence rate ratio

(IRR) because the exposure during the case time is compared to the exposure during control time, similar to the IRR observed if a full cohort study were conducted (Mittleman & Mostofsky, 2014).

All statistical analyses were conducted from September 2025 to March 2026 using R version 4.5.1 and using the survival and splines packages for the main analysis.

Results

In our sample, there are 10,755,858 heart failure hospitalizations with an average of 3.4 control days. Characteristics of those who had heart failure hospitalizations are described in Table 1. Briefly, the median age was 79 years. Approximately 52% of patients were Female, 77% were White, and 23% were fully eligible for dual Medicare-Medicaid. The median case day average of Heat Index was 23 ℃, and the median $PM_{2.5}$ was 6.9 μg/m^3. 30% of the case days were above the annual limit of 9 μg/m^3.

As seen in Figure 1, heat index exposure and $PM_{2.5}$ concentration on case days varied throughout the United States. A higher average heat index over the study period of 2016-2023 was seen in the South and Southwest. Higher $PM_{2.5}$ concentrations are in the South, California, and portions of the Midwest.

From the conditional logistic regression model, there is significant evidence that the odds of heart failure hospitalization increase as average heat index increases, as seen by the non-linear effects in Figure 2 with odds ratios calculated relative to 15 ℃. For example, the estimated odds of hospitalization was .6% (OR=1.006, 95%CI: 1.05-1.008) and 1.4% (OR=1.014, 95% CI: 1.010-1.017) higher for heat indexes at 20 ℃ and 30 ℃ relative to 15 ℃, respectively. As seen in Figure 2, a higher heat index was associated with higher odds of hospitalization for both categories of $PM_{2.5}$ exposure. The association between heat and hospitalization was higher from 20 ℃ to 30 ℃ when $PM_{2.5}$ was above 9 relative to below 9 μg/m^3, but this association levels off above 30 ℃ as data points become more sparse. The estimated odds of hospitalization for $PM_{2.5}$, adjusting for heat, was .2% higher for those exposed to $PM_{2.5}$ levels greater than 9 μg/m^3 relative to those exposed to $PM_{2.5}$ levels less than 9 μg/m^3 (OR=1.002, 95% CI: .997-1.007).

We observed modest additive interaction between heat and $PM_{2.5}$ with RERI estimates above 0 at heat indices from approximately 20 ℃ to 30 ℃. However, none of these results were statistically significant, as seen in Figure 3.

Discussion

To our knowledge, this is the first study to examine the joint effects of heat and elevated $PM_{2.5}$ on heart failure hospitalizations. There was a positive association between average heat index and heart failure hospitalizations, specifically, the risk increased relative to 15 ℃ as the heat index increased. The association between $PM_{2.5}$ and heart failure hospitalizations was positive, but the corresponding confidence interval was not statistically significant. As seen in Figure 3, there was modest evidence of additive interaction as the RERI was above 0 for many heat index values, particularly in the 20-30 ℃ range, but the corresponding confidence intervals were not statistically significant.

Previous studies studying the joint exposures of heat and $PM_{2.5}$ primarily focused on all-cause or cause-specific mortality, and found mixed results on the presence of additive interaction. Multiple studies have positive RERI for some causes of mortality, but not all. One study observed additive interaction only for internal and circulatory causes (Castro et al., 2025), while another showed a statistically significant RERI for cardiovascular mortality (Rahman et al., 2022). Another difference is that these studies focused on extreme exposures, while our study focused on the average daily exposures. In addition, while these papers were recently published, the study periods were earlier time periods, which had higher $PM_{2.5}$ case-day averages than our study, as $PM_{2.5}$ has decreased in the United States (Papadogeorgou et al., 2019).

For cardiovascular morbidity, one study in China demonstrated additive interaction for myocardial infarctions during extreme heat events with temperature as a categorical variable and $PM_{2.5}$ as a categorical variable, with exposed classified as greater than 37.5 $\mu g/m^3$ (Xu et al., 2023), which is a much higher exposure threshold than our choice of 9 $\mu g/m^3$.

Future Research

In addition to being one of the first studies to study heart failure hospitalizations as the outcome, it is also one of the first to analyze how the RERI varies across a non-linear function of one of the exposures. A goal of this research and future direction is to better understand how heat warning systems could potentially benefit from accounting for $PM_{2.5,}$ especially on hot days. If there were evidence of additive interaction, it might support heat warnings at lower temperatures when $PM_{2.5}$ is elevated. Traditionally, heat alerts have not been strongly associated with preventing illness and death in the general population (Weinberger et al., 2018), so providing recommendations for clinicians and hospitals to be aware of increased risks during times of co-exposures could also be beneficial (Sorensen & Hess, 2022).

Future sensitivity analyses will be conducted to better understand at what concentrations of $PM_{2.5}$ there are acute effects on heart failure hospitalizations. Because $PM_{2.5}$ exposure is non-linear, meaningfully capturing its variation has its challenges, particularly in the context of interaction. Previous studies and our study recognize the tradeoff in using categorical variables in the interaction term, which is computationally less intensive, but may not fully capture the effects of $PM_{2.5}$. The current analysis uses the annual $PM_{2.5}$ standard to classify exposure as potentially policy relevant, but different thresholds could be used to classify exposure. For reference, the 24-hour standard for $PM_{2.5}$ is the considerably higher concentration of 35 $\mu g/m^3$, although this level is only infrequently observed in this population. Future sensitivity analyses will also include varying the degrees of freedom to model the heat index with natural splines to assess model fit with spline specifications.

Limitations

This study is not without limitations. While the Medicare dataset is fairly robust, it has geospatial constraints, with only ZIP codes of beneficiaries provided. While our estimates attempt to address this by using the point estimates from population-weighted centroids of ZIP codes, spatial measurement error will contribute to prediction error in estimating the relevant exposures. In addition, heat index and $PM_{2.5}$ both have non-linear relationships, which increases the model complexity and may not fully capture the complexity of the joint exposures. We also focused on lag_0 effects, but acknowledge that this approach may not fully account for the cumulative association of short-term exposures. However, a distributed lag non-linear model (DLNM) would add another dimension to the non-linearity in the exposures in our interaction model.

This study also has multiple strengths. Due to the comprehensive data provided by Medicare, we have a large and diverse sample in our case-crossover study design with over 10 million hospitalizations. In addition, the case-crossover study design controls for time-invariant confounding to help make inferences of the acute exposure effects. Our environmental data's underlying model has been shown to have a lower RMSE than comparative models, indicating better prediction accuracy versus prior epidemiological studies.

Conclusion

Temperatures are increasing in the United States. More research is needed to understand how cardiovascular outcomes, such as heart failure hospitalizations, are associated with heat and pollution. Our study found that the risk of heart failure hospitalization in older adults increased as heat also increased. There was modest evidence of additive interaction between heat and pollution. Future research will build off this work to better understand which thresholds are biologically and public health policy relevant.

List of Tables

Table 1: Demographics of Medicare Heart Failure Hospitalizations from 2016-2023

Characteristics of Heart Failure Patients	N = 10,755,858
Age	79 (73, 86)
Sex	
Female	5,623,963 (52%)
Male	5,131,895 (48%)
Race/Ethnicity	
White	8,245,139 (77%)
Black	1,409,847 (13%)
Hispanic	719,055 (6.7%)
AAPI	190,436 (1.8%)
AIAN	45,316 (0.4%)
Other	67,944 (0.6%)
Missing	78,121 (0.7%)
Dual Eligibility	
None	7,672,231 (71%)
Partial	643,856 (6.0%)
Full	2,439,771 (23%)
Case-Day XIS Heat Index	23 (19, 27)
Case-Day XIS $PM_{2.5}$	6.9 (5.0, 9.6)
Case-Day XIS $PM_{2.5}$ Category	
Below 9µg/m^3	7,536,963 (70%)
9µg/m^3 and Above	3,218,895 (30%)
Median (Q1, Q3); n (%)	

List of Illustrations

Figure 1: Case Day Heat Index and $PM_{2.5}$ Over Study Period

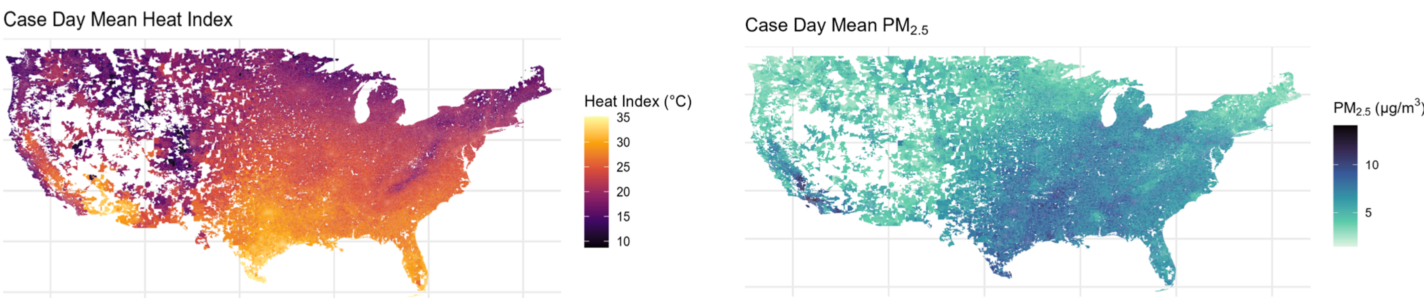


Figure 2: Effects of Heat Index on Heart Failure Hospitalizations by $PM_{2.5}$

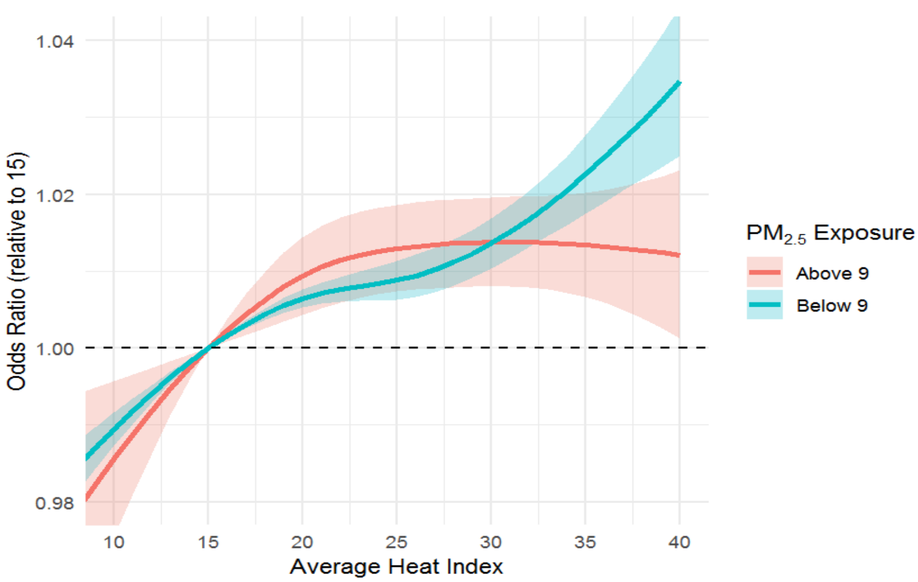
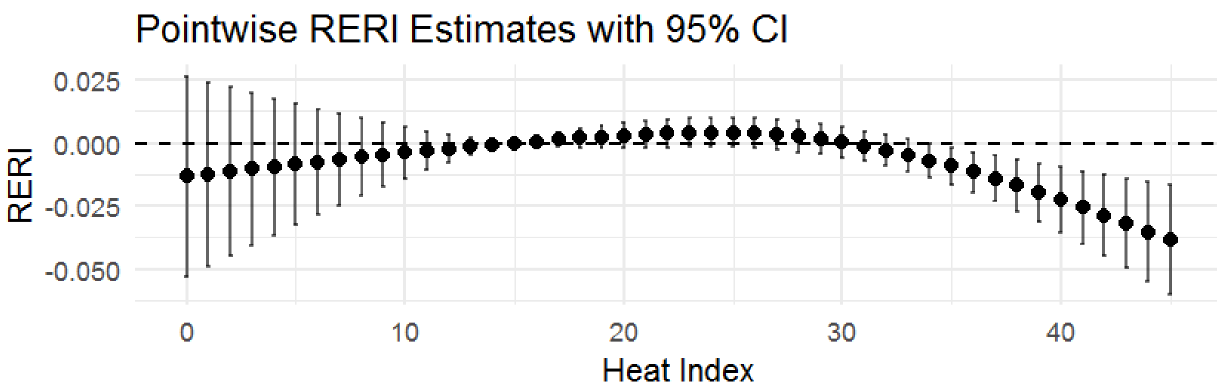


Figure 3: RERI Estimates



Supplementary

Table 1: ICD-10 codes included in the case definition

I50	Heart failure
I50.0	Congestive heart failure
I50.1	Left ventricular failure
I50.2	Systolic (congestive) heart failure
I50.3	Diastolic (congestive) heart failure
I50.4	Combined systolic and diastolic (congestive) heart failure
I50.9	Heart failure, unspecified
I11.0	Hypertensive heart disease with heart failure
I13.0	Hypertensive heart disease and renal disease with congestive heart failure
I13.2	Hypertensive heart disease and renal disease with congestive heart failure and renal failure
I09.81	Rheumatic heart failure

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