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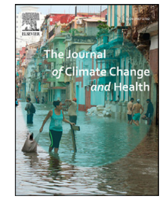

Research article

Exploring neighborhood racial and socioeconomic heterogeneity in the short-term effects of air pollution and extreme heat on medical emergencies

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ABSTRACT

Introduction: As climate change continues to affect society, understanding how adverse climatic conditions impact different communities differently is essential to equitable climate change mitigation. While research has identified the potential for climate change to impact public health in terms of air quality and extreme heat, less research has explored *inequality* regarding how these events impact public health. This paper explores inequality in the effects of climatic events on short-term health based on air pollution and severe heat.
Methods: Using two-way fixed-effects models, racial and socioeconomic heterogeneity in the effects of air pollution and extreme heat on the incidence of medical emergencies are examined.
Results: Results suggest that poor air quality predominantly affects the incidence of medical emergencies in poor, non-White neighborhoods and has minimal effects in affluent White neighborhoods. Neighborhoods with more impoverished residents experience more medical emergencies on days with extreme heat.
Conclusion: Overall, the results suggest that extreme heat has substantial effects on medical emergencies, but there is little racial heterogeneity in these effects. Notably, the results provide little evidence of an interaction effect between poor air quality and extreme heat. The results show the need for climate change mitigation strategies that are equitable for all communities.

1. Introduction

Two central outcomes of climate change are air pollution and extreme temperatures [1]. Climate change leads to an amplified greenhouse effect. Rising temperatures impact ozone levels, impacting air quality [2]. An additional way climate change reduces air quality is through increased forest fires [3].

Past research highlights an array of impacts of climate change on health [1]. Recent research found that heat waves induce spikes in mortality in the US among those with cardiovascular, vascular, and respiratory diseases [4]. These effects tend to be concentrated in the elderly and people with comorbidities [1].

Air pollution has a variety of adverse health effects [5]. Short-term exposure to air pollutants has been closely tied to “COPD (Chronic Obstructive Pulmonary Disease), cough, shortness of breath, wheezing, asthma, respiratory disease, and high rates of hospitalization (a measurement of morbidity)” [5]. Numerous studies in the US have highlighted statistically notable increases in mortality from short-term exposure to air pollution [6]. This is especially true for particulate matter that can be inhaled, specifically particles with an aerodynamic diameter of less than 20 micrometers.

Marginalized groups often suffer more from the effects of heat. Analyses in the aftermath of the 1995 Chicago heat wave found that many victims were elderly people living in disadvantaged neighborhoods without air conditioners or the means to turn them on [7]. Research similarly shows that air pollution disproportionately affects people of color and low socioeconomic status [8,9]. Recent research suggests Black and lower-income Americans are more susceptible to the effects of air pollution. Josey and colleagues [20] observed that marginalized groups exhibit higher vulnerability to airborne particulate matter and attributed this to social inequalities. They argued that Black and low-income Americans have subpar healthcare and housing and lack resources that can mitigate the effects of air pollution and therefore, suggested that socioeconomic differences are key to understanding racial disparities in the health problems caused by air pollution [20].

Ultimately, a neighborhood perspective may help to understand the potential impacts of extreme weather events. Past research has identified individual-level racial and socioeconomic factors that shape how extreme weather events are experienced, and many of the relevant factors are inherently neighborhood-level. Non-White Americans are more likely to live in an urban heat island where

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extreme heat is exacerbated by the built environment [10]. Other research suggests similar disproportionate exposure to urban air pollution in non-White neighborhoods because of inequalities in the built environment [11]. Inequalities in institutional resources pose challenges to impoverished neighborhoods in mitigating the effects of air pollution and extreme heat, like challenges to indoor ventilation, insufficient housing quality, and a lack of air conditioning and public neighborhood institutions that can provide relief from air pollution or extreme heat [7,12–15].

Recent research suggests that race and socioeconomic status drive the number of medical emergencies in a neighborhood [16,17]. While hospital admission data only offers an understanding of short-term health effects across broader regions, calls for medical emergencies show variation across smaller geographical units, providing a more nuanced understanding of how adverse climate conditions affect different neighborhoods. Moreover, extreme heat and air pollution are interrelated hazards that can have compounding effects on overall health, particularly respiratory health [21]. The potential for heat to intensify air pollution's effects underscores the importance of studying these hazards together. Broadly, air quality is generally expected to be worse during extreme heat [22]. Recent research [18] has found that there is an important interaction effect between extreme heat and wildfire smoke on cardiorespiratory hospitalizations and that this effect is worse in neighborhoods with more poverty and non-White residents. This research, however, is limited in assessing only a limited geography (California), a coarser unit of analysis (zip codes), a specific form of air pollution (wildfire smoke), and a specific type of medical event (cardiorespiratory arrests).

While it is well-established that environmental factors play a critical role in public health outcomes, the granularity of these effects across different neighborhood compositions remains less explored. This paper delves into heterogeneity in the effects of air quality and extreme heat on medical emergencies across neighborhoods.

2. Material and methods

The data for this project comes from four sources. First, information on medical incidents was taken from PulsePoint, an online platform that publicizes computer-assisted dispatch details from emergency medical and fire services departments. While US agencies can choose to employ this platform, it is not mandatory. Six hundred thirty-four agencies were active on PulsePoint during the period of analysis in the summer of 2021. These agencies typically correspond with city or county demarcations. The agencies on PulsePoint are highly varied geographically [16].

Data was gathered from every dispatch across these agencies over three months in the summer of 2021. Each dispatch provides a precise location, date and time, and nature of the emergency based on standardized classification. The data was then geocoded to specific census block groups using the point in polygon method, implanted using the *"over"* function from the *"sf"* package in *R* version 4.4.1. The data encompasses all dispatches, including false alarms, which may be present in the data but cannot be distinguished. Notably, false alarms would have to systemically be associated with *the interaction* between neighborhood racial and socioeconomic composition and daily variation in weather conditions in order to bias the results of this analysis. Randomly distributed false alarms or false alarms that vary just by neighborhood or just by day would not bias the results. Agencies are associated with census block groups based on their delineated territories in PulsePoint.

In terms of national representation, census block groups represented in the PulsePoint data have a slightly lower proportion of White and Black residents but a higher percentage of Hispanic residents. Geographically, the Western region is represented more prominently than others in the data. Urban areas seem more prevalent than rural areas in the dataset. These differences were identified based on a previous analysis of the PulsePoint data, that compared the census block groups covered by PulsePoint agencies with the entire universe of all census block groups in the United States using data from the American Community Survey [16]. Since the focus of the analysis is on within-neighborhood variation over time, these differences should be insubstantial so long as there is limited effect heterogeneity based on region.

Second, data on the demographic and socioeconomic characteristics of census block groups was taken from the 2017−2021 American Community Survey 5-year estimates, which constitute a random 5% sample of all American households. Neighborhood racial and poverty composition data are obtained from Social Explorer tables B04001 and B13004. Poverty status is defined by the U.S. Census Bureau based on income thresholds specific to family size. Third, temperature data was taken from the National Oceanic and Atmospheric Administration's Global Historical Climate Network Daily Summaries. This dataset contains daily weather records from weather stations across the US. For each census block group, the nearest weather station was identified based on the 2020 Census population centroids. The maximum temperature and relative daily humidity of each weather station on each day was subsequently assigned to each census block group on each respective day.

Fourth, air quality data was taken from the Environmental Protection Agency's Pre-Generated Data Files and county-level Daily Summary data for 2021. The dataset contains average daily Air Quality Indexes for each county from 2021. Daily average air quality indices were linked to census block groups based on the county in which the census block group was located. Ethics approval was not required for this study because only publicly-available data were used.

Methodologically, two-way fixed effects models were used to assess the effect of daily air pollution and maximum temperatures on the incidence of medical emergencies in a neighborhood. For this analysis, neighborhoods are operationalized as census block groups. Days with extreme heat were defined as days when the wet-bulb temperature exceeded 25° Celsius. The wet-bulb temperature was calculated as the weighted average of dry-bulb temperature and humidity, following the Stull [23] approximation formula for outdoor conditions. Days with poor air quality were defined as days where the Air Quality Index exceeded 100.

Table 1 presents summary statistics. Overall, 17.0% of all census block group days are extreme heat days, and 13.0% of all census block group days are poor air quality days. About 1.3% of all census block group days are both extreme heat and poor air quality days.

To examine heterogeneity in the effects of extreme heat and poor air quality on medical emergencies, a series of four models are estimated using the *"fixest"* package in *R* version 4.4.1. While this series of models will be introduced and explained specifically in terms of extreme heat, these models are also estimated for air quality. Model 1 estimates simply the effect of extreme heat on medical emergencies, not allowing for heterogeneity in effect between neighborhoods, and can be used as a baseline to evaluate model fit. Model 2 estimates heterogeneity in the effect of extreme heat in terms of neighborhood racial composition. Model 3 estimates heterogeneity in the effect of extreme heat in terms of neighborhood poverty. Model 4 estimates heterogeneity in the effect of extreme heat in terms of both neighborhood racial composition and neighborhood poverty. The full formulas for Models 1,2 and 3 is available in the appendix.

The full model (Model 4) for extreme heat can be written as follows:

$$\begin{aligned}\ln\left(\mu_{ij}\right) = {} & \beta_0 * HOT_{ij} + \beta_1 * BLACK_i * HOT_{ij} + \beta_2 * HISP_i * HOT_{ij} + \beta_3 \\ & * ASIAN_i * HOT_{ij} + \beta_4 * NATIVE_i * HOT_{ij} + \beta_5 * PACIFIC_i \\ & * HOT_{ij} + \beta_6 * OTHER_i * HOT_{ij} + \beta_7 * POV_i * HOT_{ij} + \Delta_i \\ & + \nabla_j + \in\end{aligned}$$

Table 1
Summary statistics.

Variable	Mean	Sd	Min	Pctile [25]	Pctile [75]	Max
Count	0.26	0.64	0	0	0	39
Prop. Black	0.12	0.2	0	0	0.12	1
Prop. Hispanic	0.21	0.24	0	0.036	0.3	1
Prop. Native	0.0043	0.021	0	0	0	1
Prop. Asian	0.084	0.14	0	0	0.097	1
Prop. Pacific	0.0031	0.019	0	0	0	0.69
Prop. Other	0.042	0.052	0	0.0053	0.059	0.7
Prop. Poverty	0.13	0.13	0	0.033	0.17	1
Poor AQI	0.13	0.34	0	0	0	1
Extreme Heat	0.17	0.38	0	0	0	1

where μ_{ij} represents the number of medical emergencies in neighborhood i on day j, $BLACK_i$ represents the proportion of residents in neighborhood i who are non-Hispanic Black, $HISP_i$ represents the proportion of residents in neighborhood i who are Hispanic of any race, $ASIAN_i$ represents the proportion of residents in neighborhood i who are non-Hispanic Asian, $NATIVE_i$ represents the proportion of residents in neighborhood i who are non-Hispanic American Indian or Alaska Native, $PACIFIC_i$ represents the percentage of residents in neighborhood i who are non-Hispanic Native Hawaiian or other Pacific Islander, $OTHER_i$ represents the percentage of residents in neighborhood i who are non-Hispanic and identify as belonging to some other race or two or more races, POV_i represents the proportion of residents in neighborhood i who are in poverty,[1] HOT_{ij} represents an indicator variable denoting if neighborhood i had extreme heat on day j (1 if so; 0 otherwise), Δ_i represents census block group level fixed effects, and ∇_j represents day-level fixed effects. Following these definitions, the interaction terms are calculated in the typical fashion by multiplying the two variables together. For example, $BLACK_i * HOT_{ij}$ is equivalent to zero if neighborhood i did NOT experience extreme heat on day j or if 0 % of neighborhood i's residents are non-Hispanic Black. If neighborhood i did experience extreme heat on day j, then $BLACK_i * HOT_{ij}$ is equivalent to the proportion of residents in neighborhood i that are non-Hispanic Black. Subsequently, the interaction term is non-zero and larger only if the neighborhood has a high proportion of Black residents and if the neighborhood experiences extreme heat on that day. Consequently, the coefficient for this interaction term reveals heterogeneity in the effect of extreme heat on the count of medical emergencies in terms of neighborhood proportion Black.

The main coefficients of interest in this model are the interaction terms. Time-invariant attributes of neighborhoods refer to factors that remain constant over time within each neighborhood that drive variation in the incidence of medical emergencies, such as the neighborhood population size and the age composition of the neighborhood's residents.[2] Time-varying attributes, on the other hand, represent factors that change across all census block groups nationwide on a daily basis, such as seasonal variation in outdoor activity or public health crises. The fixed effects in the model control for both types of unobserved attributes, allowing the estimates to focus on the daily effects of air pollution and extreme heat on the incidence of medical emergencies. The interaction term coefficients subsequently represent unique differences in the count of medical emergencies between types of neighborhoods on days with extreme heat, controlling for time-invariant differences between neighborhoods. For example, the β_1 coefficient in the model represents the estimated additional difference in the count of medical emergencies between a 100 % Black neighborhood and a 100 % White neighborhood that is observed on days with extreme heat, controlling for the difference that would be expected to be observed on other non-extreme heat days. A significant, positive coefficient here would indicate that Black neighborhoods face disproportionately more medical emergencies on days with extreme heat compared to White neighborhoods. Coefficients β_2 through β_7 can be interpreted analogously. Coefficient β_0 can be interpreted as the expected increase in medical emergencies on a day with extreme heat, relative to a day without extreme heat, in a 100 % non-Hispanic White neighborhood with a 0 % poverty rate. Coefficients are defined as statistically significant if the p-value is below 0.05.

By controlling for variation between census block groups and days in terms of incidence, the intention is to isolate heterogeneity in the effect of weather conditions on medical emergencies. These results should be interpreted in purely descriptive terms, however. The intention is not to precisely estimate variation in the causal effect of certain weather conditions, but rather to examine how certain weather conditions are associated with different levels of medical emergencies depending on neighborhood attributes.

3. Results

3.1. Air quality

Table 2 presents models assessing the effect of daily air quality on the incidence of medical emergencies in neighborhoods. Model 1 includes an indicator variable for whether the air quality index was poor on the given day and neighborhood and day fixed effects. The results reveal a small but statistically significant positive effect of poor air quality on medical emergencies. On days with poor air quality, neighborhoods see about 0.9% more medical emergencies.

Model 2 tests for racial heterogeneity in the effect of poor air quality on the incidence of medical emergencies. The omitted racial group is non-Hispanic White. The inclusion of the interaction terms attenuates the effect of the poor air quality from a positive and significant level to a negative and non-significant level. This indicates that in an all-White neighborhood, poor air quality has a negative, insignificant effect on the incidence of medical emergencies. The interaction between proportion Hispanic and poor air quality is positive and significant. The coefficient indicates that relative to a 100 % White neighborhood on a poor air quality day, a 100% Hispanic neighborhood will experience an additional 3.4% more medical emergencies. The interaction between proportion Other and poor air quality is also positive and significant. The coefficient indicates that relative to a 100% White neighborhood on a poor air quality day, a 100% "other" neighborhood will experience 18.9% more medical emergencies. All other coefficients are insignificant.

Model 3 tests for socioeconomic heterogeneity in the effect of poor air quality on the incidence of medical emergencies. Relative to Model 1, the interaction term attenuates the effect of the poor air quality indicator from a positive and significant level to a negative and non-significant level. This indicates in a neighborhood with no residents in poverty, poor air quality has a negative and insignificant effect on the incidence of medical emergencies. The interaction between poverty and poor air quality is positive and significant. The coefficient size suggests that a neighborhood where all residents are

[1] The inclusion of both racial and economic variables in the same model should not pose substantial issues, as the correlation between these variables is not very high in the dataset. The correlation between proportion non-Hispanic Black and proportion in poverty is 0.299, the correlation between proportion Hispanic and proportion in poverty is 0.179. Correlations under 0.3 are generally considered "negligible correlations" (Mukaka 2012).

[2] To provide descriptive context, I estimated a Poisson regression model using the panel data, regressing the count of medical emergencies on neighborhood racial/ethnic proportions. Results show that higher proportions of Black (0.719), Hispanic (0.404), Native American (1.506), and Pacific Islander (1.233) residents are associated with higher medical emergency counts, while higher proportions of Asian (-0.296) and "Other" (-0.096) residents are associated with lower counts (p<0.001 for all). The adjusted pseudo R-squared is 0.007, indicating that these variables explain only a small proportion of variation. These findings are included for context and do not reflect the within neighborhood temporal variation central to the fixed-effects models.

Table 2
Effect of air quality on medical emergencies.

	Model 1	Model 2	Model 3	Model 4
Poor AQI	0.009 *	-0.014	-0.001	-0.019 *
	[0.001, 0.016]	[-0.031, 0.004]	[-0.012, 0.010]	[-0.038, -0.001]
Prop. Black X Poor AQI		0.003		-0.012
		[-0.042, 0.048]		[-0.059, 0.035]
Prop. Hispanic X Poor AQI		0.033 *		0.024
		[0.004, 0.063]		[-0.006, 0.054]
Prop. Native X Poor AQI		-0.044		-0.088
		[-0.246, 0.159]		[-0.293, 0.117]
Prop. Asian X Poor AQI		0.052		0.058
		[-0.005, 0.110]		[-0.000, 0.115]
Prop. Pacific X Poor AQI		0.069		0.052
		[-0.344, 0.483]		[-0.361, 0.465]
Prop. Other X Poor AQI		0.173 *		0.163
		[0.000, 0.346]		[-0.010, 0.335]
Prop. Poverty X Poor AQI			0.061 *	0.066 *
			[0.010, 0.111]	[0.011, 0.120]
N	4,189,677	4,189,677	4,189,677	4,189,677
AIC	4,565,659.281	4,565,660.057	4,565,654.670	4,565,655.443
BIC	5,181,260.333	5,181,340.598	5,181,268.970	5,181,349.232
Pseudo R2	0.210	0.210	0.210	0.210

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

in poverty has 6.3% more medical emergencies on bad air quality days than a neighborhood where no residents are in poverty.

Model 4 combines tests for racial and socioeconomic heterogeneity into a single model to assess the principal drivers of heterogeneity in the effect of poor air quality on the incidence of medical emergencies. Relative to Model 2, the coefficient for the interactions between proportion Hispanic/Other and poor air quality are attenuated beyond statistical significance. Relative to Model 3, the coefficient for the interaction between poverty and poor air quality increases and remains statistically significant.

3.2. Heat

Table 3 presents an identical set of models for extreme heat. Model 1 evaluates the impact of extreme heat on any given day, taking the specific neighborhood and day into account. The findings show a significant rise in medical emergencies during days with extreme heat, increasing roughly 2.7% in affected areas. Model 2 explores racial heterogeneity in the effect of extreme heat on medical emergencies. Compared to Model 1, the previously significant adverse effect of extreme heat is reduced, but remains substantial and highly significant in Model 2. Notably, none of the interaction terms in Model 2 are significant. This suggests that extreme heat has similar adverse impacts on medical emergencies in all neighborhoods, regardless of racial composition.

Model 3 examines socioeconomic variations in the effects of extreme heat on medical emergencies. The results indicate that the interaction between neighborhood poverty and extreme heat is statistically significant. This suggests that neighborhoods with higher poverty rates experience disproportionately more medical emergencies during periods of extreme heat, potentially highlighting socioeconomic disparities in vulnerability to heat-related health issues. Model 4 integrates both racial and socioeconomic factors to explore the combined effects on medical emergencies during extreme heat. While racial composition does not significantly moderate the relationship between extreme heat and medical emergencies, the significant interaction between neighborhood poverty and extreme heat persists. This confirms that poverty

Table 3
Effect of extreme heat on incidence of medical emergencies.

	Model 1	Model 2	Model 3	Model 4
Extreme Heat	0.027 ***	0.017 *	0.017 **	0.012
	[0.019, 0.035]	[0.001, 0.033]	[0.006, 0.028]	[-0.004, 0.029]
Prop. Black X Extreme Heat		0.015		0.001
		[-0.014, 0.043]		[-0.030, 0.032]
Prop. Hispanic X Extreme Heat		0.027		0.020
		[-0.013, 0.066]		[-0.020, 0.059]
Prop. Native X Extreme Heat		0.073		0.032
		[-0.372, 0.518]		[-0.417, 0.482]
Prop. Asian X Extreme Heat		-0.008		-0.006
		[-0.084, 0.068]		[-0.082, 0.070]
Prop. Pacific X Extreme Heat		-0.078		-0.090
		[-0.561, 0.406]		[-0.571, 0.392]
Prop. Other X Extreme Heat		0.056		0.047
		[-0.114, 0.226]		[-0.123, 0.218]
Prop. Pov. X Extreme Heat			0.065 **	0.063 *
			[0.016, 0.114]	[0.008, 0.117]
N	4,189,677	4,189,677	4,189,677	4,189,677
AIC	4,565,605.926	4,565,614.295	4,565,599.802	4,565,610.072
BIC	5,181,206.977	5,181,294.836	5,181,214.102	5,181,303.861
Pseudo R2	0.210	0.210	0.210	0.210

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

remains a key factor associated with increased medical emergencies during extreme heat, even when accounting for racial composition.

3.3. Air quality and heat

Table 4 combines the terms used in Tables 2 and 3 into a single set of models. The motivation behind this model is to test the interactive effect of days with both extreme heat and poor air quality as well as to assess whether one of the effects is a dominant driver of medical emergencies. Model 1 includes the extreme heat indicator, the poor air quality indicator, the interaction between the extreme heat and poor air quality indices, and two-way fixed effects. The results reveal that extreme heat and poor air quality both independently have a positive and statistically significant association with medical emergencies. The effect size of extreme heat is substantially larger than the effect size of poor air quality. The interaction between extreme heat and poor air quality is negative and insignificant. This suggests that the effects of heat and poor air quality are independent.

Model 2 incorporates interaction terms between racial composition and both extreme heat and poor air quality. Notably, the coefficients for extreme heat, poor air quality, and their interaction are all statistically insignificant, suggesting that these environmental factors do not have an amplified effect on medical emergencies when considered alongside racial composition interactions. However, there are significant interactions between racial composition and poor air quality. Specifically, the proportion of Hispanic residents is positively associated with poor air quality, as is the proportion of Other racial groups. Notably, there is a significant negative interaction between Hispanic residents and the joint effects of extreme heat and poor air quality, which potentially suggests that the model is overfit in regard to predominately Hispanic neighborhoods.

Table 4
Effect of air pollution and heat on medical emergencies.

	Model 1	Model 2	Model 3	Model 4
Extreme Heat	0.027 ***	0.014	0.018 **	0.010
	[0.019, 0.035]	[-0.002, 0.031]	[0.007, 0.029]	[-0.007, 0.027]
Poor AQI	0.009 *	-0.015	0.000	-0.020 *
	[0.001, 0.017]	[-0.033, 0.004]	[-0.011, 0.011]	[-0.039, -0.001]
Extreme Heat X Poor AQI	-0.003	0.045	-0.023	0.029
	[-0.029, 0.022]	[-0.026, 0.116]	[-0.061, 0.016]	[-0.044, 0.103]
Prop. Black X Extreme Heat		0.015		0.003
		[-0.014, 0.043]		[-0.029, 0.034]
Prop. Black X Poor AQI		0.002		-0.012
		[-0.045, 0.048]		[-0.060, 0.036]
Prop. Hispanic X Extreme Heat		0.042		0.036
		[-0.002, 0.086]		[-0.009, 0.080]
Prop. Hispanic X Poor AQI		0.036 *		0.028
		[0.006, 0.066]		[-0.003, 0.058]
Prop. Native X Extreme Heat		0.102		0.068
		[-0.352, 0.555]		[-0.391, 0.527]
Prop. Native X Poor AQI		-0.030		-0.070
		[-0.231, 0.172]		[-0.273, 0.134]
Prop. Asian X Extreme Heat		-0.008		-0.006
		[-0.111, 0.095]		[-0.109, 0.097]
Prop. Asian X Poor AQI		0.052		0.057
		[-0.007, 0.111]		[-0.002, 0.116]
Prop. Pacific X Extreme Heat		-0.151		-0.160
		[-0.619, 0.317]		[-0.626, 0.307]
Prop. Pacific X Poor AQI		0.040		0.023
		[-0.377, 0.457]		[-0.393, 0.440]
Prop. Other X Extreme Heat		0.068		0.061
		[-0.107, 0.244]		[-0.115, 0.237]
Prop. Other X Poor AQI		0.189 *		0.179 *
		[0.013, 0.364]		[0.004, 0.354]
Prop. Black X Extreme Heat X Poor AQI		0.073		0.050
		[-0.109, 0.256]		[-0.136, 0.236]
Prop. Hispanic X Extreme Heat X Poor AQI		-0.111 *		-0.122 *
		[-0.220, -0.002]		[-0.233, -0.010]
Prop. Native X Extreme Heat X Poor AQI		-0.719		-0.784
		[-3.014, 1.575]		[-3.032, 1.463]
Prop. Asian X Extreme Heat X Poor AQI		-0.042		-0.049
		[-0.206, 0.122]		[-0.212, 0.115]
Prop. Pacific X Extreme Heat X Poor AQI		1.104		1.033
		[-0.347, 2.555]		[-0.372, 2.438]
Prop. Other X Extreme Heat X Poor AQI		-0.300		-0.298
		[-0.939, 0.339]		[-0.933, 0.336]
Prop. Poverty X Extreme Heat			0.059 *	0.053
			[0.008, 0.109]	[-0.003, 0.109]
Prop. Poverty X Poor AQI			0.056 *	0.060 *
			[0.005, 0.107]	[0.005, 0.115]
Prop. Poverty X Extreme Heat X Poor AQI			0.186	0.199
			[-0.032, 0.404]	[-0.027, 0.424]
N	4,189,677	4,189,677	4,189,677	4,189,677
AIC	4,565,603.783	4,565,617.303	4,565,591.517	4,565,607.020
BIC	5,181,231.332	5,181,483.317	5,181,258.809	5,181,512.779
Pseudo R2	0.210	0.210	0.210	0.210

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Model 3 continues to explore the interaction between extreme heat, poor air quality, and socioeconomic factors. The coefficient for extreme heat remains positive and statistically significant, confirming its strong association with increased medical emergencies. However, the coefficient for poor air quality is insignificant, suggesting that poor air quality alone does not significantly contribute to medical emergencies in this model. Interestingly, while the interaction between extreme heat and poor air quality is also insignificant, the interaction between poverty and either of these factors reveals important disparities. Specifically, the coefficient for the interaction between poverty and extreme heat is positive and significant, as is the interaction between poverty and poor air quality. This indicates that high-poverty neighborhoods experience a disproportionate impact from both extreme heat and poor air quality. Despite this, the three-way interaction between poverty, extreme heat, and poor air quality is not significant, suggesting that while poverty amplifies the individual effects of extreme heat and poor air quality, it does not significantly modify the combined impact of these factors.

Model 4 shows that the coefficient for extreme heat is insignificant, while poor AQI has a negative and significant effect on medical emergencies. The interaction between extreme heat and poor AQI is also insignificant. However, the results highlight significant effects for the proportion of Other residents and poor AQI, as well as a negative interaction between the proportion of Hispanic residents and the combined effect of extreme heat and poor AQI—once again suggesting the model may be overfit here. Additionally, poverty amplifies the impact of poor AQI, suggesting greater vulnerability in poorer neighborhoods.

4. Discussion

This paper seeks to understand the impacts of air quality and extreme heat on the occurrence of medical emergencies across neighborhoods with varying racial and socioeconomic compositions. The analyses generally reveal some heterogeneity in the effects of poor air quality, with poor air quality predominantly being associated disproportionately with medical emergencies in impoverished, non-White neighborhoods. Relative to affluent White neighborhoods, neighborhoods with more Hispanic and "other" residents, as well as neighborhoods with more impoverished residents, witness a significant increase in medical emergencies during poor air quality days.

With respect to extreme heat, the findings exhibit a more universal effect, with medical emergencies rising across neighborhoods, irrespective of racial composition. Notably, poverty appears to be strongly associated with higher vulnerability to extreme heat. This implies that extreme heat presents a more generalized health risk, although areas with higher poverty rates bear a somewhat heavier burden. This is a surprising finding and does not align with past research, which suggests that marginalized, non-White individuals and communities are more susceptible to the harmful effects of extreme heat. However, some past research has also found mixed evidence to support this hypothesis—Klinenberg [7], for example, found that Hispanic individuals had much lower mortality during the 1995 Chicago Heat Wave. It is possible that the unequal effects of extreme heat may not best be detected in terms of short-term effects on medical emergency calls. Past research has suggested that deaths caused by extreme heat are likely to be among those who are most socially isolated, which may potentially mean that no one is there to call in the medical emergency. In combination, there was no evidence to suggest an overall significant positive interaction between extreme heat and poor air quality. This lack of interaction may be due to the relatively small number of days with both extreme heat and poor air quality, which limits the ability to detect compounding effects. Additionally, the mismatch in the geographic granularity of the air quality and temperature data may further obscure potential interactions. It is also possible that the methodology employed here, which treats air quality and heat as distinct factors, may not fully capture the interactions that operate through measured air quality, such as the well-documented relationship between heat and ozone.

This study has several limitations. First, it relies on the Air Quality Index and extreme heat measurements at broader levels of geography (nearest weather station and county average), which may not capture localized variations. Consequently, the results may slightly misrepresent areas with more unique conditions that are not well-represented by the county average or nearest weather station. Second, there are challenges to estimating causal relationships from observational data. Despite the advantages of two-way fixed-effects modeling, unobserved confounding variables may still influence the results [19]. While the novel data in this paper offers insight into localized medical emergencies, emergency calls for medical emergencies may not be representative of all medical emergencies. False alarm 911 calls for medical emergencies may be present in the data, and some people who experience medical emergencies may not call 911. An additional important contextual limitation of this study is that the time period analyzed was the Summer of 2021, which was during the COVID-19 pandemic—subsequently, the findings of these analyses may be inconsistent with those done outside of the pandemic. In addition, the timing of the heat wave within the year was not accounted for, and since heat waves early in the summer tend to have higher morbidity, there is likely additional effect heterogeneity the model is not capturing [24]. Cumulative effects are similarly not examined and this analysis does not account for the delayed effects of extreme heat on health outcomes, as hospitalizations and illness often increase a few days after the initial exposure, which introduces further complexity that is beyond the scope of this study.

This analysis spurs future research across overlooked sources of inequality in the effects of climate change. Delving into localized air quality and microclimate data can offer a more granular understanding of health impacts, capturing variations potentially missed in broader neighborhood-level metrics. Future research could investigate how the timing of heat waves within a season contributes to morbidity, as early-summer heat waves tend to result in higher health impacts. Additionally, exploring the cumulative effects of successive heat waves could provide a more comprehensive understanding of the long-term health consequences of extreme weather events. Future research could also explore the lagged effects of extreme heat and air pollution on health outcomes, particularly the delayed rise in hospitalizations and illness that occurs several days after initial heat exposure, to provide a more complete understanding of how extreme weather impacts public health over time.

With some evident differential effects across racial and socioeconomic groups, a deeper exploration into intra-group differences and intersectional impacts is crucial. Such investigations could help identify more vulnerable subgroups. Individual-level health microdata could better assess the drivers of the unequal impacts of adverse weather on health. Incorporating a broader range of neighborhood factors that are pertinent to the experience of extreme weather events into an analysis would provide practical insights into the factors that contribute to racial and socioeconomic disparities in neighborhood experiences and suggest potential strategies to reduce inequality. As calls to mitigate the scale of climate change increase, so should calls for mitigating its impact on inequality.

5. Conclusion

In conclusion, this study highlights the significant role of air quality and extreme heat in shaping health outcomes across neighborhoods with varying racial and socioeconomic compositions. While poor air quality disproportionately affects medical emergencies in non-White, impoverished neighborhoods, extreme heat presents a more universal risk, with poverty emerging as a key factor in vulnerability. The lack of significant interaction between heat and air quality may be attributed to data limitations and the relatively small number of extreme weather events. These findings emphasize the need for future research to focus on localized environmental data, cumulative weather effects, and lagged health outcomes to better understand the nuanced impacts of climate change on public health. Addressing these disparities is essential as efforts to mitigate climate change move forward, ensuring that strategies also work toward reducing inequality in health risks.

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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.

CRediT authorship contribution statement

Karl Vachuska: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

Supplementary materials

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